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SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Wireline broadband access networks and home networking

Foreword

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This new Technical paper gives a valuable overview of the technologies forming modern access networks, based primarily on ITU-T access network and home networking standards ("ITU-T Recommendations"). The Technical paper's overall aim is to provide a non-expert reader with the background information necessary to an understanding of the context and content of these ITU-T Recommendations; offering practical guidance to administrations, operators and suppliers in planning and implementing the access networks of fundamental importance to our modern world.

Access network technology is advancing rapidly with close to six hundred million subscribers possessing broadband connections to the Internet[1]. Many of them connect using ITU standardized technologies covering for example; digital subscriber line (DSL) technology, cable modems, or fibre to the home (FTTH).

Fixed broadband services are delivered in a variety of ways: over direct optical fibre connections, traditional telephone networks, coaxial cable in community access television (CATV) networks, wireless networks, or even via electricity distribution grids.

A broadband connection delivers data, voice and video at unprecedented speeds, with vectored VDSL2 (Recommendation ITU-T G.993.5) achieving aggregate bit-rates in the region of 250 Mb/s, and the "G.fast for FTTdp (Fibre-to-the-Distribution Point)" standardization project, to be completed by March 2014, will increase these rates to an extraordinary 1 Gb/s. The networks enabling such high-speed data exchange are considered critical to spurring economic growth and bridging the digital divide. Today's access networks have created new opportunities to produce equipment with advanced computational and communications capabilities and to connect this equipment within a home network to the outside world via the customer's broadband service.

In summary, the access network is experiencing rapid technological change, unprecedented subscriber growth rates, a proliferation of new products and solutions, and entries to the market by a wide range of new service providers; resulting in equipment suppliers often unfamiliar with critical standards, and governments eager, but ill-equipped, to deploy these advanced technologies. Access network standardization will consequently see increased involvement from stakeholders not traditionally affiliated with ITU or even the ICT industry. More than ever before, the market for access technologies and networks is in need of coordinated international standardization and we are proud of the leading role ITU-T has earned in this respect.

ITU-T Study Group 15 is the global leader in the standardization of transport elements of access networks and home networking. Participation in ITU's standardization activities is open to all, and I invite experts in this field to join us in our mission to advance the modern communications networks upon which we all depend.

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[1] http://www.itu.int/ITU-D/ict/statistics/material/pdf/2011%20Statistical%20highlights_June_2012.pdf

Acknowledgements

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Preface

Editor: John Jay

Development of the PSTN

Following the invention of the telephone at the end of the 19th century, a wireline access network was rapidly constructed to provide commercial telephone service. Figure P-1 presents the USA as an example; the number of telephone lines grew by a factor of 60,000 in the first one hundred years after Alexander Graham Bell was awarded a US patent for "Improvement in Telegraphy". The annual growth in telephone lines in the USA did not fall below 10% until 1908.

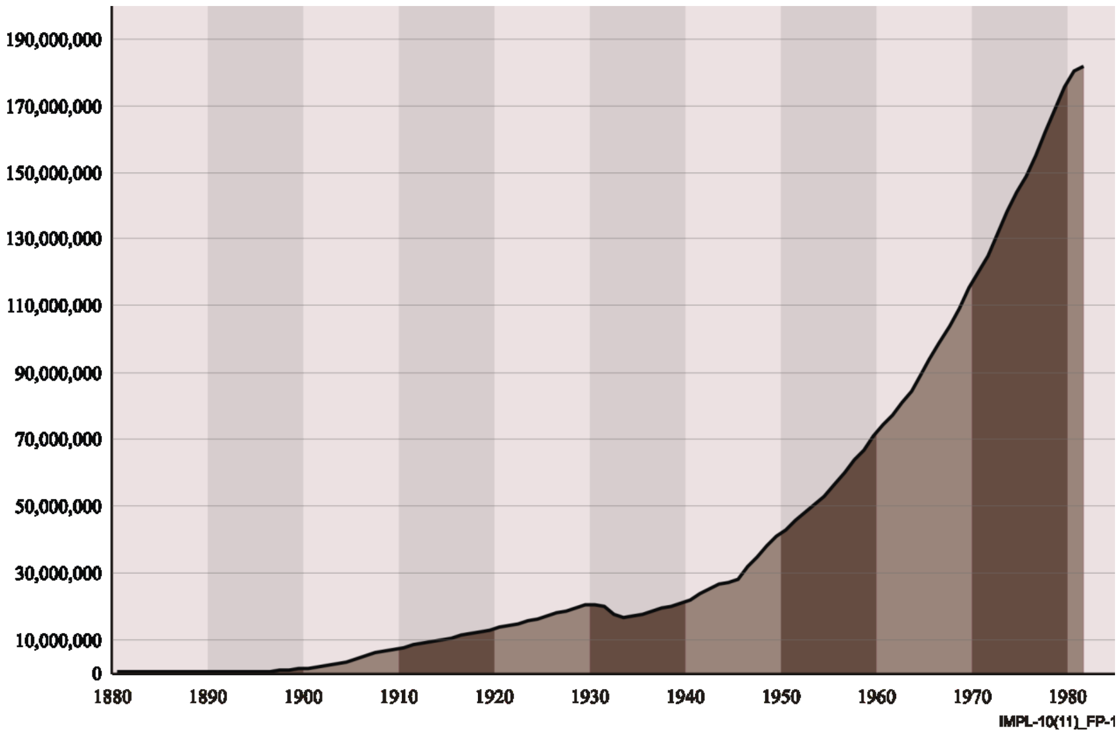


Figure P-1 – Telephone line growth in the USA from 1880 – 1980

The original design was derivative of the existing telegraph network with technical changes necessary to meet the additional requirements of consumer voice service, including safety, human factors, etc. One of the first adaptations from telegraph networks was the use of twisted wire pair (TWP) for the physical network instead of single wires to protect calls from cross-talk and electrical noise.

Telephones were originally deployed in connected pairs, however telegraph exchange technology was quickly applied to the nascent telephone service, and the Public Switched Telephone Network (PSTN), the first wireline subscriber access network, was born.

Challenges to the PSTN

For most of the 20th century, the PSTN changed little and served its purpose well. Technical advances enabled direct subscriber connections (i.e., dialling) instead of requiring manual connection by an operator, long distance calls using common subscriber equipment instead of dedicated equipment at the telephone company's facility and eventually direct dialling long distance and even overseas calls. However in the last decades of the 20th century, technical, commercial and cultural changes began to move the PSTN as it existed to obsolescence.

Digital Telephony – Digital signalling and communications techniques were first applied to the PSTN after World War II. Digital conversion increased rapidly through the 1960's & 1970's. The technology was developed and implemented to be compatible with the existing PSTN. However it enabled techniques and applications which catalysed many competitive products and services.

Digital Data Communications – The development of digital telephony made the PSTN a convenient platform for digital communications between non-telephony devices such as computers. This work initiated in the late 1950's and of course continues today. In the 1980's, as consumers began to purchase computers for their homes, their existing access to the PSTN was a natural means of putting their home devices on a digital communications network. The growth in digital data communications over the PSTN can be understood by viewing the increase in consumer modem transmission speeds over time in Figure P-2.

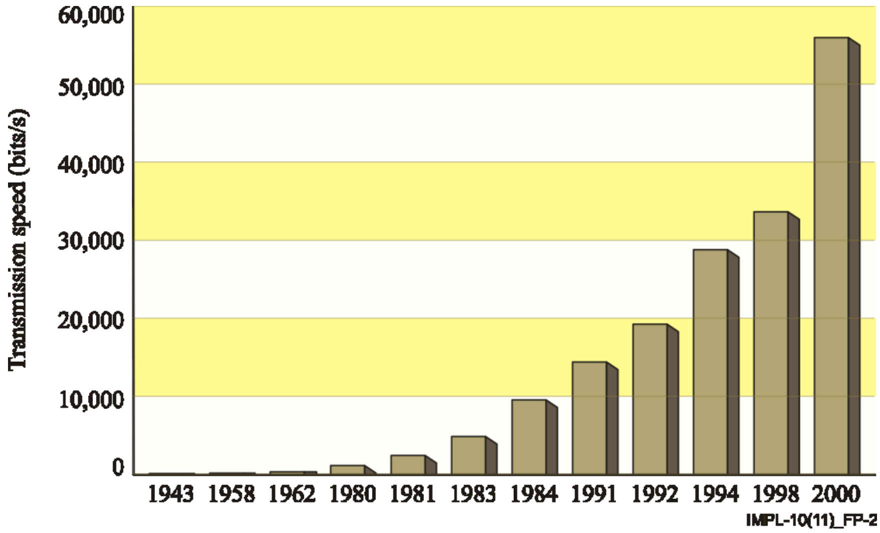


Figure P-2 – Telephone line digital modem speed by year

Video/CATV – As television (TV) proliferated in the 1950's, most subscribers received their video signals "over-the-air", i.e., using a Radio Frequency (RF) antenna to harvest broadcast signals. However in rural or mountainous areas, common home antennae were not adequate to receive over-the-air TV signals. Formal and informal collective arrangements were made to purchase, install and share a "Community Antenna" (CATV) and distribute the received broadcast television signal by a terrestrial wireline network, typically coaxial cable carrying native RF signals. The CATV signal (i.e., picture) quality was better than over-the-air and programming was less restrictive. Thus CATV subscriptions increased through the end of the century until, in places like the US, more than 90 % of all homes can be connected to a CATV system.

Digital telephony increased the bandwidth and flexibility of the PSTN, opening it up for complementary and competitive providers, products and services, enabling alien products and protocols to be attached and connected without affecting the service or reliability of Plain Old Telephone Service (POTS). Digital data communications created a whole new industry, connecting computers, devices and more importantly, consumers with information, products and services, i.e., the Internet and the World Wide Web. The emergence and growth of video financed the construction of national CATV networks which became the first direct competitor to the PSTN. These events set the stage for the next generation of the PSTN, the Wireline Broadband Network.

The Wireline Broadband Network – ISDN

Integrated Services Digital Network (ISDN) was the first attempt at a completely digital telephone/telecommunications network (as opposed to using modems over switched analogue circuits). ISDN provides one or two 64 kb/s digital service channels and a 16 kb/s digital signal channel to each subscriber. It was designed to carry voice, data, images, video, in digital format, with a standard network and device interface over, essentially, the legacy PSTN. ITU-T standards describing this application date from 1980 and are in the ITU-T I-series of Recommendations, in particular Recommendations ITU-T I.120 and I.210.

In 1988 Recommendation ITU-T I.121 was published which described an enhanced ISDN service created by multiplexing multiple 64 kb/s channels and managed using Asynchronous Transfer Mode (ATM). Even though ISDN found several important niche applications such as video conferencing and audio recording, it has never prospered as a consumer broadband access technology, Germany – with 25 million ISDN channels at one point in time – being the notable exception.

The Wireline Broadband Network – DSL

The poor adoption of ISDN as a wireline broadband access technology is attributed to several factors, including delayed standardization, failure to keep pace with advances in applications like video and interactivity, complexity of consumer solutions and limited marketing by the network operators. However the fatal blow to ISDN deployment was the rapid development and commercialization of Digital Subscriber Line (DSL – originally "Digital Subscriber Loop") as a broadband wireline technology.

DSL carries digital broadband signals on the PSTN using higher frequencies than those used for voice traffic. Thus, unlike the modems shown in Figure P-2, the customer can use the telephone and computer simultaneously and keep legacy interfaces and equipment (e.g., analogue telephone). For example, in the most common consumer realization of DSL, Asymmetric DSL (ADSL), the broadband signals are carried on frequencies between 25 and 1104 kHz.

Note – Within this Technical paper, the term "broadband" is used when qualifying a system that requires transmission channels capable of supporting rates greater than the primary rate.

Several varieties of DSL have been developed to meet different applications, such as business (Symmetric, or SDSL), academia (Symmetric-High Speed, or SHDSL) and video (Very high speed DSL, or VDSL). The performance differences are accomplished by changing the power levels and spectrum characteristics, advanced modulation techniques, channel bonding and noise management. Advanced versions of ADSL and VDSL such as ADSL2, VDSL2 and ADSL2+ are also available.

DSL's advantage of using the legacy PSTN physical plant is offset by several factors. The subscriber's data rate, or speed, reduces as the distance from the network operator's DSL modem (DSLAM, DSL Access Multiplexer) to the subscriber's DSL modem increases. A common solution is to place the DSLAM in the network in a remote terminal (RT), thus reducing the loop length to the subscriber. An example of this configuration is shown for SHDSL in Figure P-3.

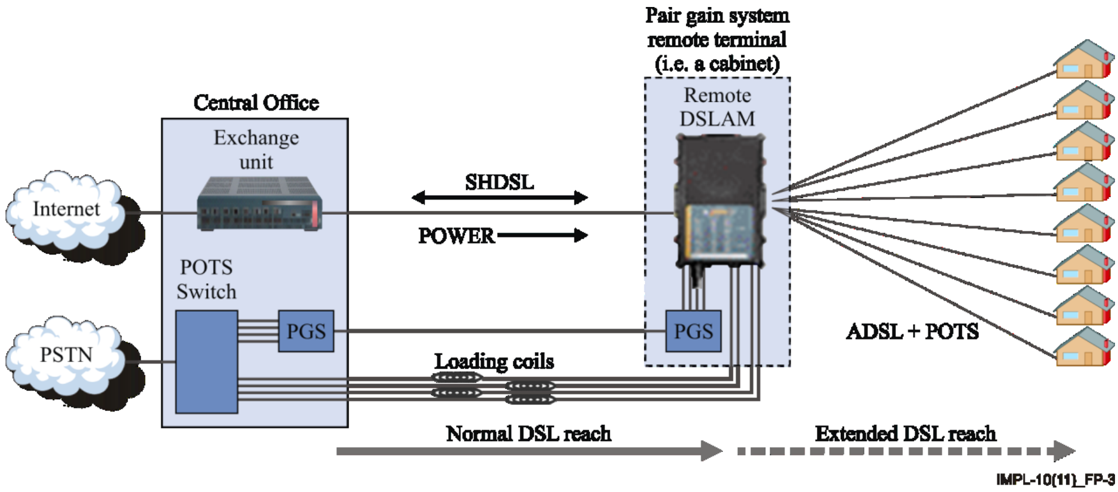


Figure P-3 – Remote SHDSL DSLAM configuration

DSL performance on the PSTN is also limited by the quality of the physical plant. Old cables damaged by age, fatigue, corrosion, or even poor handling and installation practice, can reduce DSL capability. Even the presence of lighter gauge wires (which can range from 0.4 mm to 0.9 mm) or the mix of different wire diameters reduces capability and impairs DSL service.

Table P-1 – Access network wireline data transmission standards

Modem	Data rate*	Application	Recommendation
ITU-T V.90	56 kbit/s	Data and Internet access	ITU-T V.90
ISDN BRI	144 kbit/s	2B (2 x 64 kbit/s) + D (16 kbit/s)	ITU-T I.432.x series
HDSL	2,048 kbit/s	1.5 – 2.0 Mbit/s symmetrical service on two-three pairs	ITU-T G.991.1
SHDSL	768 kbit/s	HDSL on a single pair	ITU-T G.991.2
ADSL	6 Mbit/s / 640 kbit/s	Access to Internet and multimedia databases, video distribution	ITU-T G.992.1
ADSL2	8 Mbit/s / 800 kbit/s		ITU-T G.992.3
ADSL2+	16 Mbit/s / 800 kbit/s		ITU-T G.992.5
VDSL	52 Mbit/s / 2.3 Mbit/s	Internet Access + HDTV	ITU-T G.993.1
VDSL2	100 Mbit/s		ITU-T G.993.2
VDSL2 vectoring		Internet Access + HDTV over longer loops with more users	ITU-T G.993.5

* Downstream (network to subscriber) / upstream (subscriber to network). Single values are symmetric. DSL speeds are “up to” the values in the table.

Finally, DSL performance is affected by the number of subscribers served within a distribution area, as well as the coexistence of different services in the same cable. Noise from TWP carrying DSL degrades service on other pairs in the distribution cable. The remedies are noise cancellation and spectrum selection techniques common in advanced DSL technologies like the more recent VDSL2 vectoring specifications. These techniques and the use of channel (pair) bonding extend the theoretical bandwidth delivered to consumers over copper pairs to around 1 Gbit/s, depending on the distance.

The ITU-T has published DSL standards since the late 1990's. They are summarized in Table P-1, along with telephone modem and ISDN standards.

The Wireline Broadband Network – DOCSIS

Through the 1960's and 1970's, demand for video services compelled and financed the construction of CATV networks to the point where their subscriber access was competitive with the PSTN. By the 1990's many of these smaller systems consolidated into large "Multi-Service Operators" (MSOs) who identified digital communications as a growth opportunity and a source of revenue for return on their network investments. The Data Over Cable Service Interface Specification (DOCSIS) was published in 1997. It defines the addition of high-speed data communications to an existing CATV system. Using DOCSIS, MSOs offered competing data communications on their video network, and with the development of Voice Over Internet Protocol (VoIP) offer POTS-like service. The latest version of the standard, DOCSIS 3.0, bonds up to 8 channels from the network to the terminal, to deliver up to 343 Mbit/s to the optical node. MSOs offer subscriber access speeds as high as 100 Mbit/s using this technology.

The use of the CATV network to offer digital services by DOCSIS is outside the scope of this Technical paper. However ITU-T standards describing this application are in the ITU-T J-series of Recommendations.

The Wireline Broadband Network – FTTx

The effective response from telephone operating companies has been to replace the PSTN with fibre optics. Optical fibre is capable of delivering bandwidth intensive integrated voice, data and video services in the access network to distances beyond 20 km, e.g. more than 4 times the distances allowed with TWP cables through the DSL systems.

A fibre optic wireline broadband network can have several configurations, such as Fibre-to-the-Home (FTTH), Fibre-to-the-Building (FTTB), Fibre-to-the-Curb (FTTC) and Fibre-to-the-Node (FTTN). In each case the optical network is terminated at an Optical Network Unit (ONU – also known as an Optical Network Terminal, or ONT).

The versions of FTTx are differentiated by the location of the ONU. For FTTH, the ONU is located on the subscriber's premises and serves as the demarcation between the operator's and customer's facilities. For FTTB and FTTC, the ONU serves as a common interface for several subscribers (e.g., the basement of an apartment building or a telephone pole), with the service delivered over the customers' existing TWP drop cables. For FTTN, the ONU is located in an active network node serving dozens to hundreds of subscribers from which service is delivered by existing TWP local loops.

In fact these configurations represent various degrees of fibre deployment within the access network and are complementary with other broadband technologies (wireline and wireless). For example, remote terminals (RTs) used to reduce subscriber loop lengths and improve DSL availability are often connected ("backhauled") to the telephone exchange by fibre optics – especially as those RTs convert to Internetworking Protocol (IP). VDSL is often used to provide service from the ONU in FTTB and FTTC deployments and wireless broadband access is commonly "backhauled" by fibre optics, especially "4G" services like Long Term Evolution (LTE).

There are two common architectures for FTTx: "point-to-point" (PtP) and the Passive optical network (PON). In a PtP configuration, enterprise local area network (LAN) architecture is applied to the telephone access network, with a dedicated optical fibre connection (one or two fibres) from the ONU to the telephone exchange. In a PON network, several ONU – typically up to 32 – share a single fibre connection to the network which is typically split at a passive network node. An example is shown in Figure P-4. A future configuration of PON, Wavelength Division

Multiplexing (WDM) PON, replaces the splitter with a grating so that each subscriber can be served with a dedicated channel, i.e., wavelength.

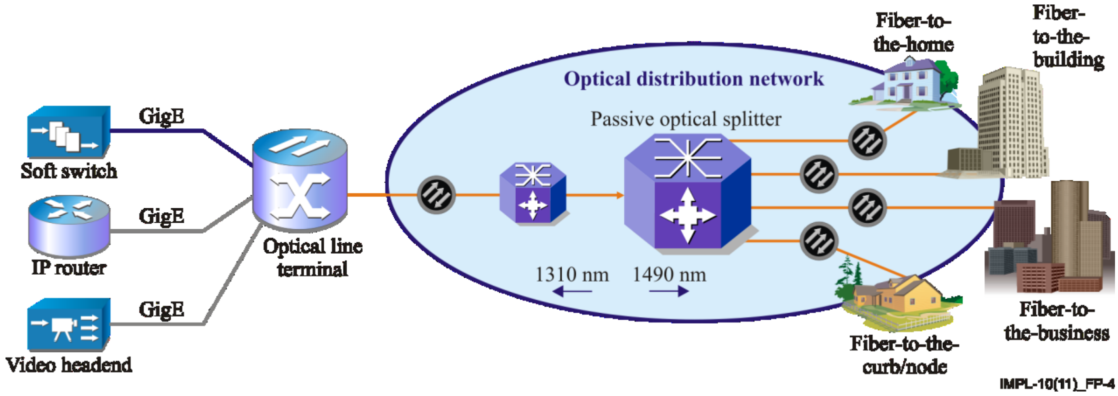


Figure P-4 – Passive optical network (PON) architecture

ITU-T has been writing standards for FTTx since the 1990's. They are in the ITU-T G.98x-series of Recommendations, *Optical line systems for local and access networks*. PtP standards describe 100 Mbit/s and 1 Gbit/s bi-directional service. PON systems have developed from bandwidth based on the ISDN primary rates to a few Mbit/s up to 10 Gbit/s service from the telephone exchange to the network. Several informative Supplements and Implementers' Guides have also been published. A summary of key ITU-T FTTx standards is shown in Table P-2.

Table P-2 – Summary of ITU-T FTTx wireline broadband standards

ITU-T G.982	Optical access networks to support services up to the ISDN primary rate or equivalent bit rates
ITU-T G.983.x	Broadband optical access systems based on Passive optical networks (PON)
ITU-T G.984.x	Gigabit-capable passive optical networks (GPON)
ITU-T G.985	100 Mbit/s point-to-point Ethernet-based optical access system
ITU-T G.986	1 Gbit/s point-to-point Ethernet-based optical access system
ITU-T G.987.x	10-Gigabit-capable passive optical network (XG-PON) systems
ITU-T G.988	ONU management and control interface specification (OMCI)

Home networking

As the performance of the broadband wireline network to the home has increased, so has the need for performance of the network within the home. Within the home individual equipment capability has improved enormously: large screen high definition televisions (HDTV); multiple personal computers (PCs), each with more computing power than industrial models a generation ago; personal entertainment devices that have shrunk large game consoles to the size of a matchbox. Now there is great opportunity to network them all. Plus, futurists forecast networking common appliances (refrigerators, thermostats), security systems, energy usage and exotic applications like opening and closing blinds and curtains in the morning and evening.

However several challenges confront this utopian vision of the fully networked home. Unless home networks can use existing physical plant (e.g., the home's electrical, telephone or coaxial cable network), constructing a wireline home network will be expensive in any home, and prohibitive on a societal basis. Also, the digital competency of the general public is different than that of trained telephone company installation teams. For every enthusiast installing a complex home network, there is a frustrated consumer unable to plug two cables together.

The ITU-T recently began to address this problem by drafting the ITU-T G.99xx-series of Recommendations providing transceiver standards for using common, existing home wiring as a broadband home network. Key ITU-T Recommendations serving as home network standards are summarized in Table P-3.

Table P-3 – ITU-T Recommendations specifying home networking standards

ITU-T G.9901, ITU-T G.9902, ITU-T G.9903, ITU-T G.9904	Home networking transceivers for operation over powerlines
ITU-T G.9951, ITU-T G.9952, ITU-T G.9953	Home networking transceivers for operation over phoneline
ITU-T G.9954	Home networking transceivers for operation over phone line and coaxial cables
ITU-T G.996x	Home networking transceivers for operation over phoneline, coaxial cables and power lines
ITU-T G.9972	Coexistence mechanism for wireline home networking transceivers (phone line, coaxial cable and powerline)
ITU-T G.9970	Generic home network transport architecture
ITU-T G.9971	Requirements of transport functions in IP home networks

Recognizing the need for strong leadership and coordination during the development of standards for wireline broadband access networks and home networking, the ITU-T designated ITU-T Study Group 15 as the "Lead Study Group on Access Network Transport" (ANT). Thus ITU-T SG 15 has developed and published this Technical paper to assist all interested parties – administrations, network operators, vendors and subscribers – in the existence and use of ITU-T Recommendations specifying wireline broadband access networks and home networking standards.

This Technical paper gives an overview of the latest ITU-T ANT standardization activities, focusing on broadband access network systems such as xDSL and PON, and on the new subject of home networking.

In conclusion this Technical paper is dedicated to the description of the ITU-T standards related to the xDSL family (HDSL, ADSL, VDSL), the various fibre access alternatives (B-PON, G-PON, XG-PON) and wireline home networking alternatives (over phone-line, coaxial cable, and power-lines). On behalf of the management and experts of ITU-T Study Group 15, we hope this Technical paper and the standards it describes contribute to the success of your ventures in wireline broadband access networks and home networking.

Table of Contents

Chapter 1
Digital subscriber lines, xDSL

Introduction

Editor: Miguel Peeters

For the past twenty years, digital subscriber line (DSL) technologies have been adopted worldwide with a high penetration by the operators and users. The main driver of its success is the constant increase of the bit rate over existing copper wires, which opens the doors to numerous new services like high speed internet and Internet Protocol television (IPTV).

However, the use of frequencies above those used by plain old telephone service did not go without numerous technological challenges caused by the physical environment. The main challenge was to optimize the performance limited by the attenuation of the loop and the crosstalk between the pairs. This was made possible by the selection of very efficient line codes. At some point, it was recognized that the bit rate could be increased further only by shortening the loops or bonding several pairs.

Thus, the technology moved from the central office to the cabinet. At the same time, IPTV services requiring guaranteed rate and almost error free transmission were launched. This highlighted the importance of robustness to impulsive noise and triggered the need for improved interleaving scheme and for retransmission. As the frequency increased, the performance was more and more limited by the crosstalk between pairs paving the way for crosstalk cancelling techniques. Accompanying this trend to higher and more stable bit rates, the ITU-T has generated a series of Recommendations dedicated to DSL systems and updated them regularly (Table 1-1).

The first series of ITU-T Recommendations, ITU-T G.991.x, on DSL targets business services. They are characterized by single carrier baseband system using the same frequencies in upstream and downstream directions. They provide symmetric services up to 6 Mbit/s with very low latency.

The second series of ITU-T Recommendations, ITU-T G.992.x, targets residential services from the central office. Using a multi-carrier modulation and frequency division duplexing, they provide asymmetric services up to 16 Mbit/s in the downstream direction, and 800 kbit/s from the central office. The variants ITU-T G.992.1 (ADSL), ITU-T G.992.3 (ADSL2), and ITU-T G.992.5 (ADSL2plus) are the most widely deployed DSL systems in the world.

The third series of ITU-T Recommendations, ITU-T G.993.x, is intended for residential and business services from the cabinet. The first variant is ITU-T G.993.1 (VDSL). It was quickly followed by the second variant, ITU-T G.993.2 (VDSL2). The latter is now the most widely deployed one. ITU-T G.993.2 is a multi-carrier system with a frequency division multiplexing similar to ITU-T G.992.3, but using a wider frequency band to provide bit rates above 100 Mbit/s. VDSL2 has been designed to keep as many common functions with ADSL2. The third variant, ITU-T G.993.5, is an addition to VDSL2 that permits to increase the rate or to extend the reach by using crosstalk cancellation between the pairs.

Table 1-2 shows the transport capacity of the three above indicated series of xDSL systems.

In addition to those three series, a set of Recommendations applicable to multiple ITU-T Recommendations were developed. For example, Recommendation ITU-T G.994.1 is a common protocol to negotiate between different xDSL technologies, Recommendation ITU-T G.997.1 provides a common management interface to DSL technologies, Recommendations ITU-T G.998.1, ITU-T G.998.2 and ITU-T G.998.3 describe common bonding protocols for DSL, and

Recommendation ITU-T G.998.4 specifies a common retransmission technique for VDSL2 and ADSL2.

Table 1-1 – ITU-T Recommendations on DSL systems

HDSL / SHDSL	HDSL	SHDSL			
	ITU-T G.991.1	ITU-T G.991.2			
ADSL	ADSL	Splitterless ADSL	ADSL2	Splitterless ADSL2	ADSL2plus
	ITU-T G.992.1	ITU-T G.992.2	ITU-T G.992.3	ITU-T G.992.4	ITU-T G.992.5
VDSL	VDSL	VDSL2	VDSL2 with Vectoring		
	ITU-T G.993.1	ITU-T G.993.2	ITU-T G.993.5		
Common aspects	Handshake	Overview DSL systems	Test procedures	Single ended line testing	
	ITU-T G.994.1	ITU-T G.995.1	ITU-T G.996.1	ITU-T G.996.2	
	Physical layer management for DSL	Multi-pair bonding	Interfaces PHY / LL	Improved impulse noise protection for DSL transceivers	
	ITU-T G.997.1	ITU-T G.998.1 /2/3	ITU-T G.999.1	ITU-T G.998.4	

Table 1-2 Transport capacity of the xDSL systems

	Bit rate	Maximum frequency
HDSL	1.544 and 2.048 Mbit/s (on one/two/three pairs)	485 kHz
SHDSL	192-5696 kbit/s (on one pair) 384-11392 kbit/s (on two pairs)	350 kHz
ADSL	6.144 Mbit/s downstream 640 kbit/s upstream	1.1 MHz
Splitterless ADSL	1.536 Mbit/s downstream 512 kbit/s upstream	552 kHz
ADSL2	8 Mbit/s downstream 800 kbit/s upstream	1.1 MHz
Splitterless ADSL2	1.536 Mbit/s downstream 512 kbit/s upstream	552 kHz
ADSL2plus	16 Mbit/s downstream 800 kbit/s upstream	2.2 MHz
VDSL	52 Mbit/s downstream 2.3 Mbit/s upstream	12 MHz
VDSL2	50-200 Mbit/s bidirectional (e.g. 120 Mbit/s downstream and 80 Mbit/s upstream or 100/100 Mbit/s)	30 MHz

1.1 HDSL and SHDL

Editor: Massimo Sorbara

This section deals with high bit rate digital subscriber line (HDSL) and symmetric high bit rate digital subscriber line (SHDSL) systems.

1.1.1 Transmission medium

The transmission medium over which the HDSL/SHDSL digital transmission systems are expected to operate is the local line distribution (or access cable) network. A local line distribution network employs cables of twisted wire-pairs to provide services to customers. In a local line distribution network, customers are connected to the local exchange via local lines (twisted wire-pairs). A metallic local line is able to simultaneously carry bidirectional digital information in the appropriate HDSL/SHDSL format.

To simplify the provisioning of HDSL/SHDSL, a digital transmission system must be capable of satisfactory operation over the majority of metallic local lines without requirement of any special conditioning. In order to permit the use of HDSL/SHDSL transmission systems on the maximum possible number of local lines, the restrictions imposed by HDSL/SHDSL requirements are kept to the minimum necessary to guarantee acceptable operation.

The minimum digital local line (DLL) requirements for HDSL/SHDSL applications are the following:

- no loading coils;
- only twisted pair or quad cable;
- no additional shielding necessary;
- when bridged taps are present, their acceptable maximum number is related to various factors (their length, type of termination, position in the DLL, etc.).

A digital local line is constructed of one or more cable sections that are spliced or interconnected together. The distribution or main cable is structured as follows:

- cascade of cable sections of different diameters and lengths;
- bridged taps (BTs) (usually 1-2) may exist at various points in installation and distribution cables.

A general description of the DLL physical model is shown in Figure 1.1-1 and typical examples of cable characteristics are given in Table 1.1-1.

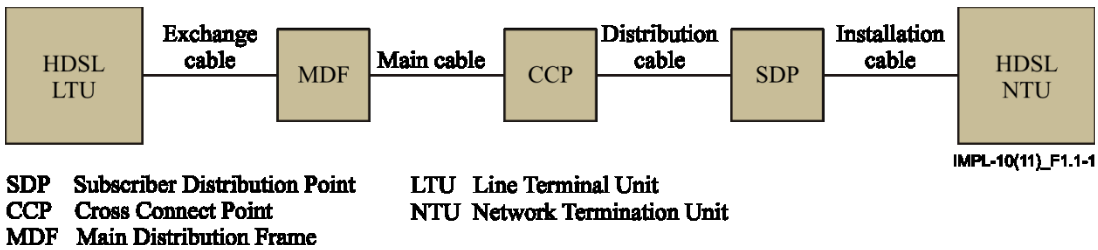


Figure 1.1-1 – DLL physical model

The transmitted signal will suffer from impairments due to cable insertion loss, crosstalk, impulse noise, and the non-linear variations with frequency of DLL characteristics. These impairments are described in detail in Recommendation ITU-T G.991.1.

1.1.2 HDSL

(For further information see Recommendation ITU-T G.991.1.)

This section describes a transmission technique called high bit rate digital subscriber line (HDSL), which targets efficient provisioning of bit synchronous services, e.g. 1.544 Mbit/s and 2.048 Mbit/s (such as ITU-T G.703 or ITU-T G.704 signals), on twisted wire-pairs in the access cable network. This section describes only some requirements for the individual HDSL systems. For a description of the other characteristics such as modulation methods, frame structures, operation and maintenance, etc. reference should be made to Recommendation ITU-T G.991.1.

Table 1.1-1– Cable characteristics

	Exchange cable	**Main cable**	**Distribution cable**	**Installation cable**
Wire diameter (mm)	0.5; 0.6; 0.32; 0.4	0.3-1.4	0.3-1.4	0.4; 0.5; 0.6; 0.8; 0.9; 0.63
Structure	SQ (B) or TP (L)	SQ (B) or TP (L)	SQ (B) or TP (L)	SQ or TP or UP
Maximum number of pairs	1200	2400 (0.4 mm) 4800 (0.32 mm)	600 (0.4 mm)	2 (aerial) 600 (in house)
Installation		underground in ducts	underground or aerial	aerial (drop) in ducts (in house)
Capacitance (nF/km at 800 Hz)	55 ... 120	25 ... 60	25 ... 60	35 ... 120
Wire insulation	PVC, FRPE	PE, paper pulp	paper, PE, Cell PE	PE, PVC

TP Twisted Pairs
SQ Star Quads
UP Untwisted Pairs
L Layer
B Bundles (units)

PE Polyethylene
PVC Polyvinylchloride
Pulp Pulp of paper
Cell PE Cellular Foam Polyethylene
FRPE Fire Resistant PE

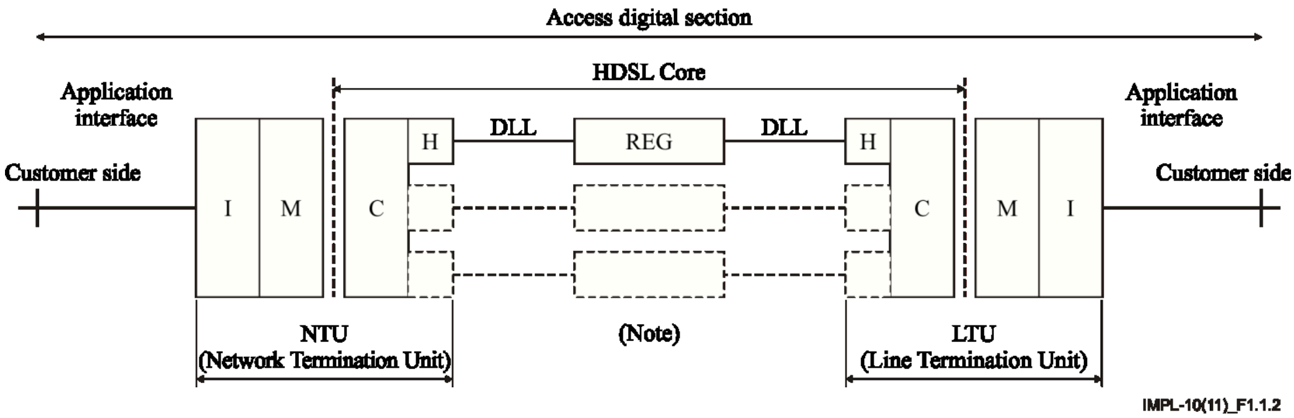
NOTE – This table is intended to describe the cables presently installed in the local loop. Not all of the above cable types are suitable for HDSL systems.

1.1.2.1 Transmission method

The transmission system provides for duplex transmission on 2-wire metallic local lines. Duplex transmission shall be achieved through the use of an echo cancellation hybrid (ECH). With the echo cancellation method, the echo canceller (EC) produces a replica of the transmitted signal (the echo) that is subtracted from the total received signal. The echo is the result of imperfect balance of the hybrid and impedance discontinuities, caused e.g. by splicing different kind of cables.

NOTE – All DSL services require bidirectional, or "duplex" transmission of data, even if the bit rates in opposite directions are asymmetrical. DSL modems separate the signals in opposite directions using duplexing methods. There are four different duplexing methods: four wire duplexing, echo cancellation, time-division-duplexing and frequency-division duplexing. The last three methods use one twisted-pair (two wires) for both directions of transmission. HDSL systems use echo cancellation, while ADSL (Section 1.2) and VDSL (Section 1.3) mainly use frequency-division duplexing.

An access digital section which uses HDSL technology can be considered as a number of functional blocks, see Figure 1.1-2. The functionalities at the exchange side constitute the line termination unit (LTU) and act as master to the (slave) customer side functionalities, which collectively form the network termination unit (NTU) and to the REGs where applicable.



Description of functional blocks:

C	Common circuitry
H	HDSL transceiver
I	Interface
M	Mapping
REG	Regenerator
DLL	Digital local line

NOTE – A fully equipped HDSL core consists of one, two or three H, REG and DLL combinations depending on HDSL transceiver data transmission rate. REGs are optional.

Figure 1.1-2 – Access digital section employing HDSL technology

1.1.2.2 Transport capacity

Transmission is foreseen on different numbers of pairs:

- transmission on three pairs: transmission on three DLLs is provided by three parallel HDSL transceivers, each operating at 784 kbit/s (for 2048 kbit/s applications) and using 2B1Q (two binary one quaternary) line code.
- transmission on two-pairs: transmission on two DLLs is provided by two parallel HDSL transceivers, each operating at 1168 kbit/s using 2B1Q or carrierless amplitude/phase modulation (CAP) line code for 2048 kbit/s applications or at 784 kbit/s using 2B1Q line code for 1544 kbit/s applications.
- transmission on one-pair: transmission on one DLL is provided by one HDSL transceiver operating at 2320 kbit/s and using 2B1Q or CAP line codes.

The line codes of HDSL systems are 2B1Q and CAP. The implementers may choose one of these alternatives; only one line code has to be realized in a HDSL transmission system.

In the main body of ITU-T G.991.1, systems with 2B1Q for 2048 kbit/s applications are described. In Annex A of ITU-T G.991.1, systems with 2B1Q for 1544 kbit/s applications on two pairs are described. Systems using a CAP line code are covered in Annex B of ITU-T G.991.1.

Line symbol rate: An individual HDSL transceiver system is a two-wire bidirectional transceiver system for metallic wires. Three systems may be utilized, as said above: one transporting a bit rate of 784 kbit/s over three pairs used in parallel, a second with an increased bit rate of 1168 kbit/s on two pairs in parallel, and a third with an increased bit rate of 2320 kbit/s on one pair.

ITU-T G.991.1 defines the common circuitry for combining and controlling one, two, or three HDSL transceiver systems, depending on the bit rate of the transceiver system used. The common circuitry and the necessary number of HDSL transceiver systems form the HDSL core, which is independent of the possible applications.

1.1.2.3 HDSL embedded operations channel

The HDSL frame structure defines some bytes of overhead, which are dedicated to the realization of an embedded operations channel (EOC). The LTU in the exchange serves as the master unit, which sends commands to the NTU at the customer premises location, acting as the slave unit to perform operation, administration, and maintenance functions. Some of these functions require the slave to activate changes in the circuitry. Other functions can be invoked to read from and write to data registers located in the slave.

The LTU, as the master of the HDSL EOC, always issues the commands. The slave responds to the properly addressed messages by acknowledging to the master that the message was received correctly. Thus, the HDSL EOC protocol operates in a command/response mode with the master issuing the command and the slave responding.

Pair-specific messages are transmitted and acknowledged on the addressed pair only. In the slave (NTU) the evaluation and the acknowledgment is carried out separately for each HDSL transceiver system (subsystem), i.e. every subsystem echoes the received EOC-message independently of the code on the other subsystems.

This subsystem oriented handling of the EOC-protocol allows for a regenerator implementation based on independent modules for each pair. This general principle is also provided in the NTU, i.e. messages which require an action on a single pair (e.g. read noise margin) are executed only on those pairs where the message has been received correctly.

Global messages, not addressing functions of a single pair, like loopback in the NTU, may be sent over all pairs in parallel or over one single pair, as selected by the LTU. The NTU will evaluate the message on one single pair only, which may be selected by monitoring the EOC for a valid global message or by any performance monitoring. The NTU, after receiving three consecutive valid messages on the selected pair, enters the corresponding state and performs the appropriate action. The acknowledgment of the received messages shall be sent over all pairs in parallel and the LTU evaluates the acknowledgment on one single pair only. So the LTU and the NTU may evaluate the messages on different pairs.

1.1.2.4 Start-up

The start-up procedure is designed as a local procedure for each pair. It is a process characterized by a sequence of signals produced by the NTU, the LTU and the regenerator (REG). Start-up results in an establishment of two-way transmission (if possible) between the application interfaces, i.e. synchronization of the receivers, training of the echo cancellers and training of the equalizers to the point that the requirements for reliable communications are met. Also, tip-ring polarity reversal and pair interchanges are automatically detected and compensated at the NTU. It is the task of the operation and maintenance block to detect when the start-up procedure for all pairs is completed and to initiate a transparent transmission of user data.

1.1.3 SHDSL

(For further information see Recommendations ITU-T G.991.2.)

This section describes a symmetric transmission method (Symmetric High Bit Rate Digital Subscriber Line, SHDSL) at variable bit rates for data transport in telecommunications access networks. The principal characteristics of the SHDSL systems may be summarized as follows:

- provisions for duplex operation over mixed gauge two-wire or optional four-wire twisted metallic pairs;
- specification of the physical layer functionality, e.g. line codes and forward error correction;

- specification of the data link layer functionality, e.g. frame synchronization and framing of application and OAM data;
- provisions for optional use of repeaters for extended reach;
- provisions for spectrum compatibility with other transmission technologies deployed in the access network;
- provisions for regional requirements, including functional differences and performance requirements.

This section describes only some characterizes of the SHDSL transmission system. For a complete description of the all the characteristics see Recommendation ITU-T G.991.2.

1.1.3.1 Transmission method

Figure 1.1-3 is a block diagram of an SHDSL transceiver unit (STU) transmitter showing the functional blocks and interfaces that are referenced in the specification. It illustrates the basic functionality of the STU-R (STU at the remote end) and the STU-C (STU at the central office or exchange end). Each STU contains both an application invariant section and an application specific section. The application invariant section consists of the PMD (physical medium dependent) and PMS-TC (physical medium-specific transmission convergence Layer) layers, while the application specific aspects are confined to the TPS-TC (transmission protocol-specific TC layer) layer and device interfaces. As shown in the figure, one or more optional signal regenerators may also be included in an SHDSL span. Management functions, which are typically controlled by the operator's network management system, are not shown in Figure 1.1-3.

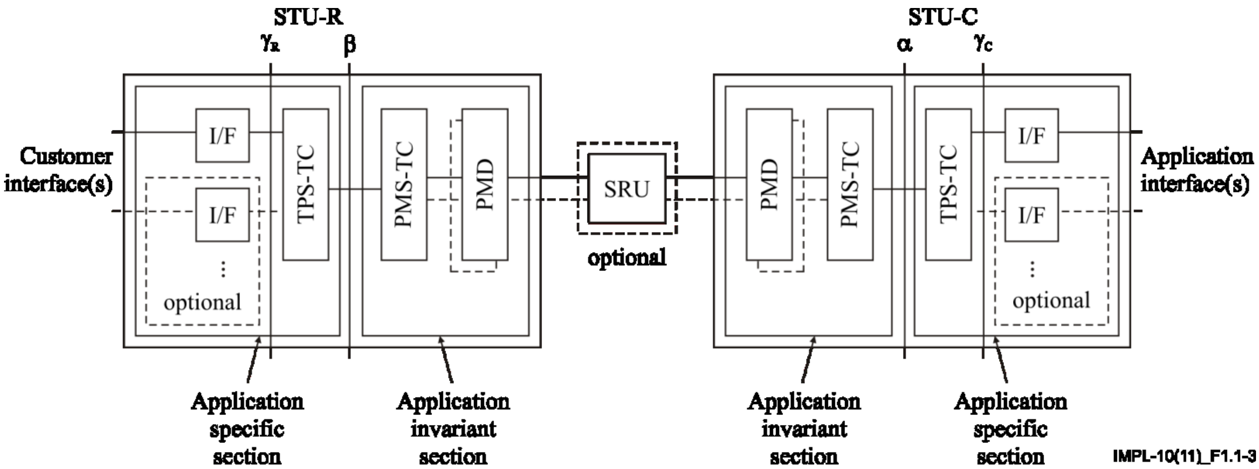


Figure 1.1-3 – STU-x functional model

The functions at the central office side constitute the STU-C (or LTU). The STU-C acts as the master both to the customer side functions of the STU-R (or NTU) and to any regenerators.

The STU-C and STU-R, along with the DLL and any regenerators, make up an SHDSL span. The DLL may consist of a single copper twisted wire-pair, or (in optional configurations) multiple copper twisted wire-pairs. In the multi-pair cases, each STU contains multiple separate PMD layers, interfacing to a common PMS-TC layer. If enhanced transmission range is required, one or more signal regenerators may be inserted in the loop at intermediate points. These points shall be chosen to meet applicable criteria for insertion loss and loop transmission characteristics.

The principal functions of the PMD layer are:

- symbol timing generation and recovery;
- coding and decoding;
- modulation and demodulation;
- echo cancellation;
- line equalization;
- link start-up.

The PMD layer functionality is described in detail in clause 6 of ITU-T G.991.2.

The PMS-TC layer contains the framing and frame synchronization functions, as well as the scrambler and descrambler. The PMS-TC layer is described in clause 7 of ITU-T G.991.2.

The PMS-TC is connected across the α and ß interfaces in the STU-C and the STU-R, respectively, to the TPS-TC layer. The TPS-TC is application specific and consists largely of the packaging of user data within the SHDSL frame. This may include multiplexing, demultiplexing, and timing alignment of multiple user data channels. Supported TPS-TC user data framing formats are described in Annex E of ITU-T G.991.2.

The TPS-TC layer communicates with the Interface blocks across the γ_R and γ_C interfaces. Depending upon the specific application, the TPS-TC layer may be required to support one or more channels of user data and associated interfaces. The definition of these interfaces is outside the scope of ITU-T G.991.2 and, therefore, also of this Technical paper.

1.1.3.2 Transport capacity

The transceivers of the SHDSL systems are designed for duplex operation over mixed gauge two-wire twisted metallic pairs. Two-pair operation is optionally supported for extended reach applications. Optional signal regenerators for both single-pair and two-pair operation are also specified.

The transceivers are capable of supporting selected symmetric user data rates in the range of 192 kbit/s to 2312 kbit/s in increments of 8 kbit/s and an optional two-pair operational mode that is capable of supporting user data rates from 384 kbit/s to 4624 kbit/s in increments of 16 kbit/s, using a trellis coded pulse amplitude modulation (TC-PAM) line code. Regional requirements may limit the specific user data rates for use within particular regions.

The transceivers are designed to be spectrally compatible with other transmission technologies deployed in the access network, including other DSL systems (see Sections 1.2 and 1.3). Note, however, that SHDSL transceivers do not support the use of analogue splitting technology for coexistence with either POTS or ISDN.

1.1.3.3 Remote management access

The STU-C shall maintain the master management database for the entire SHDSL span. Other units are only required to store enough information to accurately send information via the EOC. The information contained in the master database is accessible from any SHDSL unit that has a craft port and from network management if it is available. The craft access is in the form of a virtual-terminal interface (or virtual-craft-port interface). This interface is defined so that it can be used by any attached unit to access the terminal screen of another unit on the same SHDSL span. Support for this feature is optional, with the exception of the STU-C, which shall support the "host" side of at least one remote terminal connection. The virtual-terminal interface consists of connect, disconnect, keyboard, and screen messages. After a connection has been established, input characters from the craft port are sent in keyboard data messages to the "host" unit.

1.1.3.4 EOC transport

The EOC shall be transported in the SHDSL frame in some bits of the overhead. The operation is very similar to that defined for HDSL as described above in Section 1.1.2.3. For a detailed description of the SHDSL embedded operations channel, see clause 9.5 of Recommendation ITU-T G.991.2.

1.2 ADSL technology

Editor: Frank Van der Putten

This section describes the Asymmetric Digital Subscriber Line (ADSL) technology that allows multi-megabit per second data transmission over existing telephone wires, between the Central Office (CO) equipment and the Customer Premises Equipment (CPE) at the remote end. Data transmission occurs simultaneously in both downstream (from CO to CPE) and upstream (from CPE to CO) directions (i.e., full duplex).

The ADSL technology has been first specified in Recommendation ITU-T G.992.1 in 1999. A second generation (ADSL2) has been specified in ITU-T G.992.3 in 2002. For both generations, reduced complexity and operation has been specified in ITU-T G.992.2 and ITU-T G.992.4, respectively, referred to as splitterless ADSL and splitterless ADSL2. For ADSL2, a wider spectrum operation has been specified in ITU-T G.992.5 (ADSL2plus) for higher downstream data rates.

As such, the ADSL technology is specified in a family of five ITU-T Recommendations. Each of these is elaborated in this section.

1.2.1 ADSL

(For further information see Recommendation ITU-T G.992.1.)

This section deals with the physical layer characteristics of the asymmetric digital subscriber line (ADSL) interface to metallic loops. The content of this section is mainly based on that of ITU-T G.992.1, which has been written to ensure the proper interfacing and interworking of ADSL transmission units at the customer end (ATU-R, ADSL transceiver unit at the remote terminal end) and at the network operator end (ATU-C, ADSL transceiver unit at the central office end) and also to define the transport capability of the units. Proper operation is to be ensured when these two units are manufactured and provided independently.

A single twisted pair of telephone wires is used to connect the ATU-C to the ATU-R (Figure 1.2-1). The ADSL transmission units must deal with a variety of wire pair characteristics and typical impairments (e.g. crosstalk and noise). The transmission system is designed to operate on two-wire twisted metallic cable pairs with mixed gauges. ITU-T G.992.1 is based on the use of cables without loading coils, but bridged taps are acceptable in all but a few unusual situations (see also Chapter 4).

An ADSL transmission unit can simultaneously convey all of the following:

- downstream (transport of data in the ATU-C to ATU-R direction) simplex bearers, duplex bearers, a baseband analogue duplex channel, and ADSL line overhead for framing, error control, operations, and maintenance;
- upstream (transport of data in the ATU-R to ATU-C direction) duplex bearers, a baseband analogue duplex channel, and ADSL line overhead for framing, error control, operations, and maintenance.

On the subscriber line, both the transmit signal and receive signal are present. The frequency bands used for downstream and upstream transmission can be different if frequency division multiplexing (FDM) is used or can be (partly) overlapped in spectrum. With FDM, the receiver can separate out the useful receive signal by simply filtering out the frequency band used by the transmit signal. If transmit spectrum (partly) overlaps the receive spectrum, then a more complex echo canceller is required in the receiver. Typically, echo cancellation allows for higher data rates on short loops, while FDM allows for higher data rates on longer loops. Most service providers have given preference to FDM as it allows ADSL to be offered over a larger set of the subscriber lines.

The ADSL systems specified in ITU-T G.992.1 support a minimum of 6.144 Mbit/s downstream and 640 kbit/s upstream net data rate.

Two categories of performance are specified. Category I performance is required for compliance with ITU-T G.992.1; performance enhancement options are not required for category I equipment. Category II is a higher level of performance. Category II performance and characteristics are not required for compliance with ITU-T G.992.1.

ADSL provides a variety of bearer channels in conjunction with other services:

- ADSL transmission on the same pair with voiceband transmission (including POTS (plain old telephone service) and voiceband data services). ADSL utilizes a frequency band above the POTS and it is separated from it by filtering;
- ADSL transmission on the same pair with ISDN (integrated services digital network), as defined in Appendices I and II of ITU-T G.961. The ADSL occupies a frequency band above the ISDN, and is separated from it by filtering;
- ADSL transmission on the same pair with voiceband transmission (including POTS and voiceband data services), and with ISDN in an adjacent pair as defined in Appendix III of ITU-T G.961;
- In the direction from the network operator to the customer premises (i.e. downstream) the bearer channels may consist of full duplex low-speed bearer channels and simplex high-speed bearer channels; in the other direction (i.e. upstream) only low-speed bearer channels are provided.

By negotiation during initialization, ITU-T G.992.1 in combination with ITU-T G.994.1 provide for U-interface (Figure 1.2-1) compatibility and interoperability between transceivers complying with ITU-T G.992.1 and between those transceivers that include different combinations of options.

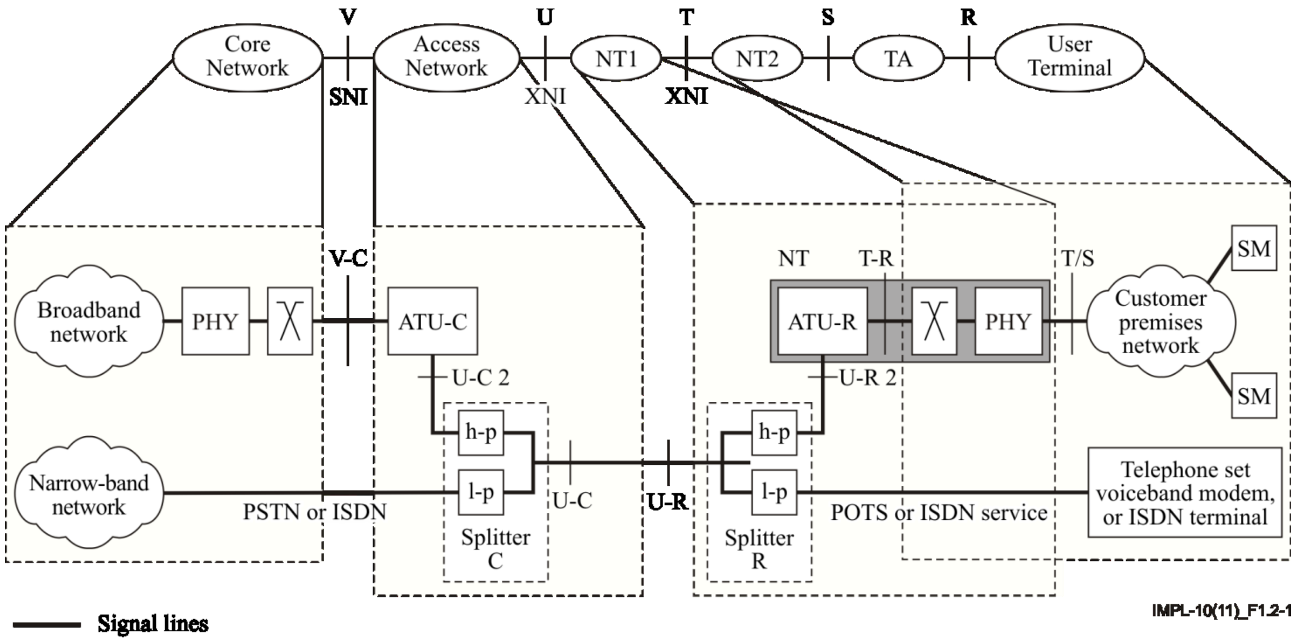
1.2.1.1 Reference models

The system reference model shown in Figure 1.2-1 illustrates the functional blocks required to provide ADSL service.

The ADSL transmission system uses the discrete multitone (DMT) modulation technique.

NOTE – DMT is a digital transmission technique of the multicarrier type, which is based on the principle of subdividing the available bandwidth of the transmission channel in a number of sub-bandwidths and of using each of the obtained sub-channels for the transmission of a suitable part of the overall signal. These multicarrier techniques, when compared with the traditional single-carrier modulation techniques, allows the assignment of the transmission capacity to each sub-channel is made on the basis of the characteristics of that channel in terms of attenuation and noise level. In this way it is possible to optimize the transmission sending more information on the sub-channels which guarantees a better signal to noise ratio.

The DMT technique adopted for the ADSL systems is based on the subdivision of the input signal in 256 parallel sub-channels. Each of these sub-channels modulates, with the QAM technique, one of the 256 sub-carrier of the system. The practical implementation of the modulation and demodulation in ADSL is completely digital by the use of the fast Fourier transform (FFT).



NOTE 1 – The U-C and U-R interfaces are fully defined in ITU-T G.992.1. The V-C and T-R interfaces are defined in terms of logical functions, not physical. The T/S interface is not defined in ITU-T G.992.1.

NOTE 2 – The V-C interface may consist of interface(s) to one or more (STM or ATM) switching systems.

NOTE 3 – Implementation of the V-C and T-R interfaces is optional when interfacing elements are integrated into a common element.

NOTE 4 – One or other of the high-pass filters, which are part of the splitters, may be integrated into the ATU-x; if so, then the U-C 2 and U-R 2 interfaces become the same as the U-C and U-R interfaces, respectively.

NOTE 5 – A digital carrier facility (e.g. SDH extension) may be interposed at the V-C.

NOTE 6 – Due to the asymmetry of the signals on the line, the transmitted signals shall be distinctively specified at the U-R and U-C reference points.

NOTE 7 – The nature of the customer installation distribution and customer premises network (e.g. bus or star, type of media) is not at present specified.

NOTE 8 – More than one type of T-R interface may be defined, and more than one type of T/S interface may be provided from an ADSL NT (e.g. NT1 or NT2 types of functionalities).

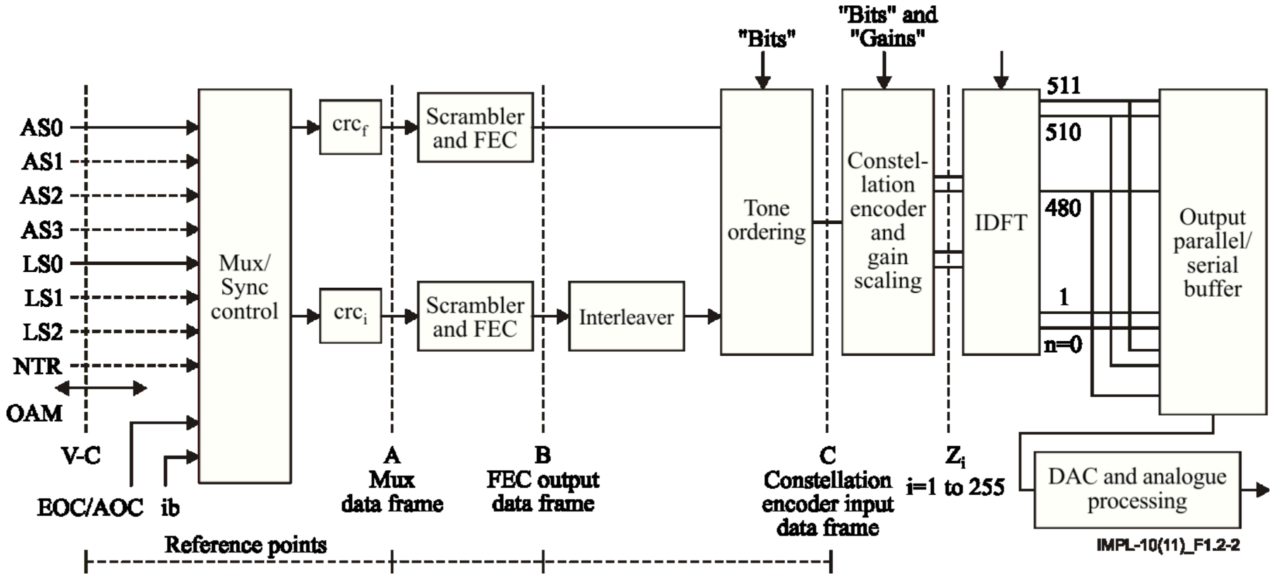
NOTE 9 – Specification for the splitters are given in Annex E of ITU-T G.992.1.

Figure 1.2-1 – ADSL system reference model

An ATU uses discrete frequencies (i.e., DMT subcarriers at multiples of 4.3125 kHz) and transmits a number of bits on each of those frequencies (i.e., 0 to 15 bits per frequency, depending on wire pair characteristics and impairments at that frequency). The bits consist of user data bits, with addition of ADSL line overhead for framing, error control, operations, and maintenance. An ATU-C uses 256 subcarriers for downstream transmission. For upstream transmission, an ATU-R uses 32 subcarriers for operation over POTS and 64 subcarriers for operation over ISDN. This results from the consideration that more data rate (and hence bandwidth) is needed for downstream (i.e., from the network towards the customer) than for upstream (i.e., from the customer to the network).

Figures 1.2-2 to 1.2-5 are models for facilitating accurate and concise DMT signal waveform descriptions. In these figures Z_i is DMT subcarrier i (defined in the frequency domain), and x_n is the nth inverse discrete Fourier transform (IDFT) output sample (defined in the time domain). (Note. x_n is not indicated in the figure, but nth is indicated.) The digital-to-analogue convertor (DAC) and analogue processing block of Figures 1.2-2 to 1.2-5 construct the continuous transmit voltage waveform corresponding to the discrete digital input samples. The use of the figures as a transmitter reference model allows all initialization signal waveforms (ASx, LSx) to be described through the sequence of DMT symbols, $\{Z_i\}$, required to produce that signal. The four figures are specific for STM and ATM and for downstream and upstream. A modem implements only one of these.

ATM and STM are application options. ATU-C and ATU-R may be configured for either STM bit sync transport or ATM cell transport.

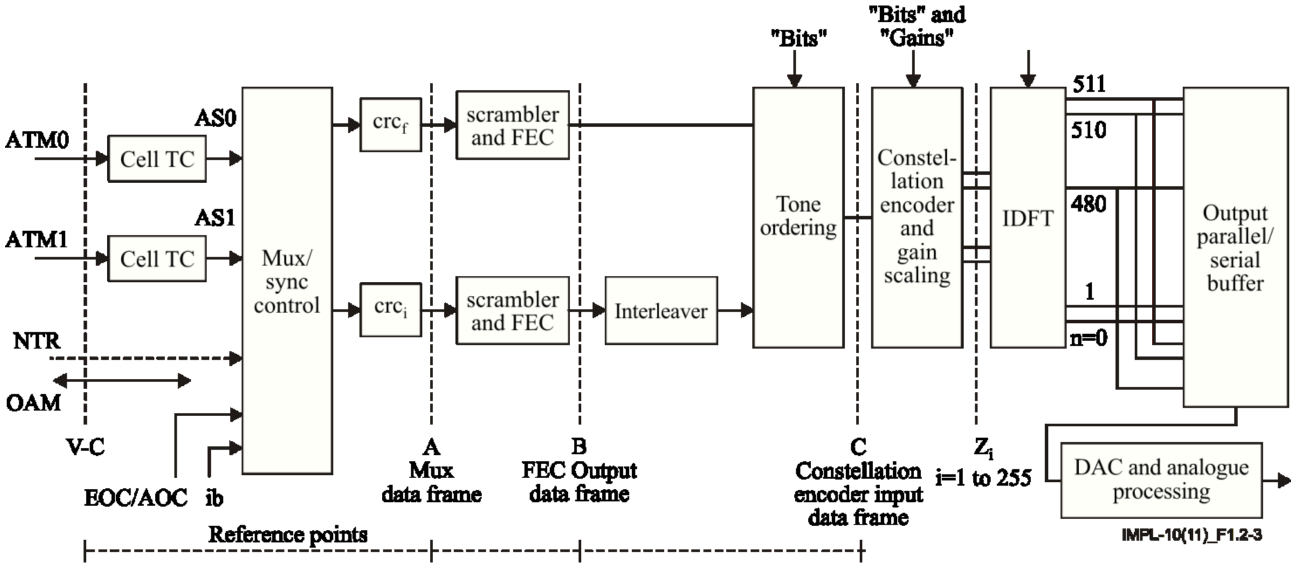


ASx	Any one of the simplex bearer channels AS0 to AS3
LSx	Any one of the duplex bearer channels
NTR	Network timing reference: 8 kHz reference to be transmitted downstream
OAM	Operation, administration and maintenance
EOC	Embedded operations channel (between the ATU-C and ATU-R)
AOC	ADSL overhead control channel
CRC	Cyclic redundancy check
FEC	Forward error correction
IDFT	Inverse discrete Fourier transform
DAC	Digital-to-Analogue Converter

NOTE – Solid versus dashed lines are used to indicate required versus optional capabilities respectively. This figure is not intended to be complete in this respect, see clauses 6 and 7 of ITU/T G.992.1 for specific details.

Figure 1.2-2 – ATU-C transmitter reference model for STM transport

Figure 1.2-3 is a block diagram of an ADSL transceiver unit-central office (ATU-C) transmitter showing the functional blocks and interfaces for the downstream transport of ATM data.



NOTE 1 – Solid versus dashed lines are used to indicate required versus optional capabilities respectively. This figure is not intended to be complete in this respect, see clauses 6 and 7 of ITU-T G.992.1 for specific details.

NOTE 2 – For the meaning of the acronyms see Figure 1.2-2.

Figure 1.2-3 – ATU-C transmitter reference model for ATM transport

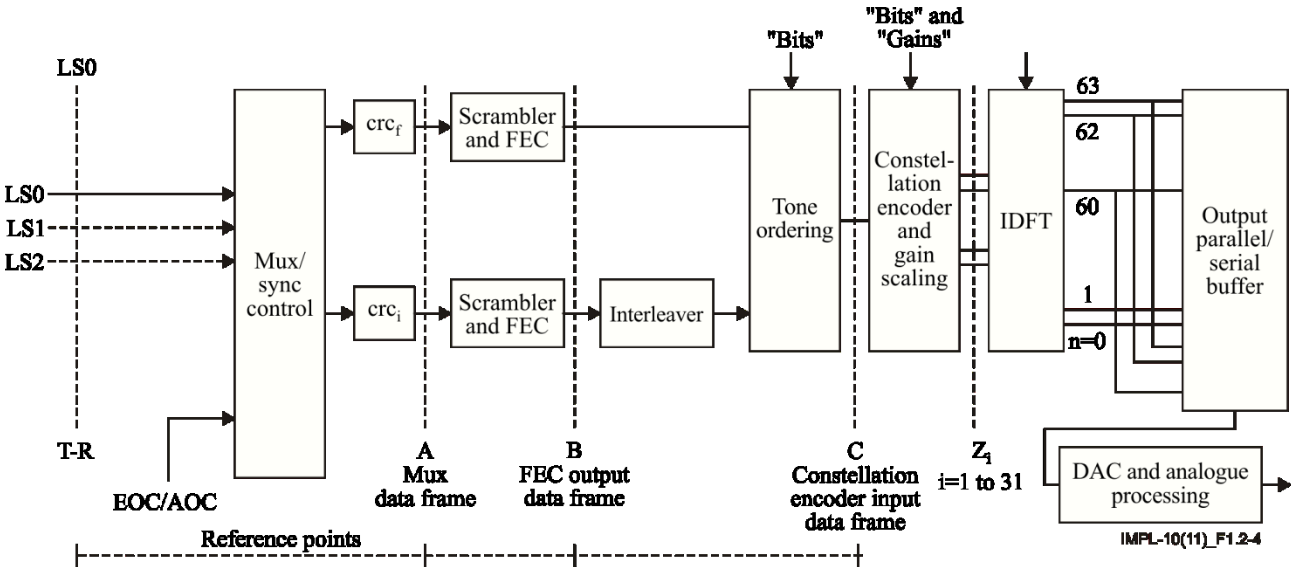
Figure 1.2-4 is a block diagram of an ATU-R transmitter showing the functional blocks and interfaces for the upstream transport of STM data. The blocks ASx, NTR and OAM are missing in respect of Figure 1.2-2 because in the upstream the simplex bearer channels, network timing reference and operation, administration and maintenance T-R interface are not present. For operation over POTS, the IDFT input and output samples are numbered 1 to 31 and 0 to 63 respectively (as shown in Figure 1.2-4 and 1.2-5 for the POTS case). For operation over ISDN, these are numbered 1 to 63 and 0 to 127, respectively. More IDFT samples are provided for ISDN since upstream sub-carriers in the lower part of the spectrum must remain unused as to not overlap in spectrum with the underlying service (which is about 80 kHz for ISDN and only about 4 kHz for POTS).

Figure 1.2-5 is a block diagram of an ATU-R transmitter showing the functional blocks and interfaces for the upstream transport of ATM data. For operation over POTS, the IDFT input and output samples are numbered 1 to 31 and 0 to 63 respectively (as shown in Figure 1.2-5). For operation over ISDN, these are numbered 1 to 63 and 0 to 127 respectively.

The reference models for ATM transport (Figures 1.2-3 and 1.2-5) only differ from the reference models for STM transport (Figures 1.2-2 and 1.2-4) in the addition of a transmission convergence function (cell TC), which inserts idle ATM cells into the AS0 and AS1 bearer channels to achieve rate matching of the ATM user data stream to the ADSL bearer channel net data rate.

In all the figures two paths are shown between the Mux/Sync control and Tone ordering: the "fast" path which provides low latency and the interleaved path which provides very low error rate and greater latency. In Figures 1.2-1 and 1.2-3 the allocation of user data at the V-C interface to these paths is configured by the network operator through the OAM interface.

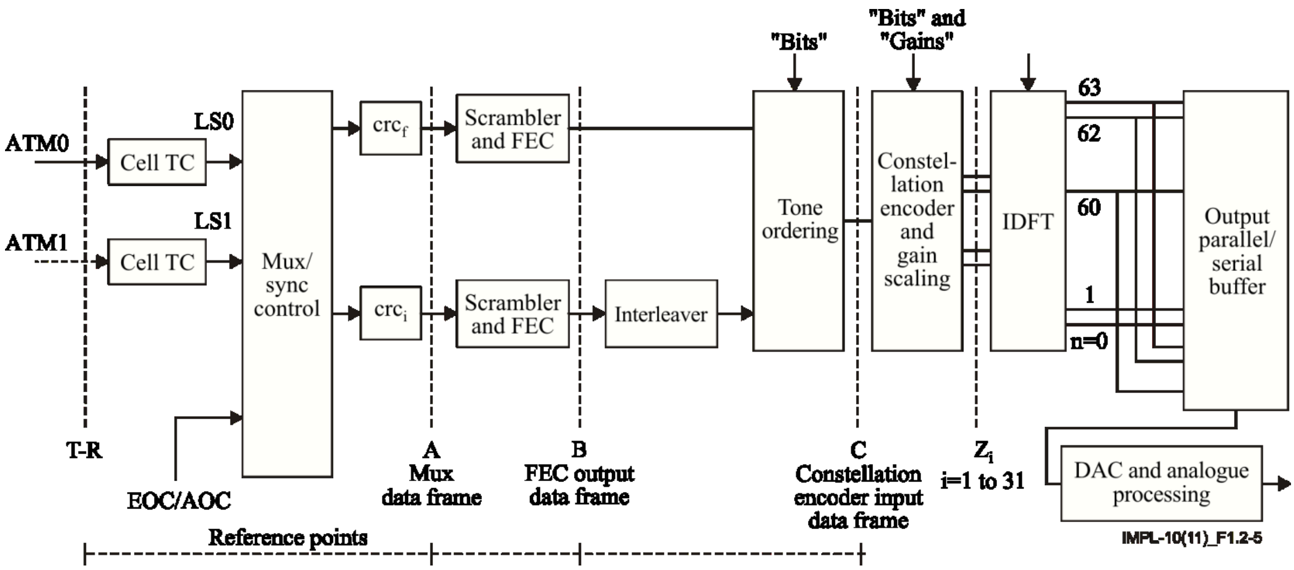
An ADSL system supporting STM is capable of operating in a dual latency mode for the downstream direction, in which user data is allocated to both paths (i.e. fast and interleaved), and a single latency mode for both the downstream and upstream directions, in which all user data is allocated to one path (i.e. fast or interleaved). An ADSL system supporting STM transport may be capable of operating in an optional dual latency mode for the upstream, in which user data is allocated to both paths (i.e. fast and interleaved).



NOTE 1 – Solid versus dashed lines are used to indicate required versus optional capabilities respectively. This figure is not intended to be complete in this respect, see clauses 6 and 7 of ITU-T G.992.1 for specific details.

NOTE 2 – For the meaning of the acronyms see Figure 1.2-2.

Figure 1.2-4 – ATU-R transmitter reference model for STM transport



NOTE 1 – Solid versus dashed lines are used to indicate required versus optional capabilities respectively. This figure is not intended to be complete in this respect, see clauses 6 and 7 of ITU-T G.992.1 for specific details.

NOTE 2 – For the meaning of the acronyms see Figure 1.2-2.

Figure 1.2-5 – ATU-R transmitter reference model for ATM transport

An ADSL system supporting ATM transport is capable of operating in a single latency mode, in which all user data is allocated to one path (i.e. either fast or interleaved). An ADSL system supporting ATM transport may be also capable of operating in an optional dual latency mode, in which user data is allocated to both paths (i.e. fast and interleaved).

1.2.1.2 Transport capacity

An ADSL system may transport up to seven user data streams on seven bearer channels simultaneously:

- up to four independent downstream simplex bearers [unidirectional from the network operator (i.e. V-C interface) to the CI (i.e. T-R interface)], labelled ASx in Figure 1.2-2;
- up to three duplex bearers (bidirectional between the network operator and the CI), labelled LSx in Figure 1.2-2 and 1.2-4.

The three duplex bearers may alternatively be configured as independent unidirectional simplex bearers, and the rates of the bearers in the two directions (network operator toward CI and vice versa) do not need to match.

All bearer channel data rates are programmable in any combination of integer multiples of 32 kbit/s. The ADSL data multiplexing format is flexible enough to allow other transport data rates, such as channelization based on existing 1.544 Mbit/s, but the support of these data rates (non-integer multiples of 32 kbit/s) will be limited by the ADSL system's available capacity for synchronization.

The maximum net data rate transport capacity of an ADSL system will depend on the characteristics of the loop on which the system is deployed, and on certain configurable options that affect overhead. The ADSL bearer channel rate is configured during the initialization and training procedure.

For STM transport, if the ADSL system provides a particular bearer channel ASx or LSx, then the bearer channel supports the 32 kbit/s integer multiples up to the data rate listed in Table 1.2-1 (32 kbit/s x 192 = 6144 kbit/s). Support for integer multiples beyond those required and indicated in Table 1.2-1 is optional. Bearer channel LS0 also supports 16 kbit/s.

For ATM transport, if the ADSL system provides a particular bearer channel ASx or LSx, then the bearer channel supports the 32 kbit/s integer multiples up to the data rate listed in Table 1.2-2. Support for integer multiples beyond those required and indicated in Table 1.2-2 is optional. For ATM transport, less bearer channels are provided since the service multiplexing occurs at the ATM level, whereas for STM transport, each bearer channel is carrying a specific service.

Table 1.2-1 – Required 32 kbit/s integer multiples for transport of STM

Bearer channel	Lowest required integer multiple	Largest required integer multiple	Corresponding highest required data rate (kbit/s)
AS0	1	192	6144
AS1	1	144	4608
AS2	1	96	3072
AS3	1	48	1536
LS0	1	20	640
LS1	1	20	640
LS2	1	20	640

Table 1.2-2 – Required 32 kbit/s integer multiples for transport of ATM

Bearer channel	Lowest required integer multiple	Largest required integer multiple	Corresponding highest required data rate (kbit/s)
AS0	1	192	6144
AS1	1	144	4608
LS0	1	20	640
LS1	1	20	640

ITU-T G.992.1 Annex F (for North America) and ITU-T G.992.1 Annex G (for Europe) define performance requirements against an objective of coverage over test loops and in the presence of defined noise models. Test loops and noise models are defined in ITU-T G.996.1.

1.2.1.3 Framing

Figures 1.2-2 and 1.2-3 show functional block diagrams of the ATU-C transmitter with reference points for data framing. Up to four downstream simplex data channels and up to three duplex data channels are synchronized to the 4 kHz ADSL DMT frame rate, and multiplexed into two separate data buffers (fast and interleaved). A cyclic redundancy check (CRC), scrambling, and forward error correction (FEC) coding is applied to the contents of each buffer separately, and the data from the interleaved buffer then passes through an interleaving function. The two data streams are then tone ordered, and combined into a data symbol that is input to the constellation encoder. After constellation encoding, the data are modulated to produce an analogue signal for transmission across the customer loop.

A framing pattern (to identify which bits belong to which data buffer) is not inserted into the data symbols of the frame or superframe structure. Alternatively, DMT frame (i.e. symbol) boundaries are delineated by the cyclic prefix inserted by the modulator (see section 1.2.1.6). As shown in Figure 1.2-6, superframe boundaries are determined by the synchronization symbol, which is also inserted by the modulator, and which carries no user data.

Because of the addition of FEC redundancy bytes and data interleaving, the data frames (i.e. bit-level data prior to constellation encoding) have different structural appearance at the three reference points through the transmitter. As shown in Figures 1.2-2 and 1.2-3, the reference points for which data framing will be described in the following sections are:

- A (Mux data frame): the multiplexed, synchronized data after the CRC has been inserted. Mux data frames are generated at a nominal 4 kbaud (i.e., every 250 μs);
- B (FEC output data frame): the data frame generated at the output of the FEC encoder at the DMT symbol rate, where a FEC block may span more than one DMT symbol period;
- C (constellation encoder input data frame): the data frame presented to the constellation coder.

ADSL uses the superframe structure shown in Figure 1.2-6. Each superframe is composed of 68 data frames, numbered from 0 to 67, which are encoded and modulated into DMT symbols, followed by a synchronization symbol, which carries no user or overhead bit-level data and is inserted by the modulator to establish superframe boundaries. From the bit-level and user data perspective, the DMT symbol rate is 4000 baud (period = 250 μs), but in order to allow for the insertion of the synchronization symbol the transmitted DMT symbol rate is 69/68 × 4000 baud.

Each data frame within the superframe contains data from the fast buffer and the interleaved buffer. The size of each buffer depends on the assignment of bearer channels made during initialization.

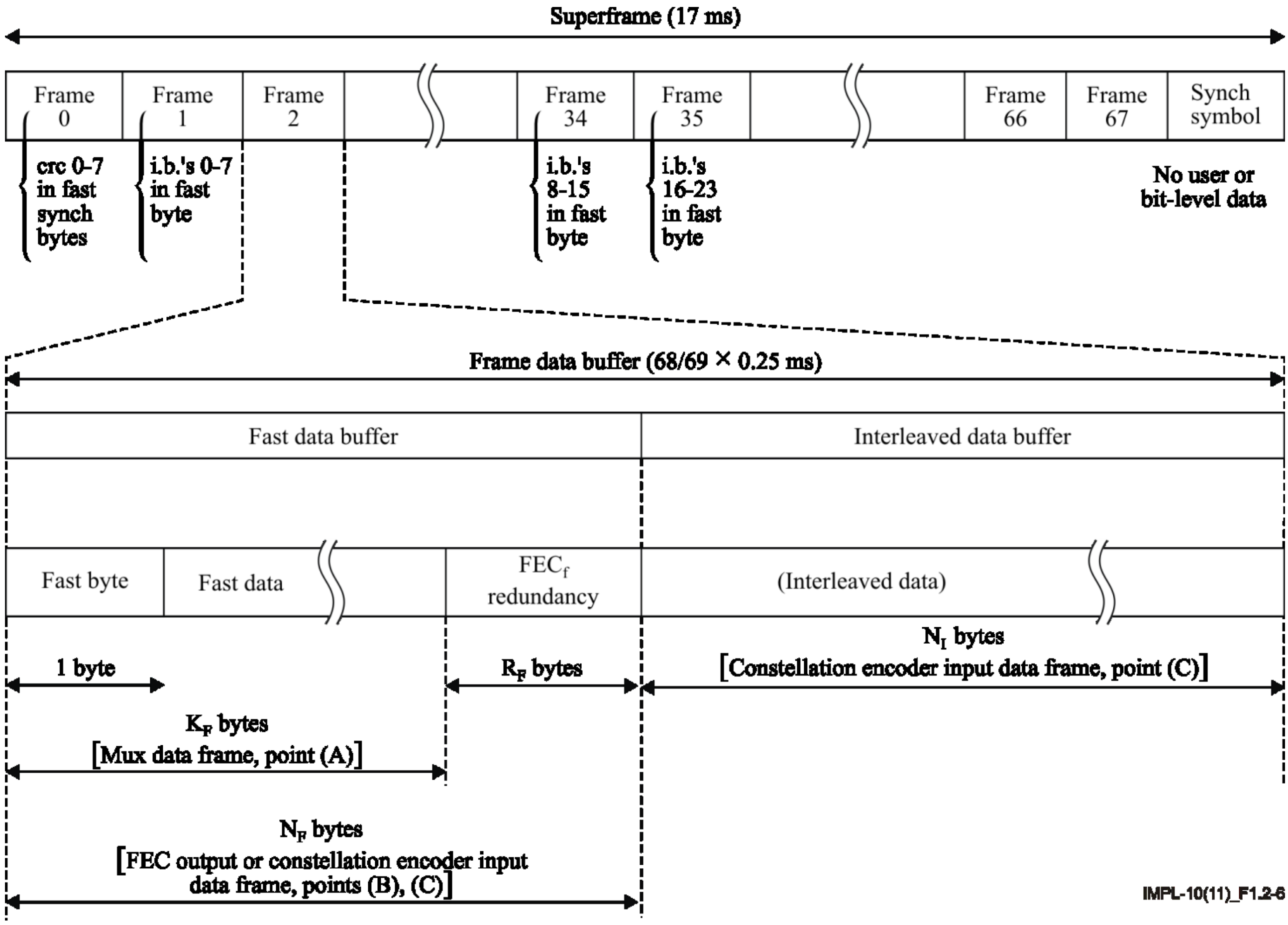


Figure 1.2-6 – ADSL superframe structure – ATU-C transmitter

During each ADSL superframe, eight bits are reserved for the CRC on the fast data buffer (crc0-crc7), and 24 indicator bits (ib0-ib23) are assigned for OAM functions and NTR (Network Timing Reference) transport. The indicator bits allocated to OAM functions report, to the transmitting end, defects (in sync symbol and signal power) and anomalies (in ATM cell delineation, FEC, and CRC) detected at the receiving end. The indicator bits allocated to NTR transport allow the ATU-R to make available, to the ATU-C, an 8 kHz signal that is synchronized to the NTR input.

1.2.1.4 Scrambler, FEC and interleaving

The binary data streams output from the fast and interleaved data buffers are scrambled separately using the following algorithm for both:

$$d'_n = d_n \oplus d'_{n-18} \oplus d'_{n-23}$$

where d_n is the n-th output from the fast or interleaved buffer (i.e., input to the scrambler), and d'_n is the n-th output from the corresponding scrambler. These scramblers are applied to the serial data streams without reference to any framing or symbol synchronization. Descrambling in receivers can likewise be performed independent of symbol synchronization.

The ATU-C supports downstream transmission with at least any combination of the (N, K=N-R) Reed-Solomon FEC coding capabilities shown in Table 1.2-3. The ATU-C also support upstream transmission with at least any combination of the FEC coding capabilities shown in Table 1.2-4.

The Reed-Solomon (R-S) code words in the interleave buffer are interleaved through convolution, with interleaving depth D and related capabilities shown in Table 1.2-4.

Table 1.2-3 – Minimum FEC coding capabilities for ATU-C

Parameter	Fast buffer	Interleaved buffer
Data bytes per R-S code word	$N_F = 0, \ldots, 255$	$N_I = 0, \ldots, 255$
Parity bytes per R-S code word	$R_F = 0, 2, 4, 6, 8, 10, 12, 14, 16$	$R_I = 0, 2, 4, 6, 8, 10, 12, 14, 16$
DMT symbols per R-S code word	S = 1	S = 1, 2, 4, 8, 16
Interleave depth	Not applicable	D = 1, 2, 4, 8, 16, 32, 64
NOTE – N_I and R_I are an integer multiple of S.		

The ATU-R supports upstream transmission with at least any combination of the (N, K=N-R) Reed-Solomon FEC coding and interleaving capabilities shown in Table 1.2-4. The ATU-R also supports downstream transmission with at least any combination of the FEC coding and interleaving capabilities shown in Table 1.2-3.

Table 1.2-4 – Minimum FEC coding capabilities for ATU-R (Table 8-3/G.992.1)

Parameter	Fast buffer	Interleaved buffer
Data bytes per R-S code word	$N_F = 0, \ldots, 255$	$N_I = 0, \ldots, 255$
Parity bytes per RS code word	$R_F = 0, 2, 4, 6, 8, 10, 12, 14, 16$	$R_I = 0, 2, 4, 6, 8, 10, 12, 14, 16$
DMT symbols per RS code word	S = 1	S = 1, 2, 4, 8, 16
Interleave depth	not applicable	D = 1, 2, 4, 8
NOTE – N_I and R_I are an integer multiple of S.		

1.2.1.5 Tone ordering, trellis coding, and constellation encoding

A DMT time-domain signal has a high peak-to-average ratio (its amplitude distribution is almost Gaussian), and large values may be clipped by the digital-to-analogue converter. The error signal caused by clipping can be considered as an additive negative impulse for the time sample that was clipped. The clipping error power is almost equally distributed across all tones in the symbol in which clipping occurs. Clipping is therefore most likely to cause errors on those tones that, in anticipation of a higher received SNR (Signal-to-Noise Ratio), have been assigned the largest number of bits (and therefore have the densest constellations). These occasional errors can be reliably corrected by the FEC coding if the tones with the largest number of bits have been assigned to the interleave buffer. The interleaving cuts a long string of errors in pieces which each can be corrected by the FEC. In the fast path, the FEC can handle only very short strings of errors. For that reason, typically, FEC in fast path is disabled when trellis coding is used.

The numbers of bits and the relative gains to be used for every tone is calculated in the ATU-R receiver, and sent back to the ATU-C according to a defined protocol. The pairs of numbers are typically stored, in ascending order of frequency or tone number *i*, in a bit and gain table.

The "tone-ordered" encoding first assigns the $8 \times N_F$ bits from the fast data buffer to the tones with the smallest number of bits assigned to them, and then the $8 \times N_I$ bits from the interleave data buffer to the remaining tones.

Block processing of Wei's 16-state 4-dimensional trellis code is optional to improve system performance. Trellis coding was already used in voice band modems and is a technique which combines the concepts of coding and modulation such that a significantly lower bit error ratio results. Alternatively, trellis coding allows a significantly higher data rate while maintaining the bit error ratio.

Note. Trellis codes are sophisticated examples of sequential codes, usually with QAM modulation. Straightforward use of QAM allows the detector and decoder to make a separate instantaneous decision on each symbol or message transmitted through the communication channel. Trellis codes map a series of groups of bits into a series of successive symbols transmissions to improve performance. The difference between simple line coding and trellis coding might be compared to the difference between a letter and a word. There are 26 letters in the English alphabet and an archaic means of speaking to another person might be to spell every word, rather than to say the word itself. If the listener were to hear any letter incorrectly, there is no way to correctly interpret the word without looking at the context (which he could not do with simple letters, or QAM, because he must decide which letter was sent before looking at the next letter). Trellis codes are analogous to introducing spoken language rather spelling. Many more than 26 words can be formed, but the listener need not hear each letter correctly as long as he can infer the words from the context. Trellis codes similarly make it more reliable to decode a transmitted sequence of symbols, even though there are a much larger number of message possibilities that could have been conveyed. (From Thomas Starr, *et al.*, "Understanding DSL Technology", Prentice Hall)

In trellis codes, data bytes from the data frame buffer are extracted according to a reordered bit allocation table, b'_i. Then, because of the 4-dimensional nature of the code, the extraction is based on pairs of consecutive b'_i, rather than on individual ones, as in the non-trellis-coded case. Furthermore, due to the constellation expansion associated with coding, the bit allocation table, b'_i, specifies the number of coded bits per tone, which can be any integer from 2 to 15. Given a pair (x, y) of consecutive b'_i, $x + y - 1$ bits (reflecting a constellation expansion of 1 bit per 4 dimensions, or one half bit per tone) are extracted from the data frame buffer and encoded into two binary words v and w (containing x and y bits respectively), which are used to look up two constellation points in the encoder constellation table.

For a given subcarrier, the encoder selects an odd-integer point (X, Y) from the square-grid constellation based on the b bits of either binary words v or w. For example, for $b = 2$, the four constellation points are labelled 0, 1, 2, 3 corresponding to $(v_1, v_0) = (0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$, respectively. Figure 1.2-7 shows example constellations for $b = 2$ and $b = 4$.

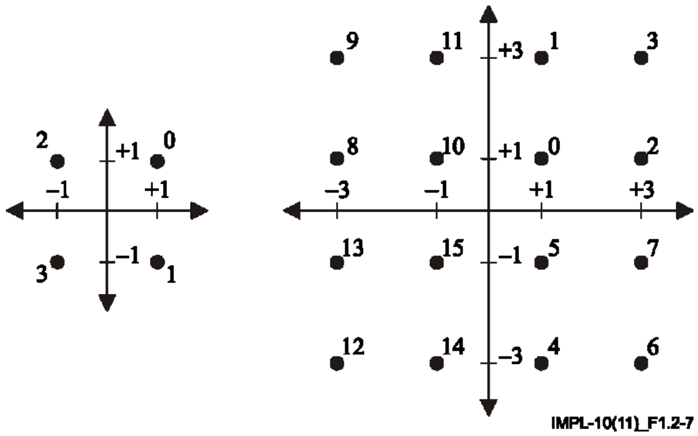


Figure 1.2-7 – Constellation labels for *b* = 2 and *b* = 4

Figure 1.2-8 shows the constellation for the case $b = 5$.

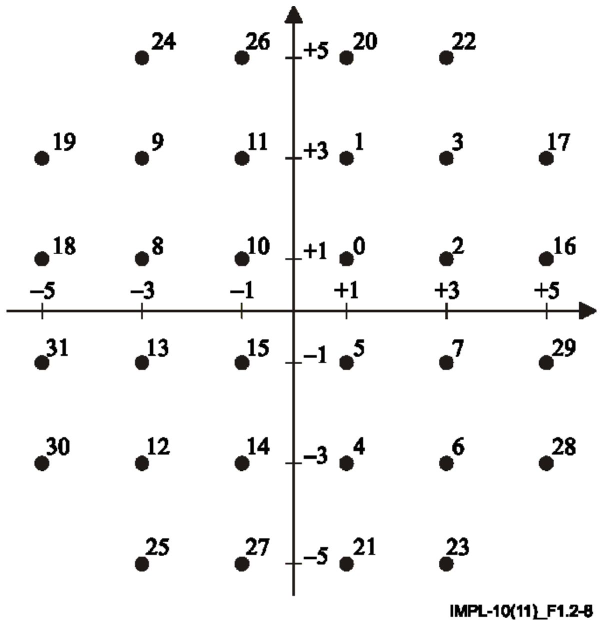


Figure 1.2-8 – Constellation labels for *b* = 5

Each constellation point (X_i, Y_i), corresponding to the complex value $X_i + jY_i$ at the output of the constellation mapper, is scaled by the power-normalization factor $\chi(b_i)$ and the gain adjuster g_i, to result in a complex number Z_i, defined as:

$$Z_i = g_i \times \chi(b_i) \times (X_i + jY_i)$$

The values (X, Y) are scaled such that all constellations, regardless of size, have the same average power. The required scaling, $\chi(b_i)$, is a function only of the constellation size.

The gain g_i values are selected by the receiver and intended for fine gain adjustment within a range from −14.5 dB and of +2.5 dB, which may be used to equalize the SNR margin for all sub-carriers. The values of g_i are assigned during initialization, and may also be updated during showtime via an on-line reconfiguration (OLR) procedure.

1.2.1.6 Modulation

The frequency spacing, Δf, between subcarriers is 4.3125 kHz, with a tolerance of ±50 ppm, and a maximum of 255 carriers (at frequencies $n\Delta f$, n = 1 to 255) is used. The lower limit of n depends on both the duplexing and service options selected. For example, for operation of ADSL above POTS, if overlapped spectrum is used to separate downstream and upstream signals, then the lower limit on n is determined by the POTS splitting filters; if frequency-division multiplexing (FDM) is used the lower limit is set by the downstream-upstream separation filters.

In all cases the cut-off frequencies of these filters are completely at the discretion of the manufacturer, and the range of usable n is determined during the channel estimation.

The modulating transform defines the relationship between the 512 real values x_n and the Z_i:

$$x_n = \sum_{i=0}^{511} \exp\left(\frac{j\pi ni}{256}\right) Z_i \qquad \text{for } n = 0 \text{ to } 511$$

The constellation encoder and gain scaling generate only 255 complex values of Z_i. In order to generate real values of x_n, the input values (255 complex values plus zero at DC and one real value for Nyquist if used) are augmented so that the vector Z has Hermitian symmetry. That is,

$$Z_i = \text{conj}\,(Z'_{512-i}) \qquad \text{for } i = 257 \text{ to } 511$$

A fixed 512-bit pseudo-random binary sequence (PRBS) is modulated onto each sync symbol, with 2 bits per subcarrier. The synchronization symbol permits recovery of the frame boundary after micro-interruptions that might otherwise force retraining.

For operation over POTS, subcarrier 64 is a pilot subcarrier. For operation over ISDN, subcarrier 96 is a pilot subcarrier. The data modulated onto the pilot subcarrier is a constant {0,0}. Use of this pilot allows resolution of sample timing in a receiver modulo-8 samples. Therefore a gross timing error that is an integer multiple of eight samples could still persist after a micro-interruption (e.g. a temporary short-circuit, open circuit or severe line hit); correction of such timing errors is made possible by the use of the synchronization symbol.

1.2.1.7 Embedded operations channel

An embedded operations channel (EOC) for communication between the ATU-C and ATU-R is used for in-service and out-of-service maintenance and for the retrieval of ATU-R status information and ADSL performance monitoring parameters.

The ADSL EOC allows the ATU-C (acting as master of the link) to invoke commands and the ATU-R (acting as slave) to respond to the commands. The ATU-C determines the EOC rate of the ADSL link; therefore only one EOC message is inserted in the upstream direction (by the ATU-R) for each received EOC message. One exception to this is for the "dying gasp" message, which is the only autonomous message currently allowed from the ATU-R and is inserted as soon as appropriate bytes are available.

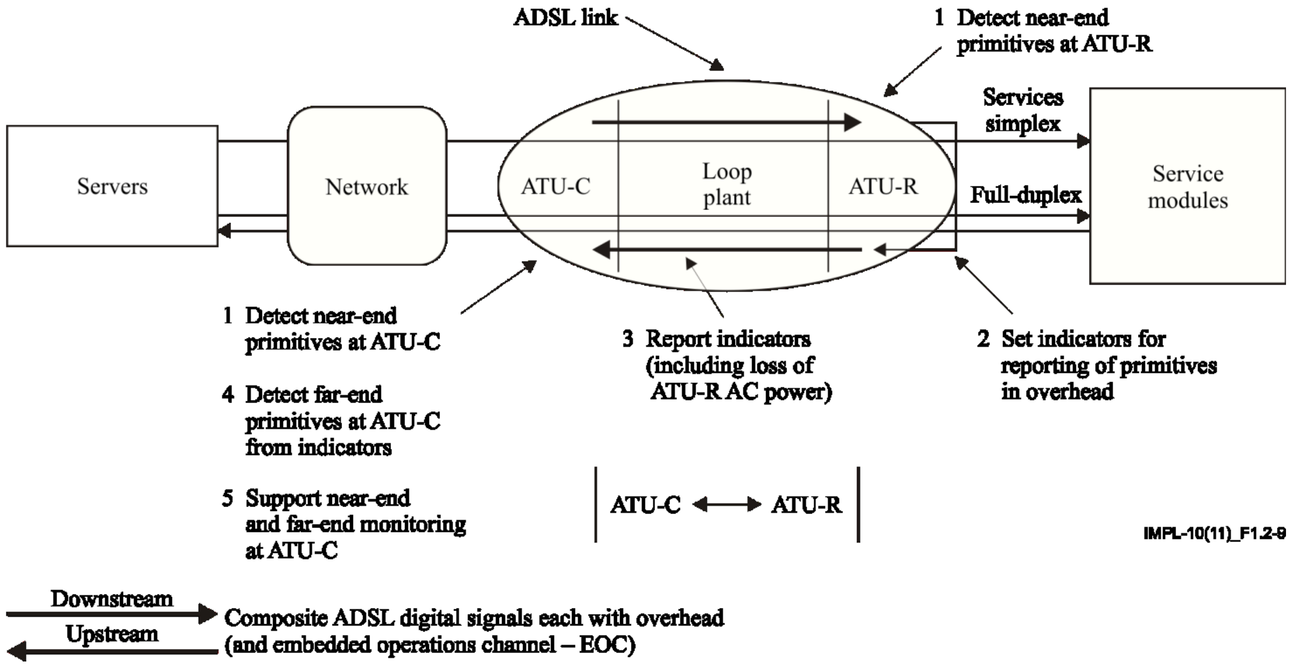
The EOC commands allow the ATU-C to read the ATU-R registers, which are defined as:

- ATU-R vendor ID: 8 bytes (see 9.3.3 of ITU-T G.994.1);
- ATU-R revision number: vendor discretionary;
- ATU-R serial number (32 bytes): vendor discretionary;
- Self-Test results: Pass/fail indication with additional vendor discretionary information;
- Line attenuation (1 byte);

- SNR Margin (1 byte);
- ATU-R configuration (30 bytes): the ATU-R configuration data for framing, FEC and interleaving.

1.2.1.8 In-service performance monitoring and surveillance

ADSL systems have been designed to deliver packet-/cell-based payloads. However, when ADSL systems operate in the STM mode non-cell based data paths may also be transported. The performance monitoring capabilities required to maintain those data paths are embedded within the packet/cell systems. The ADSL system supports the data path monitoring requirements as required by the specific payload technology (Figure 1.2-9).



NOTE 1- Near-end means performance of the loop-side received signal at the input of the ATU.

NOTE 2 – Far-end means performance of the downstream loop-side received signal at the input of the ATU-R, where this performance is reported to the ATU-C in upstream indicators, or performance of the upstream loop-side received signal at the input of the ATU-C, where this performance is reported to the ATU-R in downstream overhead indicators; this case is a mirror image of the above.

Figure 1.2-9 – In-service surveillance of the ADSL link shown from standpoint of ATU-C

Four line-related near-end anomalies are defined:

- Forward error correction interleaved (FEC-I) anomaly;
- Forward error correction fast (FEC-F) anomaly;
- Cyclic redundancy check interleaved (CRC-I) anomaly;
- Cyclic redundancy check fast (CRC-F) anomaly.

Two line-related near-end defects are defined:

- Loss-of-signal (LOS) defect;
- Severely errored frame (SEF) defect.

For STM transport, various payload types can be used. These payload types and path-related anomalies are not specified in ITU-T G.992.1.

For ATM transport, six near-end path related anomalies are defined:

- No cell delineation interleaved (NCD-I) anomaly;
- No cell delineation fast (NCD-F) anomaly;
- Out of cell delineation interleaved (OCD-I) anomaly;
- Out of cell delineation fast (OCD-F) anomaly;
- Header error control interleaved (HEC-I) anomaly;
- Header error control fast (HEC-F) anomaly;

For ATM transport, two near-end path related defects are defined:

- Loss of cell delineation interleaved (LCD-I) defect;
- Loss of cell delineation fast (LCD-F) defect.

One other near-end power related primitive is defined:

- Loss-of-power (LPR).

For each of the near-end anomalies, defects and primitive, a related far-end anomaly, defect or primitive is defined. The far-end reports anomalies and defects once per superframe through the related indicator. The ATU-R reports the LPR (loss-of-power) primitive as an autonomous "dying gasp" emergency priority message in the EOC.

Failures, performance parameters and storage and reporting thereof are defined in Recommendation ITU-T G.997.1.

1.2.1.9 Test parameters

The attenuation (ATN) and signal-to-noise ratio (SNR) margin test parameters apply to on-demand test requests; e.g. to check for adequate physical media performance margin at acceptance and after repair verification, or at any other time following the execution of initialization and training sequence of the ADSL system. ATN and SNR, as measured by the receivers at both the ATU-C and the ATU-R are accessible from the ATU-C, but they are not required to be continuously monitored. They are made available on-demand.

Attenuation (ATN) is the difference in dB between the power received at the near-end and that transmitted from the far-end;

Signal-to-Noise Ratio (SNR) margin is the signal-to-noise ratio margin measured at the near-end.

For each of the above two near-end test parameters, a related far-end test parameter is defined. The ATU-R reports the test parameters through the EOC.

1.2.1.10 Initialization

ADSL transceiver initialization is required in order, for a physically connected ATU-R and ATU-C pair, to establish a communications link. In order to maximize the throughput and reliability of this link, ADSL transceivers determine certain relevant attributes of the connecting channel and establish transmission and processing characteristics suitable to that channel. The time line of Figure 1.2-10 provides an overview of this process.

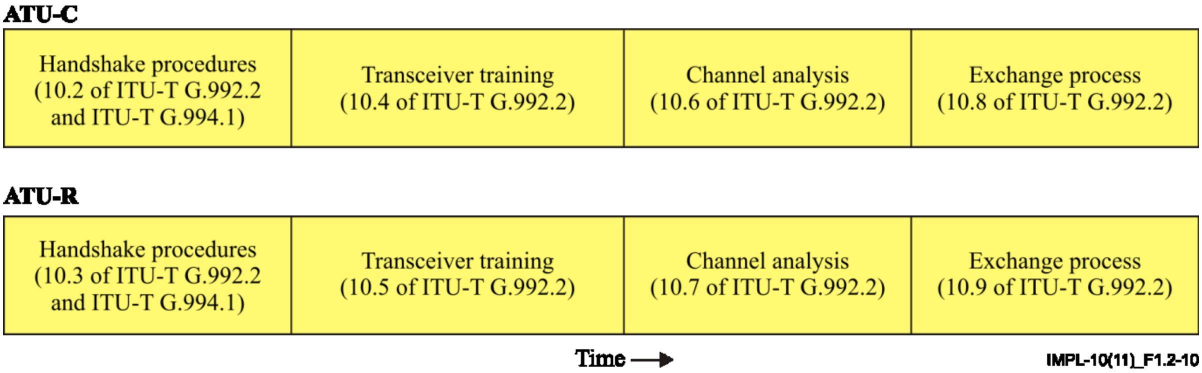


Figure 1.2-10 – Overview of initialization

At the start of initialization, both ATU-C and ATU-R follow the detailed procedures for handshake as defined in Recommendation ITU-T G.994.1. These procedures allow the ATUs to exchange information (e.g., which ADSL Recommendations are supported by the transceiver and enabled by the network operator). If ITU-T G.994.1 procedures select ITU-T G.992.1 as the mode of operation, both the ATU-C and ATU-R transition to transceiver training, as defined in ITU-T G.992.1.

In Figure 1.2-10, each receiver can determine the relevant attributes of the channel through the transceiver training and channel analysis procedures (e.g., the channel attenuation for each subcarrier). Certain processing and transmission characteristics can also be established at each receiver during this time.

In the transceiver training phase, the ATU-R transmits the R-REVERB signal that allows the ATU-C to measure the upstream wideband power in order to adjust the ATU-C transmit power level, to adjust its receiver gain control, and to synchronize its receiver and train its equalizer. The ATU-C transmits the C-REVERB signal that allows the ATU-R to adjust its automatic gain control (AGC) to an appropriate level.

During channel analysis, the ATU-C communicates a set of downstream and upstream configuration options and transmits the C-MEDLEY signal, which is a wideband pseudo-random signal that allows the ATU-R to estimate the downstream SNR. The ATU-R transmits the R-MEDLEY signal, which is a wideband pseudo-random signal that allows the ATU-C to estimate the upstream SNR.

During the exchange process, each receiver shares with its corresponding far-end transmitter certain transmission settings that it expects to see. Specifically, each receiver communicates to its far-end transmitter the number of bits and relative power levels to be used on each DMT subcarrier, as well as any messages and final data rates information. For highest performance, these settings should be based on the results obtained through the transceiver training and channel analysis procedures.

1.2.1.11 ADSL overhead control channel (AOC)

The ADSL overhead control channel (AOC) is used for on-line adaptation and reconfiguration of the bits and relative power levels to be used on each DMT subcarrier (i.e., bit swapping). The AOC data are carried as overhead bytes in the ADSL framing structure.

Note. Bit swapping is a way of keeping the line more stable by constantly monitoring the frequency carriers in use and reusing them if possible. The bit swap process enables the connection to either change the number of bits assigned to each individual sub-channel or, if necessary, increase / decrease the power level (gain) whilst still maintaining the data flow.

Either ATU may initiate a bit swap; the swapping procedures in the upstream and downstream channels are independent, and may take place simultaneously. These procedures allow adaptation to changes in the attributes of the channel after initialization.

1.2.1.12 Specific requirements for an ADSL system operating in the frequency band above POTS

ITU-T G.992.1 Annex A defines those parameters of the ADSL system that are unique to an ADSL service that is frequency-division duplexed with POTS.

The band from 25 to 1104 kHz in the downstream direction is the widest possible band (used for ADSL over POTS implemented with overlapped spectrum, i.e. with overlapping of the downstream and the upstream frequency bands). Figure 1.2-11 shows a representative spectral mask for the transmit signal. The ADSL modem confines the power spectral density (PSD) of its transmit signal to be within the transmit PSD mask. Below 3093 kHz PSD masks is determined by the DMT signal that is peak as in the figure but also has average requirements defined elsewhere. Above 3093 kHz the PSD mask is determined by intrinsic noise sources like oscillators, there peak is not the right word and dBm/Hz is used.

The low-frequency stop-band is defined as the POTS band; the high-frequency stop-band is defined as frequencies greater than 1104 kHz. The nominal aggregate transmit power is 20.4 dBm if all downstream subcarriers are used.

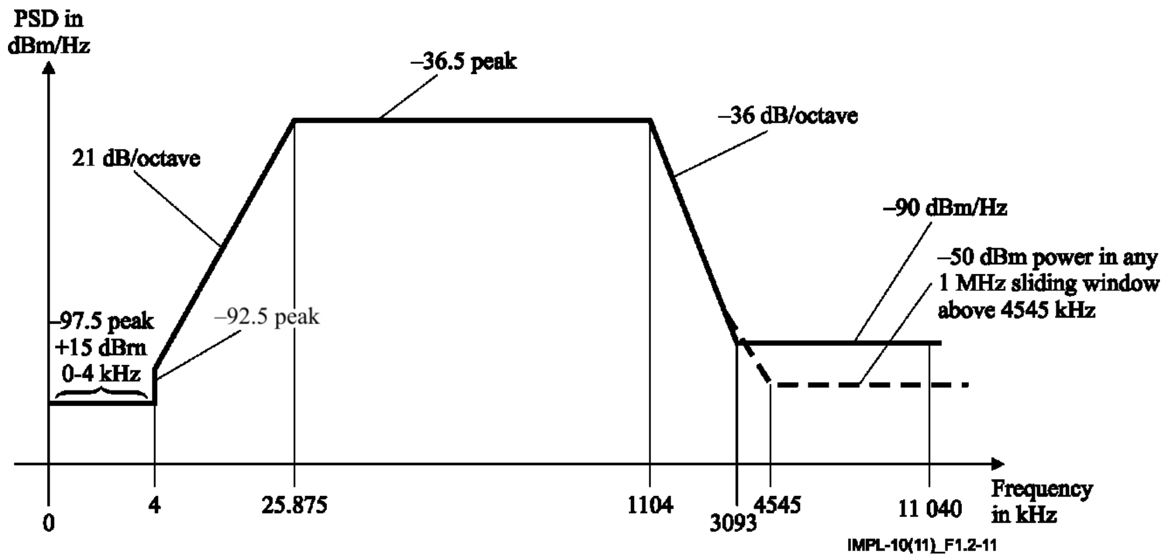


Figure 1.2-11 – ATU-C transmitter PSD mask

Figure 1.2-12 defines a spectral mask for the ATU-C transmitted signal, which results in reduced NEXT into the ADSL upstream band, relative to the mask in Figure 1.2-11. Adherence to this mask will in many cases result in improved upstream performance of the other ADSL systems in the same or adjacent binder group, with the improvement dependent upon the other interferers. This mask differs from the mask in Figure 1.2-11 only in the band from 4 kHz to 138 kHz. The nominal aggregate transmit power is 19.8 dBm if all downstream subcarriers are used.

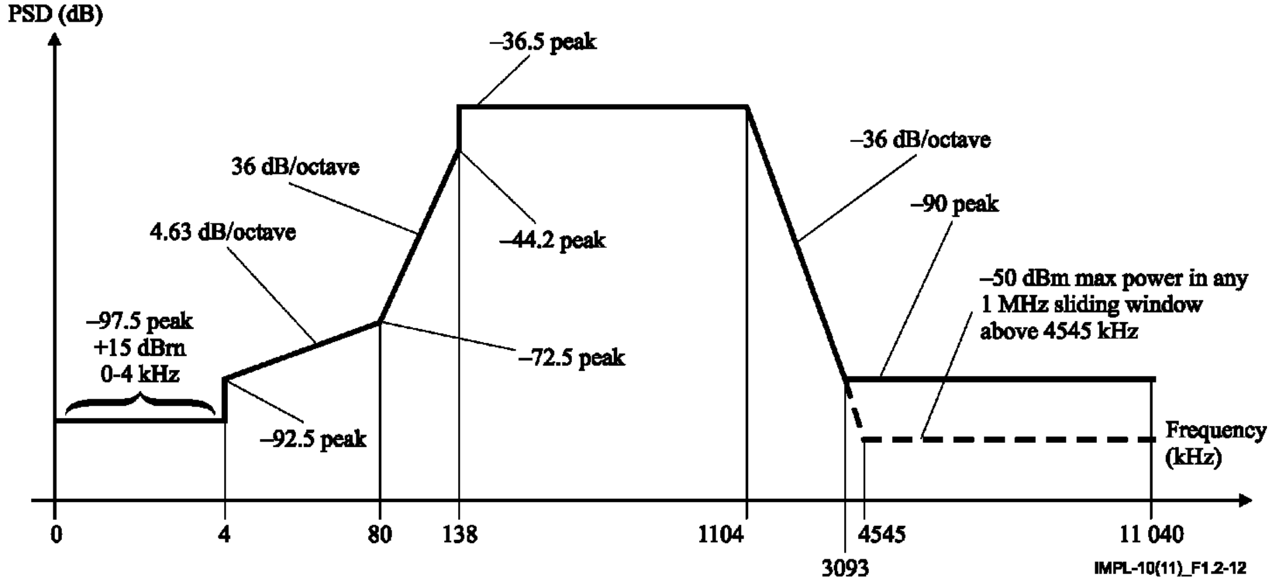


Figure 1.2-12 – ATU-C transmitter PSD mask for reduced NEXT

Figure 1.2-13 shows a PSD mask for the ATU-R transmitted signal in the upstream direction. The passband is defined as frequency range over which the modem transmits, which may be narrower than the 25.875 to 138 kHz shown. The low-frequency stop-band is defined as the voiceband. The nominal aggregate transmit power is 12.5 dBm if all upstream subcarriers are used.

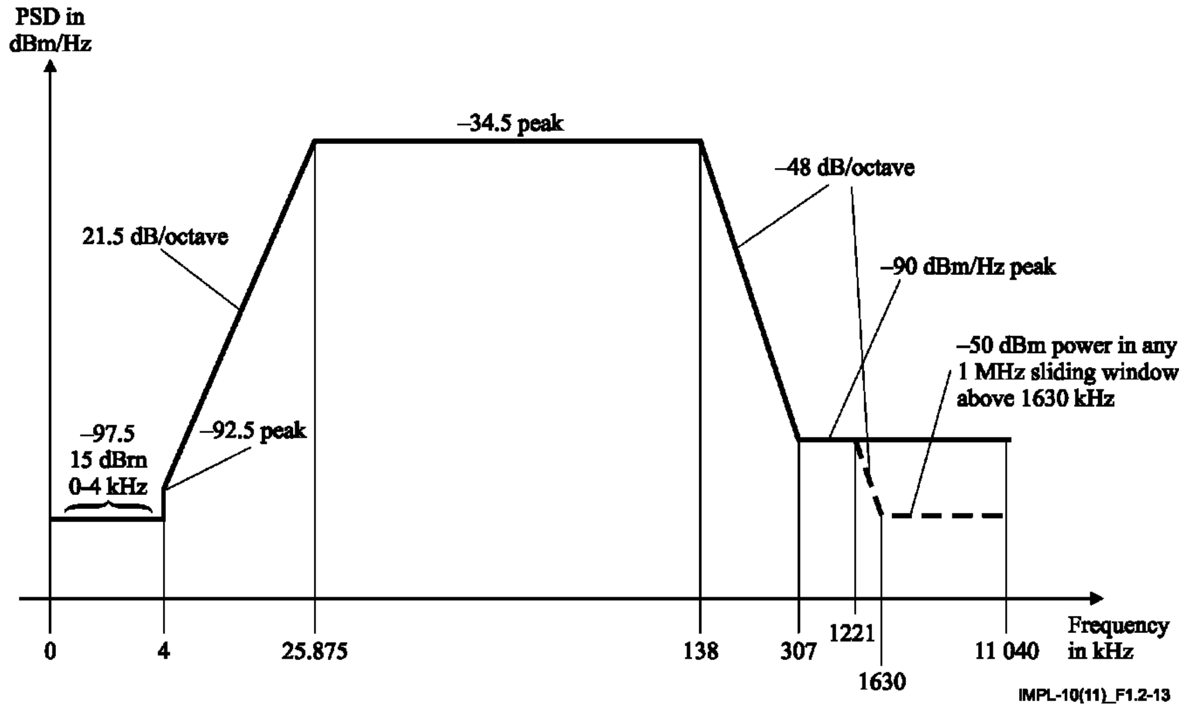


Figure 1.2-13 – ATU-R transmitter PSD mask

1.2.1.13 Specific requirements for an ADSL system operating in the frequency band above ISDN, as defined in Recommendation ITU-T G.961 Appendices I and II

ITU-T G.992.1 Annex B defines those parameters of the ADSL system that are unique to an ADSL service that is frequency-division duplexed with ISDN-BA (ISDN – basic access). The scope is to establish viable ways enabling the simultaneous deployment of asymmetric services and 160 kbit/s (2B+D) basic rate access with the constraint to use existing transmission technologies and 2B1Q/4B3T line signals as those specified in Recommendation ITU-T G.961 Appendices I and II.

Figure 1.2-14 shows the spectral mask for the ATU-C transmit signal. The low-frequency stop-band is the upstream band (at 138 kHz) or the ISDN-BA band (at 80/90 kHz); the high-frequency stop-band is defined as frequencies greater than 1104 kHz. The value of PSD in the 80 (90) to 138 kHz region depends on the low-pass and high-pass filter designs. The filters cause an acceptable reduction of the ISDN-BA performance when combined with ADSL. The nominal aggregate transmit power is 19.9 dBm if all upstream subcarriers are used.

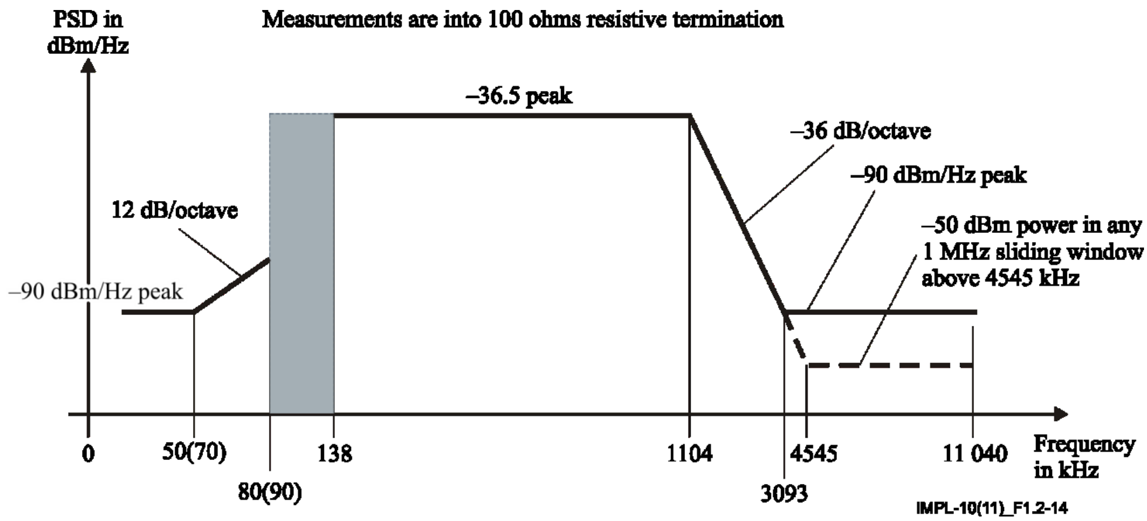


Figure 1.2-14 – ATU-C transmitter PSD mask

Figure 1.2-15 shows the spectral mask for the ATU-R transmit signal. The low-frequency stop-band is defined as the ISDN band, the high-frequency stop-band is defined as frequencies greater than 276 kHz. The value of PSD in the 80 (90) to 138 kHz region depends on the low-pass and high-pass filter designs. The filters cause an acceptable reduction of the ISDN-BA performance when combined with ADSL. The nominal aggregate transmit power is 13.3 dBm if all upstream subcarriers are used.

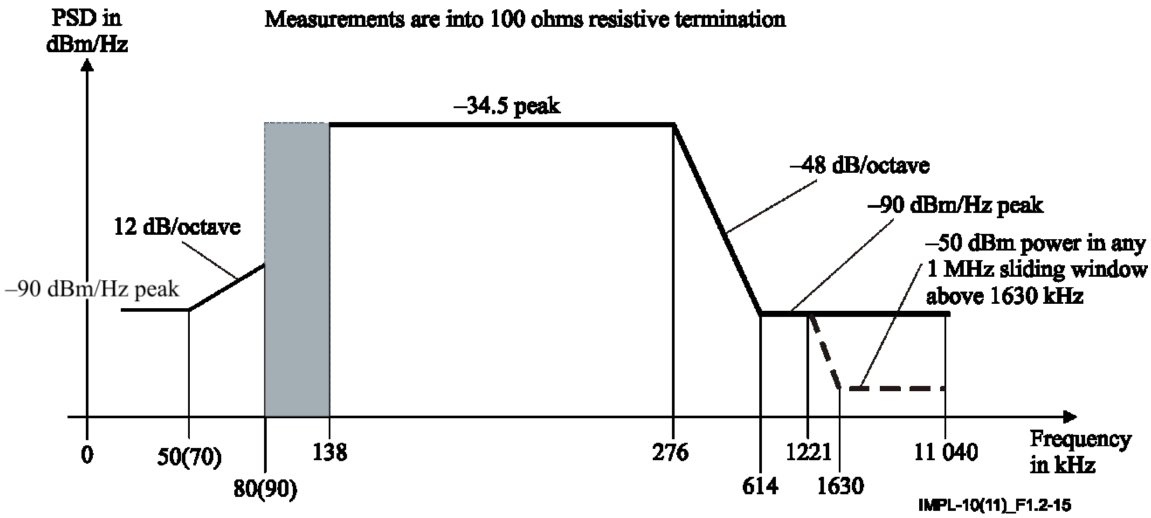


Figure 1.2-15– ATU-R transmitter PSD mask

1.2.1.14 Specific requirements for an ADSL system operating in the same cable as ISDN as defined in Recommendation ITU-T G.961 Appendix III

ITU-T G.992.1 Annex C describes those specifications of the ADSL system that are unique to an ADSL service that is frequency-division duplexed with POTS and coexisting in the same binder as TCM-ISDN (time compression multiplexing – ISDN), as defined Recommendation ITU-T G.961 Appendix III. The modifications described in the above quoted Annex C to ITU-T G.992.1 allow a performance improvement from the ADSL system described in Section 1.2.1.12 in an environment coexisting with TCM-ISDN in the same cable. The main modification is the operation with dual bitmap.

NOTE – A bitmap is a table that contains for each sub-carrier the number of bits mapped onto it (which determines the constellation used) and the gain setting (which determines the power at which the sub-carrier is transmitted). A bitmap is determined by the receiver during initialization based on channel characteristics. While ITU-T G.992.3 Annex A (over POTS) and ITU-T G.992.3 Annex B (over ISDN) operate with a single bit map, ITU-T G.992.3 Annex C (with TCM-ISDN) operates with a dual bit map, one used under TCM-ISDN FEXT noise conditions and one used under TCM-ISDN NEXT noise conditions.

The data stream of TCM-ISDN is transmitted in a TCM-ISDN timing reference (TTR) period of 2.5 milliseconds (400 Hz). The central office (CO) transmits the stream in the first half of the TTR period and remote terminal (RT) transmits in the second half of the TTR period. Therefore, the ATU-C receives NEXT noise from the ISDN in the first half of the TTR period ($NEXT_C$ duration) and FEXT noise from the ISDN in the second half of the TCM-ISDN period ($FEXT_C$ duration). On the other hand, ATU-R receives FEXT noise from the ISDN in the first half of the TTR period ($FEXT_R$ duration) and NEXT noise from the ISDN in the second half of the TTR period ($NEXT_R$ duration).

During initialization, the ATU-R receiver determines two downstream bit tables. The Bitmap-F_R is based on an SNR measurement in the $FEXT_R$ duration. The Bitmap-N_R is based on an SNR measurement in the $NEXT_R$ duration. The ATU-C receiver determines two upstream bit tables. The Bitmap-F_C is based on an SNR measurement in the $FEXT_C$ duration. The Bitmap-N_C is based on an SNR measurement in the $NEXT_C$ duration.

Each 34 TTR periods, 345 DMT symbols are transmitted (34 x 2.5 ms = 345 x 0.25 ms x 68 / 69). The ATU-C transmits $FEXT_R$ symbols using Bitmap-F_R (in $FEXT_R$ duration), and transmits $NEXT_R$ symbols using Bitmap-N_R (in $NEXT_R$ duration) according to the result of initialization. The ATU-R transmits $FEXT_C$ symbols using Bitmap-F_C (in $FEXT_C$ duration), and transmits $NEXT_C$ symbols using Bitmap-N_C (in $NEXT_C$ duration) in the same manner.

The ATU-C may disable the bitmaps Bitmap-N_C and Bitmap-N_R, and hence choose to operate the ADSL with data transmission during FEXT durations only.

1.2.2 Splitterless ADSL

(For further details see Recommendation ITU-T G.992.2.)

This section describes the splitterless ADSL system which is very similar to the ADSL system described in the previous section, except for its ease of installation and for its lower implementation complexity. Splitterless ADSL allows the provision of simultaneous voiceband transmission, including POTS and V-series data transmission, and a number of digital channels. Splitterless ADSL is a transmission system that interfaces the telecommunications network and the customer installation in terms of their interaction and electrical characteristics. The text of this section is based on that of ITU-T G.992.2. The requirements of ITU-T G.992.2 apply only to a single asymmetric digital subscriber line. Operation in the frequency band over ISDN is still to be specified.

A single twisted pair of telephone wires is used to connect the ATU-C to the ATU-R. The ADSL transmission units must deal with a variety of wire pair characteristics and typical impairments (e.g. crosstalk and noise). The transmission system is designed to operate on two-wire twisted metallic cable pairs with mixed gauges and over the customer premises wiring. ITU-T G.992.2 is based on the use of cables without loading coils, but bridged taps are acceptable in all but a few unusual situations.

ITU-T G.992.2 transmission unit can simultaneously convey a downstream and upstream simplex bearer, a baseband analogue duplex channel, and ADSL line overhead for framing, error control, operations, and maintenance. ITU-T G.992.2 supports a maximum of 1.536 Mbit/s downstream and 512 kbit/s upstream net data rates.

In an annex of ITU-T G.992.2 it is also described the transmission technique used to support the simultaneous transport on a single twisted-pair of voiceband services and both simplex upstream and downstream bearer channels when they are subject to crosstalk from TCM-ISDN as defined in Appendix III of ITU-T G.961.

By negotiation during initialization, ITU-T G.992.2 provides for U-interface compatibility and interoperability between transceivers complying with ITU-T G.992.2 and between those transceivers that include different combinations of options.

1.2.2.1 Reference models

The system reference model shown in Figure 1.2-16 describes the functional blocks required to provide splitterless ADSL service.

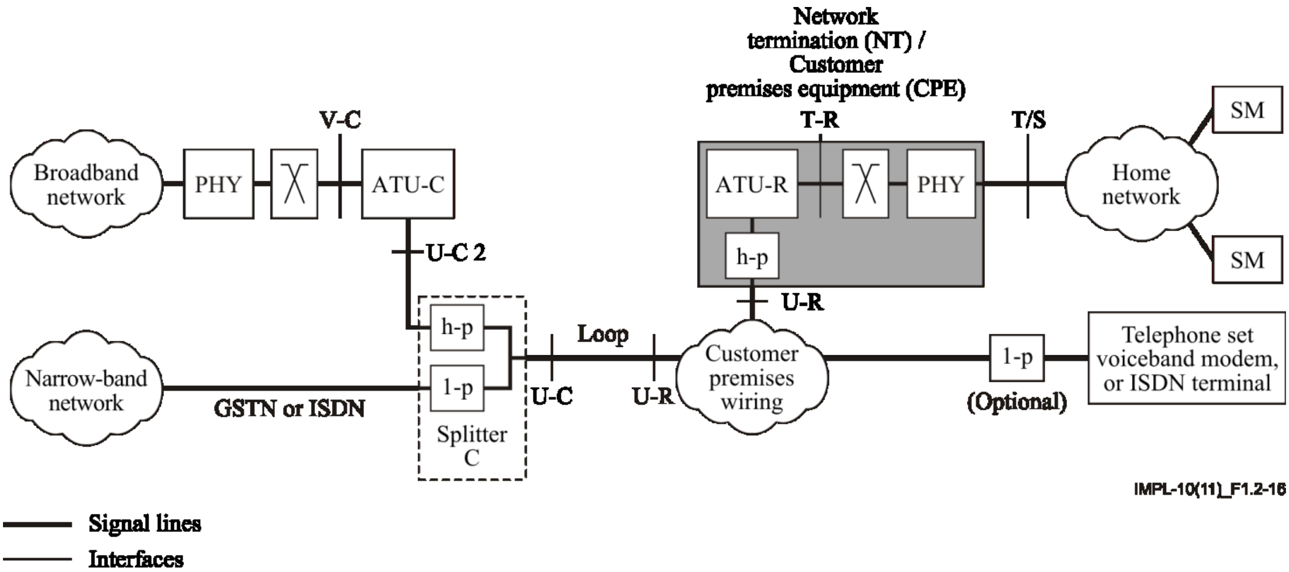
The splitterless ADSL system reference model is very similar to the ADSL system reference model, except for its ease of installation:

- the high-pass part of the POTS splitter is integrated into the Customer Premises Equipment (NT/CPE);
- the low-pass part of the POTS splitter is distributed throughout the premises as one in-line filter per telephone set, voiceband modem or ISDN terminal (the low-pass filter is qualified as "optional" in the figure because its need depends on whether or not the device is disturbed by the presence of the ADSL signal);
- the splitterless ADSL signal is available throughout the customer premises wiring, which allows the splitterless ADSL NT/CPE to be connected at an existing POTS or ISDN wall socket.

The splitterless ADSL also allows for lower implementation complexity due to:

- the reduced minimum net data rate requirements (1.536 Mbit/s instead of 6.144 Mbit/s downstream; 512 kbit/s instead of 644 kbit/s upstream);
- the operation with a single bearer channel (one downstream bearer channel instead of seven and one upstream bearer channel instead of three);
- the operation without trellis coding;
- the reduced minimum requirements on FEC coding (up to R=8 instead of 16);
- the reduced minimum requirements on interleaving depth (up to D=16 instead of 64);
- the reduced number of downstream subcarriers (128 instead of 256) and spectrum usage (552 kHz).

Two important functionalities are added in splitterless ADSL as compared to ADSL: a fast retrain procedure (see Section 1.2.2.3) and power management (see Section 1.2.2.4).



NOTE 1 – An optional ATU-R splitter may be utilized to isolate customer premises wiring and voiceband equipment from the ADSL signal.
NOTE 2 – SM = Service module

Figure 1.2-16 – System reference model

1.2.2.2 Transport capacity

The ATU transports a single duplex bearer channel. The bearer channel data rate is programmable in multiples of 32 kbit/s.

The maximum net data rate transport capacity of the ATU will depend on the characteristics of the loop on which the system is deployed, and on certain configurable options that affect overhead. The ATU bearer channel net data rate is configured during the initialization and training procedures.

Bearer channel AS0 (downstream) supports the transport of data at all integer multiples of 32 kbit/s from 64 kbit/s to 1.536 Mbit/s. Bearer channel LS0 (upstream) supports all integer multiples of 32 kbit/s from 32 kbit/s to 512 kbit/s.

The ITU-T G.992.1 Annex D (for North America) and Annex E (for Europe) define performance requirements against an objective of coverage over test loops and in the presence of defined noise models. Test loops and noise models are defined in ITU-T G.996.1.

1.2.2.3 Fast retrain

A fast retrain procedure is defined to adapt transmission characteristics to changing line conditions caused by e.g., phone on/off hook transitions. The fast retrain procedure is also used in an escape from handshake to fast retrain and in power management transitions.

Figure 1.2-17 shows the flowchart of the various components of the fast retrain procedure and how it relates to the initialization procedures.

If errors occur during showtime, a Fast Retrain Procedure may also be invoked.

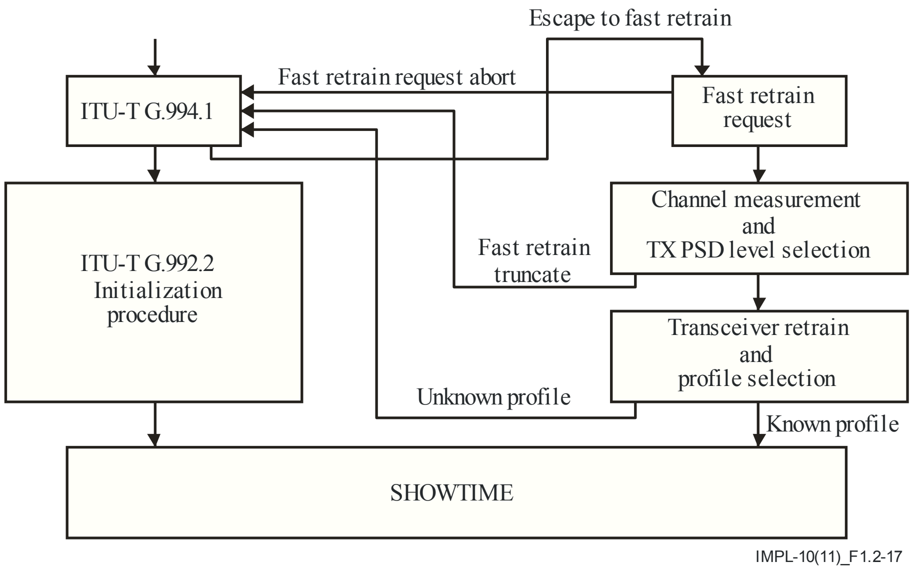


Figure 1.2-17– Flowchart of fast retrain

The fast retrain procedure is based on the concept of stored profiles. The ATU supports a minimum of two profiles. A maximum of 16 profiles may be supported. The profiles at least contain the following information:

- Bitmap (bits and gains table);
- FEC parameters R and S;
- Interleaver depth D.

The fast retrain procedure allows for a fast switching between profiles, allowing to adapt transmission characteristics to changing line conditions (caused by e.g., phone on/off hook transitions) within a few seconds, rather than going through the full initialization procedure which may take a few tens of seconds.

1.2.2.4 Power management

Power management defines a set of power management states for the ADSL link and the use of the EOC channel to coordinate power management between the ATUs. Power reduction can be achieved by minimizing the energy transmitted by the ATU onto the U-C and U-R reference points (see Figure 1.2-1) as well as by reducing the power consumed by the ATU (e.g., reducing clock speed, turning off drivers). A set of stable splitterless ADSL link states are defined between the

ATU-R and ATU-C (Table 1.2-5) by specifying the signals that are active on the link in each state. In addition, link transition events (Figure 1.2-18) and procedures are defined.

ADSL link states are defined to allow an ATU to enter a low power state (e.g., in periods of low or no user data traffic) without totally disconnecting the link (so data transmission can resume quickly when user data traffic ramps up). These states are stable states and are generally not expected to be transitory.

Table 1.2-5 – ITU-T G.992.2 Power management states

State	Name	Support	Description
L0	Full On	Mandatory	The ADSL link is fully functional.
L1	Low Power	Optional	The L1 state maintains full L0 state functionality at a lower net data rate (except for power management transitions). Power reduction in L1 can be achieved by methods provided in the exchange entry procedure (e.g. reduced data rata, reduced number of tones, and reduced power per tone). The reductions are implementation specific.
L2			Reserved for use by ITU-T.
L3	Idle	Mandatory	There is no signal transmitted at the U-C and U-R reference points. The ATU may be powered or unpowered in L3.

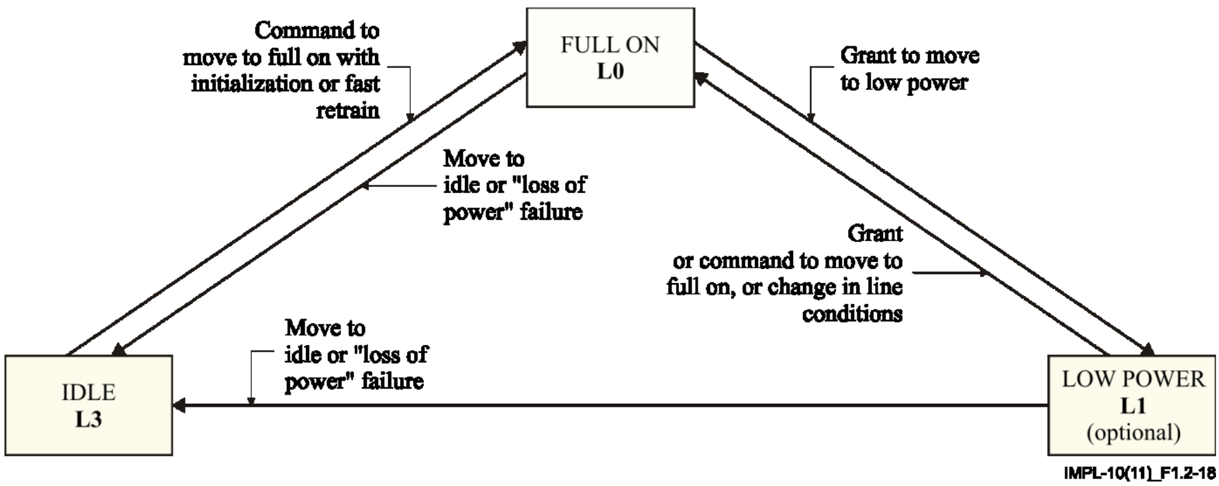


Figure 1.2-18 – Power management states and transitions

The ATU-R and ATU-C coordinate transitions between power states using the EOC, handshake, exchange entry, and fast retrain procedures.

1.2.3 ADSL2

(For further information see Recommendation ITU-T G.992.3.)

ADSL2 is the second generation of ADSL specified with the main purposes of increasing the bit rate in the downstream and in the upstream direction and of adding new features relative to the ADSL specified in Recommendation ITU-T G.992.1. ADSL2 is defined in ITU-T G.992.3 and it is based on the first generation of ADSL specified in Recommendation ITU-T G.992.1. It is intended that ITU-T G.992.3 be implemented in multi-mode devices that support both Recommendations ITU-T G.992.3 and ITU-T G.992.1.

Recommendation ITU-T G.992.1 was approved in 1999. Since then, several potential improvements have been identified in areas such as data rate versus loop reach performance, loop diagnostics, deployment from remote cabinets, spectrum control, power control, robustness against loop impairments and radio frequency interference (RFI), and operations and maintenance. The present version (2009) provides a new ADSL U-interface specification, including the identified improvements, which ITU-T believes will be most helpful to the ADSL industry.

Relative to Recommendation ITU-T G.992.1, the following application-related features have been added:

- Improved application support for an all-digital mode of operation and voice-over-ADSL operation;
- Packet TPS-TC (Transmission Protocol-Specific Transmission Convergence layer) function allows for the transport of e.g., Ethernet packets over ADSL2, in addition to the existing STM and ATM TPS-TC functions;
- Mandatory support of 8 Mbit/s downstream and 800 kbit/s upstream for TPS-TC function #0 and frame bearer #0;
- Support for inverse multiplexing over ATM (IMA) in the ATM TPS-TC;
- Improved configuration capability for each TPS-TC with configuration of latency, bit error ratio (BER) and minimum, maximum and reserved data rates.

Relative to Recommendation ITU-T G.992.1, the following PMS-TC-related (physical media-specific transmission convergence) features have been added:

- A more flexible framing, including support for up to 4 frame bearers, 4 latency paths;
- Parameters allowing enhanced configuration of the overhead channel;
- Frame structure with receiver-selected coding parameters;
- Frame structure with optimized use of Reed-Solomon (RS) coding gain;
- Frame structure with configurable latency and bit error ratio;
- Operations, administration and management (OAM) protocol to retrieve more detailed performance monitoring information;
- Enhanced on-line reconfiguration capabilities, including dynamic rate repartitioning.

Relative to Recommendation ITU-T G.992.1, the following PMD-related features have been added:

- New line diagnostics procedures available for both successful and unsuccessful initialization scenarios, loop characterization and trouble-shooting;
- Enhanced on-line reconfiguration capabilities including bit swaps and seamless rate adaptation;

- Optional short initialization sequence for recovery from errors or fast resumption of operation;
- Optional seamless rate adaptation with line rate changes during showtime;
- Improved robustness against bridged taps with receiver-determined pilot tone;
- Improved transceiver training with exchange of detailed transmit signal characteristics;
- Improved SNR measurement during channel analysis;
- Subcarrier blackout to allow RFI measurement during initialization and showtime;
- Improved performance with mandatory support of trellis coding;
- Improved performance with data modulated on the pilot tone;
- Improved RFI robustness with receiver-determined tone ordering;
- Improved transmit power cutback possibilities at both the central office (CO) and remote side;
- Improved initialization with receiver- and transmitter-controlled duration of initialization states;
- Improved initialization with receiver-determined carriers for modulation of messages;
- Improved channel identification capability with spectral shaping during channel discovery and transceiver training;
- Mandatory transmit power reduction to minimize excess margin under management layer control;
- Power-saving feature for the central office ATU with new L2 low power state;
- Power-saving feature with new L3 idle state;
- Spectrum control with individual tone masking under operator control through the CO-MIB (Central office – management information base);
- Improved conformance testing, including increase in data rates for many existing tests
- Through negotiation during initialization, the capability of equipment to support Recommendation ITU-T G.992.3 or Recommendation ITU-T G.992.1 is identified. For reasons of interoperability, equipment may support both Recommendations such that it is able to adapt to the operating mode supported by the far-end equipment.

A detailed description of all the above, new features are in ITU-T G.992.3.

1.2.4 Splitterless ADSL2

(For further information see Recommendation ITU-T G.992.4.)

Splitterless ADSL2 is the second generation of splitterless ADSL, with the main purposes of increasing the bit rate in the downstream and in the upstream direction and of adding new features relative to the ADSL specified in Recommendation ITU-T G.992.2. It is defined in ITU-T G.992.4 and it is based on the first generation ITU-T Rec. G.992.2. Splitterless ADSL2 may be easily implemented in multi-mode devices that support both ITU-T G.992.4 and ITU-T G.992.2 with the following major additions and revisions:

- Improved application support for an all-digital mode of operation and voice over ADSL operation;
- A new packet TPS-TC function and a STM TPS-TC function in addition to the existing ATM support;

- Support for IMA in the ATM TPS-TC;
- Improved configuration capability for each TPS-TC with configuration of latency, BER and minimum, maximum and reserve data rate;
- New line diagnostic procedures available for both successful and unsuccessful initialization scenarios;
- Enhanced on-line reconfiguration capabilities including bit swaps, dynamic rate repartitioning, and seamless rate adaptation;
- A more flexible TPS-TC function including support for up to 4 frame bearers, 4 latency paths, and control parameters allowing enhanced configuration of the overhead channel;
- Performance improvements including mandatory support for R = 16, one bit constellations, and trellis coding;
- A more robust initialization procedure that includes splitterless capability features of the ITU-T G.992.2 fast retrain procedure, CO and CP (customer premises) controlled adaptive signal durations, receiver determined adaptive frequency modulation for data exchange, and an optional adaptive length fast start-up procedure;
- Improved RFI and spectrum management tools including transmit power cutback at both ends of the line, spectrum shaping, sub-carrier black-out lists to avoid RFI, and improved sub-carrier ordering to help mitigate the propagation of RFI from sub-carrier to sub-carrier;
- Power-saving features including mandatory reduction of excess margin under management layer control and a new L2 power management link state with low power features for the central office.

A detailed description of all the above, new features are in ITU-T G.992.4.

1.2.5 DSL2plus

(For further information see Recommendation ITU-T 992.5.)

ADSL2plus is the extended bandwidth version of the second generation of ADSL, based on the second generation ADSL Recommendation ITU-T G.992.3. ADSL2plus is defined in ITU-T G.992.5. It is intended that ITU-T G.992.5 be implemented in multi-mode devices that support Recommendations ITU-T G.992.5 (ADSL2plus), ITU-T G.992.3 (ADSL2) and ITU-T G.992.1 (ADSL).

An extended bandwidth ADSL transmission unit (ADSL2plus transceiver) can simultaneously convey all of the following: a number of downstream frame bearers; a number of upstream frame bearers; a baseband plain old telephone service POTS/ISDN duplex channel, and ADSL line overhead for framing, error control, operations and maintenance. Systems support a net data rate ranging up to a minimum of 16 Mbit/s downstream (instead of 8 Mbit/s downstream in ADSL2) and 800 kbit/s upstream. Support of net data rates above 16 Mbit/s downstream and support of net data rates above 800 kbit/s upstream are optional.

The support of higher downstream net data rates makes ADSL2plus more suited for the transport of (multi-channel) IPTV services.

The ADSL2plus extended bandwidth is the main difference with ADSL2. The ADSL2plus framing, scrambling, FEC, interleaving, trellis coding and modulation functionality is the same as for ADSL2 (which in turn is an improved version of the ADSL functionality). Where ADSL and ADSL2 use 256 downstream subcarriers for a maximum downstream frequency of 1.104 MHz, ADSL2plus uses 512 downstream subcarriers a maximum downstream frequency of 2.208 MHz. The ADSL2plus transmit PSD (power spectral density) masks are shown in following subsections.

1.2.5.1 Specific requirements for an ADSL2plus system operating in the frequency band above POTS

ITU-T G.992.5 Annex A defines those parameters of the ADSL2plus system that are unique to an ADSL2plus service that is frequency-division duplexed with POTS.

The band from 25 to 2208 kHz is the widest possible band (used for ADSL2plus over POTS implemented with overlapped spectrum). Figure 1.2-19 shows a representative spectral mask for the transmit signal. The low-frequency stop-band is defined as the POTS band; the high-frequency stop-band is defined as frequencies greater than 2208 kHz. The nominal aggregate transmit power is 20.4 dBm if all downstream subcarriers are used.

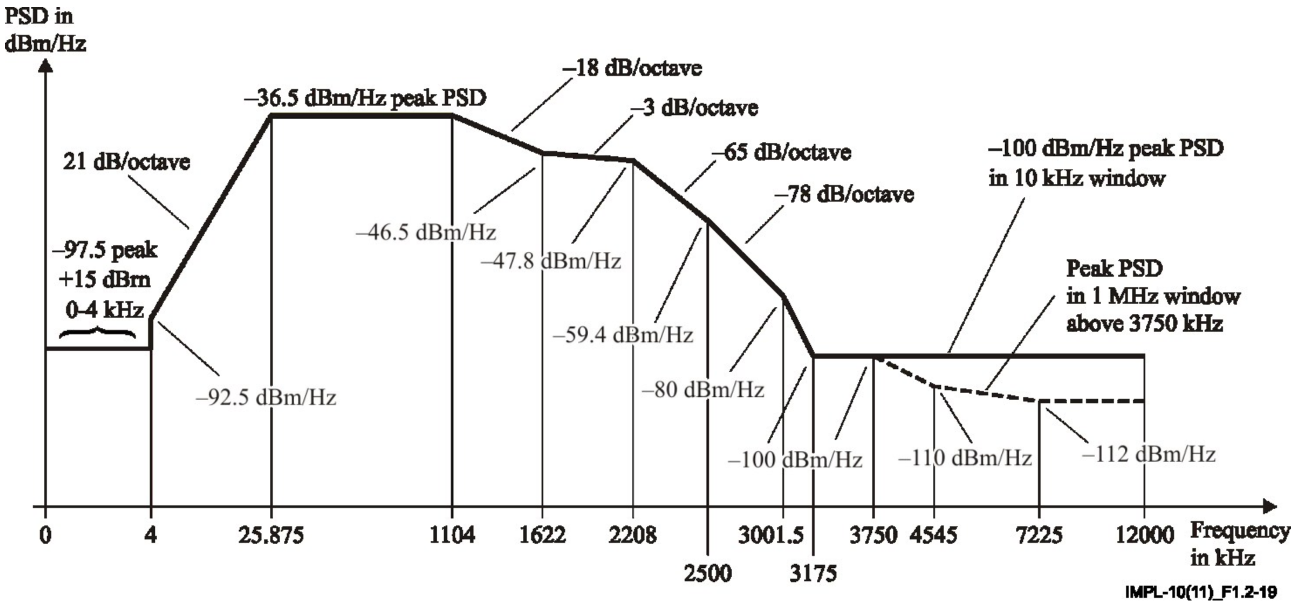


Figure 1.2-19 – ATU-C transmitter PSD mask

Figure 1.2-20 defines a spectral mask for the ATU-C transmitted signal, which results in reduced NEXT into the ADSL2plus upstream band, relative to the mask in Figure 1.2-19. Adherence to this mask will in many cases result in improved upstream performance of the other ADSL(2)(plus) systems in the same or adjacent binder group, with the improvement dependent upon the other interferers. This mask differs from the mask in Figure 1.2-19 only in the band from 4 kHz to 138 kHz. The nominal aggregate transmit power is 19.9 dBm if all downstream subcarriers are used.

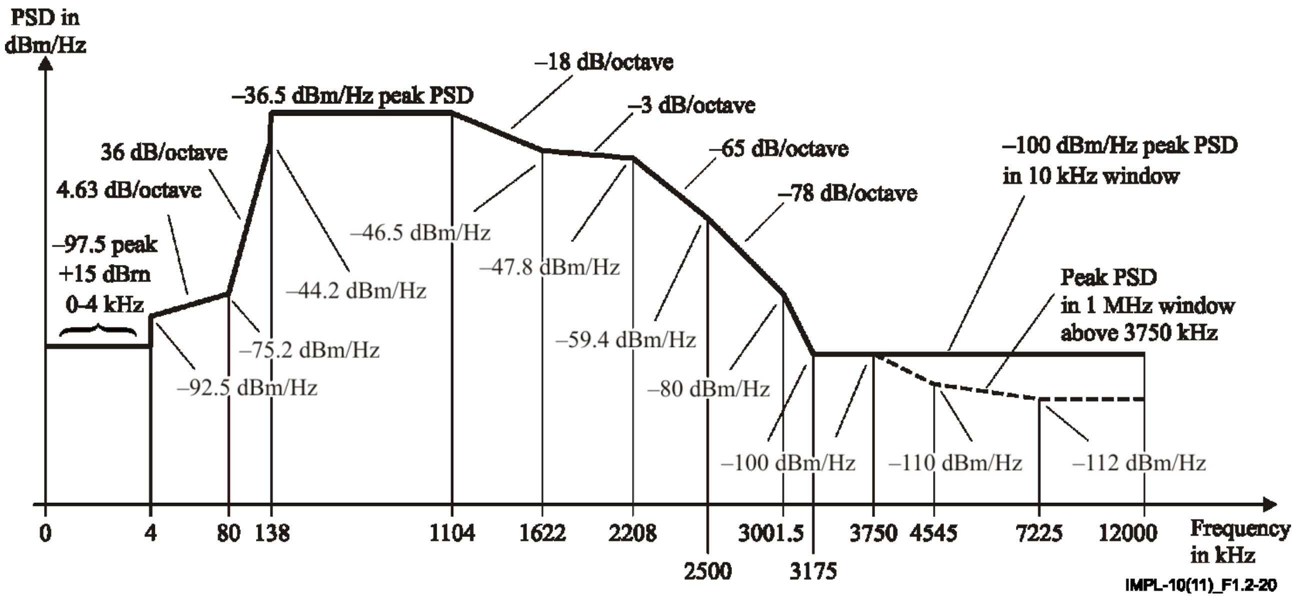


Figure 1.2-20 – ATU-C transmitter PSD mask for reduced NEXT

Figure 1.2-21 shows a PSD mask for the ATU-R transmitted signal. The passband is defined as frequency range over which the modem transmits, which may be narrower than the 25.875 to 138 kHz shown. The low-frequency stop-band is defined as the voiceband. The nominal aggregate transmit power is 12.5 dBm if all upstream subcarriers are used.

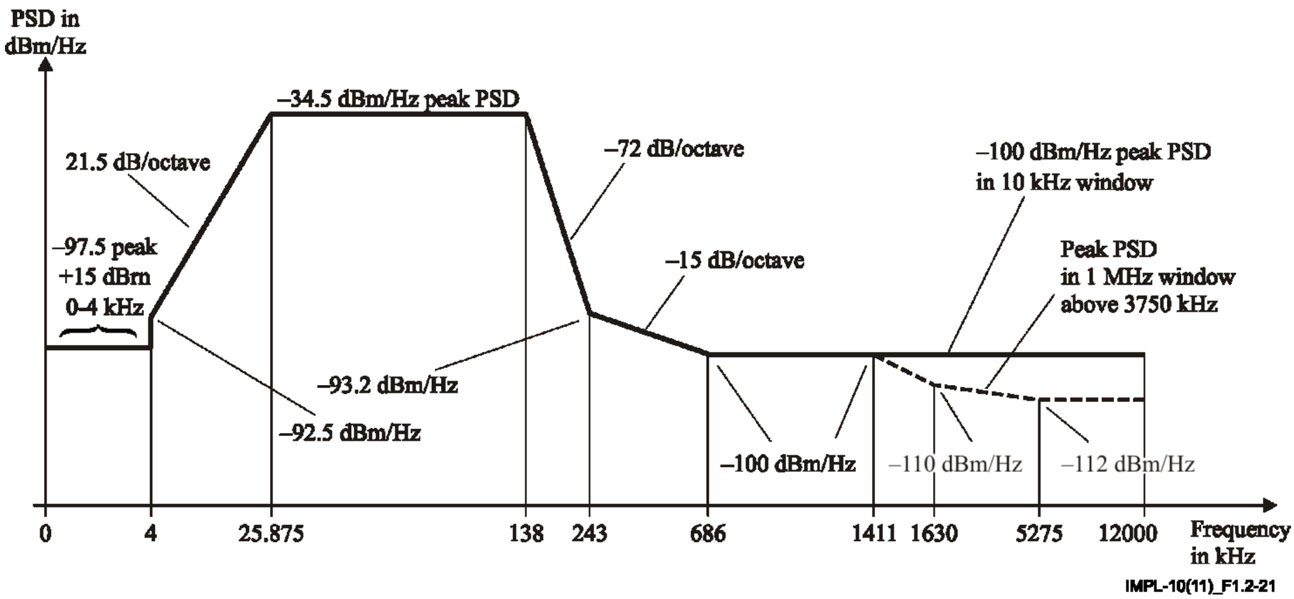


Figure 1.2-21 – ATU-R transmitter PSD mask

1.2.5.2 Specific requirements for an ADSL2plus system operating in the frequency band above ISDN as defined in Recommendation ITU-T G.961 Appendices I and II

Annex C of ITU-T G.992.5 defines those parameters of the ADSL system that have been left undefined in the main body of the Recommendation because they are unique to an ADSL service that is frequency-division duplexed with ISDN basic access on the same digital subscriber line. The scope is to establish viable ways enabling the simultaneous deployment of ADSL and 160 kbit/s

(2B + D) basic rate access with the constraint to use existing transmission technologies as those specified in Appendices I and II of ITU-T G.961.

Figure 1.2-22 defines the limit spectral mask for the transmit signal. The low-frequency stopband is the ISDN band and is defined as frequencies below 120 kHz; the high-frequency stopband is defined as frequencies greater than 2208 kHz. The nominal aggregate transmit power is 19.9 dBm if all upstream subcarriers are used.

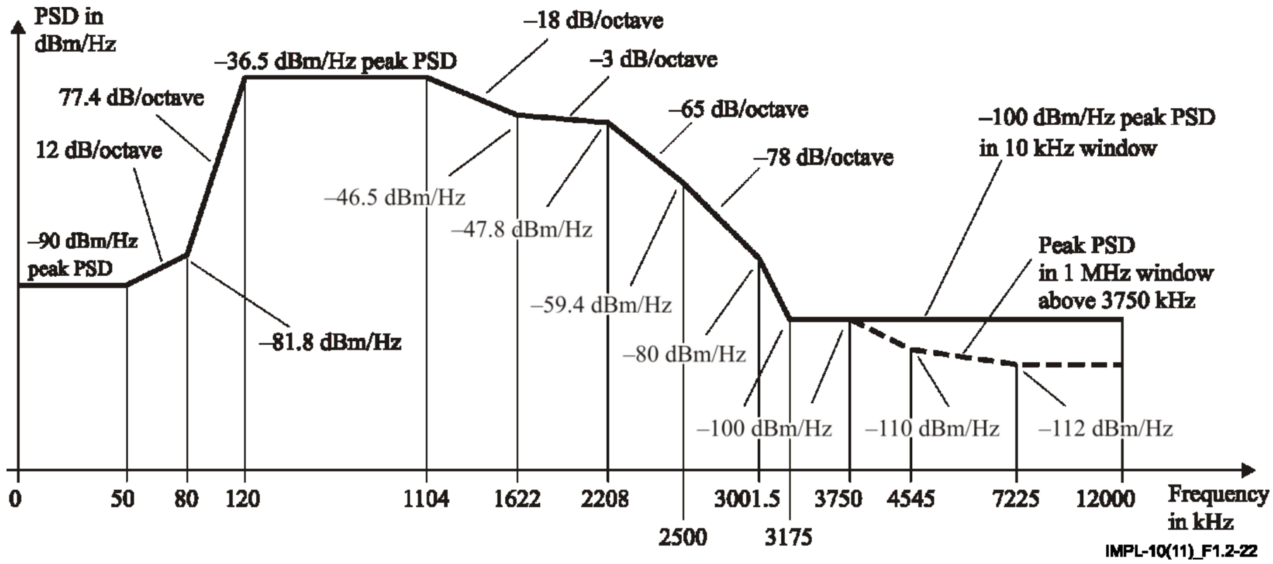


Figure 1.2-22 – ATU-C transmitter PSD mask

Figure 1.2-23 defines the limit spectral mask for the ATU-C transmitted signal, which results in reduced NEXT into the ADSL2plus upstream band, relative to the mask of Figure 1.2-22. Adherence to this mask will, in many cases, result in improved upstream performance of the other ADSL2plus systems in the same or adjacent binder group, with the improvement dependent upon the other interferers. This mask differs from the mask of Figure 1.2-22 only in the band from 50 kHz to 254 kHz.

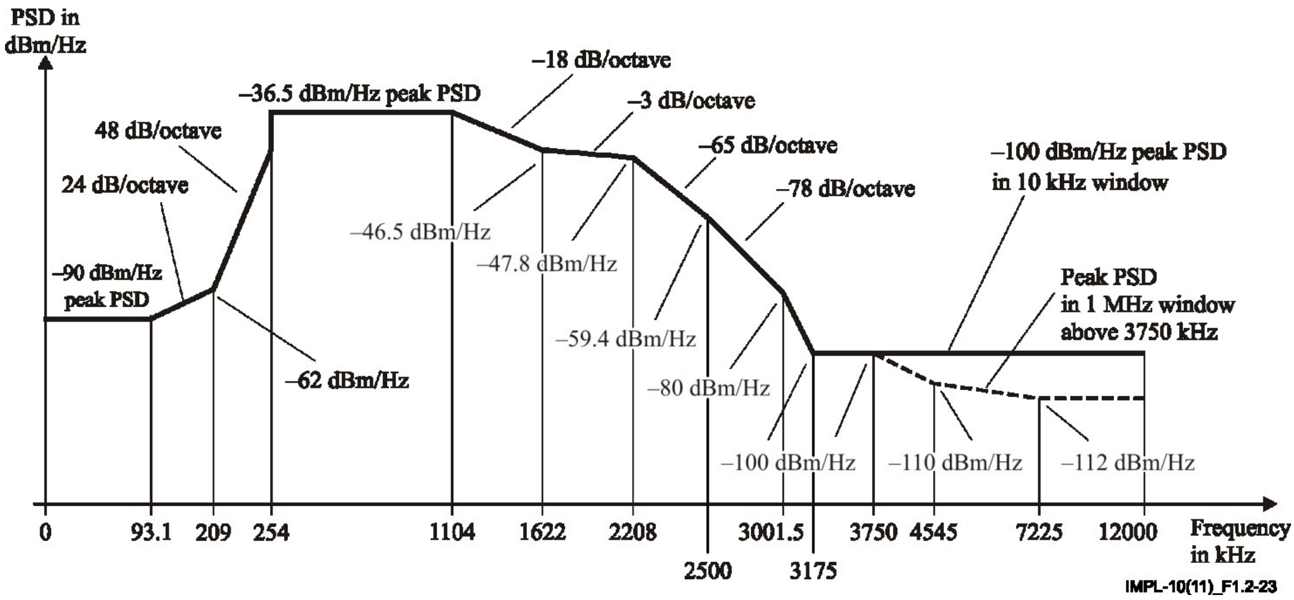


Figure 1.2-23 – ATU-C transmitter PSD mask for non-overlapped spectrum operation

The passband is defined as the band from 254 to 2208 kHz. The low-frequency stop-band is defined as frequencies below 254 kHz and includes the ISDN band; the high-frequency stop-band is defined as frequencies greater than 2208 kHz. The nominal aggregate transmit power is 19.9 dBm if all upstream subcarriers are used.

Figure 1.2-24 defines the spectral mask for the upstream transmit signal. The passband is defined as the band from 120 kHz to 276 kHz and is the widest possible band used. The low-frequency stop band is the ISDN band and is defined as frequencies below 120 kHz; the high-frequency stop band is defined as frequencies greater than 276 kHz. The nominal aggregate transmit power is 13.9 dBm if all upstream subcarriers are used.

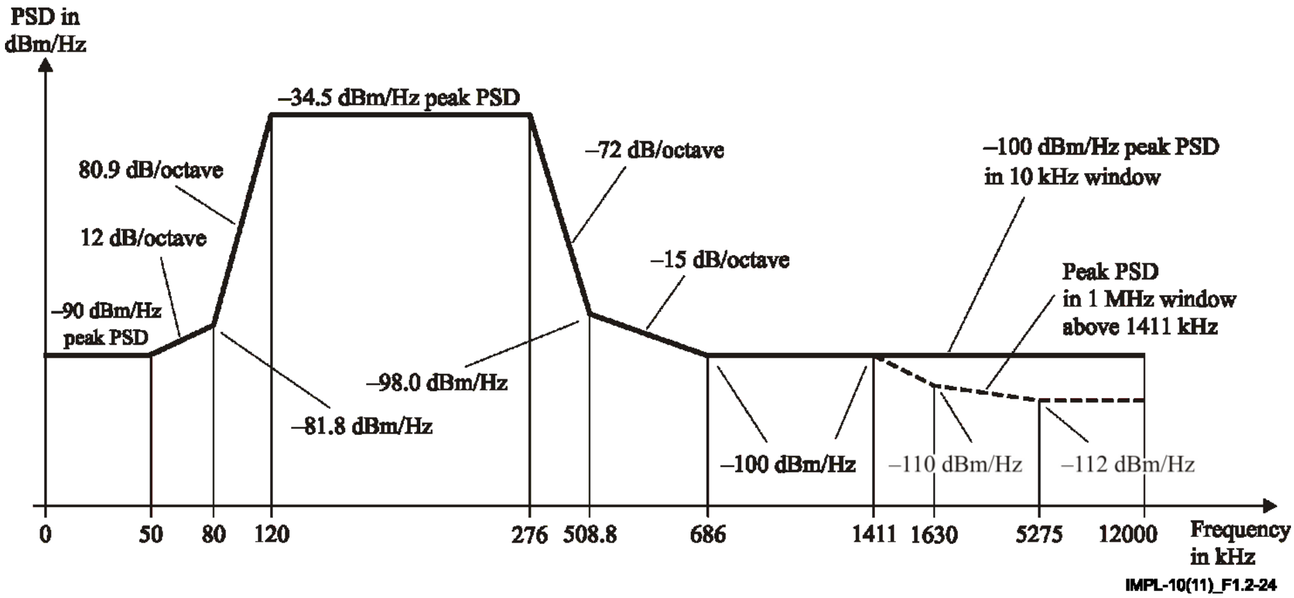


Figure 1.2-24 – ATU-R transmitter PSD mask

1.3 VDSL family

Editor: Frank Van der Putten

This section deals with two DSL systems: VDSL and VDSL2. Moreover there is the description of the vectoring technique applied to VDSL2.

1.3.1 VDSL

(For further information see Recommendation ITU-T G.993.1.)

VDSL (very high speed digital subscriber lines) permits the transmission of asymmetric and symmetric aggregate data rates up to tens of Mbit/s on twisted pairs. VDSL is an access technology that exploits the existing infrastructure of copper wires that were originally deployed for POTS services. While POTS uses approximately the lower 4 kHz and ADSL/HDSL use approximately 1 MHz of the copper wire spectrum, VDSL uses up to 12 MHz of the spectrum. VDSL includes worldwide frequency plans that allow asymmetric and symmetric services in the same group of wire pairs (known as a binder). This is accomplished by designating bands for the transmission of upstream and downstream signals.

VDSL supports transmission at a bidirectional data rate (the sum of downstream and upstream directions) up to about 80 Mbit/s on twisted pairs.

VDSL transceivers must overcome many types of ingress interference from radio and other transmission techniques that occur in the same frequencies of typical deployment scenarios. Similarly, VDSL power transmission levels have been designed to minimize potential egress interference into other transmission systems.

As with other DSL technologies, VDSL uses Recommendation ITU-T G.994.1 to handshake and initiate the transceiver training sequence.

VDSL supports a Fibre-to-the-Node deployment architecture with an optical network unit (ONU) appropriately placed in the existing metallic access network and the Local Exchange or Central Office deployment architecture without an ONU. The first architectural model covers Fibre-to-the-cabinet (FTTCab), fibre-to-the-curb (FTTC), fibre-to-the-building (FTTB) type of deployment; the second one is fibre-to-the-exchange (FTTEx) type of deployment (Figure 1.3-1). Existing unscreened twisted metallic access wire-pairs are used to convey the signals to and from the network termination placed at the customer's premises.

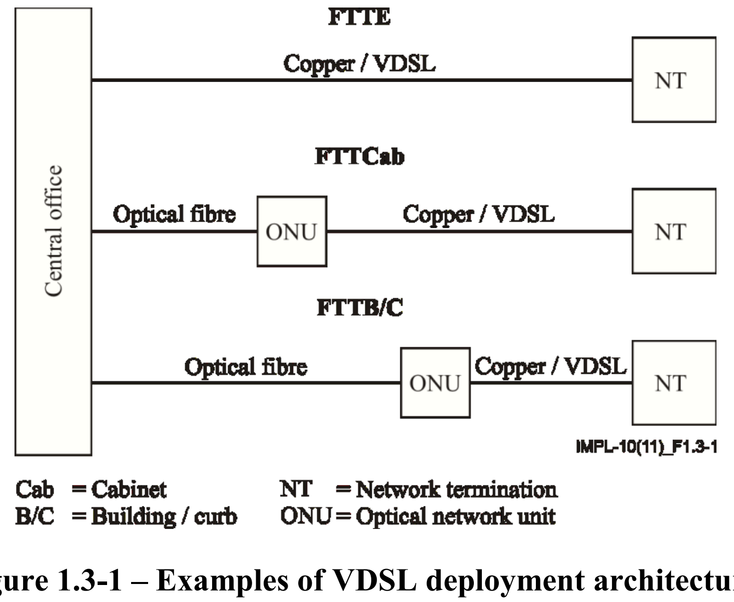


Figure 1.3-1 – Examples of VDSL deployment architectures

VDSL provides two or four data paths with bit rate under the control of the network operator, consisting of one or two downstream and one or two upstream data paths. A single data path in each direction can be of high latency (with lower BER expected) or low latency (with higher BER expected). Use of two data paths in each direction provides one data path of each type. The dual latency configuration (high and low) is thought to be the minimum that is capable of supporting a sufficient full service set, although it is possible to support both the single latency model with programmable latency, and two paths/latencies. The model assumes that forward error correction (FEC) will be needed for part of the payload and that deep interleaving will be required to provide adequate protection against impulse noise.

VDSL provides for service-splitter functional blocks to accommodate shared use of the physical transmission media for VDSL and either POTS or ISDN-BA. The rationale behind this is to provide network operators freedom to evolve their networks in one of two ways: complete change out or overlay. Support for active network termination (NT) provides termination of the point-to-point VDSL transmission system and presents a standardized set of user-network interfaces (UNIs) at the customer's premises. The NT provides the network operator with the ability to test the network up to the UNI at the customer's premises in the event of a fault condition or via night-time routine checks.

VDSL service would non-invasively coexist with the narrow-band services on the same pair. Failure of power to the VDSL NT or failure of the VDSL service does not affect any existing narrow-band services. This may imply that the splitter filter is of a passive nature not requiring external power in order to provide frequency separation of the VDSL and existing narrow-band signals.

It is envisaged that VDSL will find applications in the transport of various protocols. For each transport protocol, different functional requirements must be developed for the transport protocol specific – transmission convergence layer (TPS-TC). This section covers the functional requirements for the transport of asynchronous transfer mode (ATM) and packet transfer mode (PTM). However the VDSL core transceiver would be capable of supporting future additional transport protocols.

VDSL was first defined in a foundation document in 2001. This foundation document specified the duplexing method, bandplans, upstream power back-off (UPBO), and the transport of ATM and PTM. It was completed with framer (PMS-TC) and modulation (PMD) in 2004. The present version of ITU-T G.993.1 also specifies the DMT modulation and related framing in the main body; an Annex defines the specifics of an implementation in systems using QAM modulation.

1.3.2 VDSL2

(For further information see Recommendation ITU-T G.993.2.)

VDSL2, specified in ITU-T G.993.2, defines an enhancement to ITU-T G.993.1 (VDSL) that supports transmission at a bidirectional net data rate (the sum of upstream and downstream rates) up to 200 Mbit/s on twisted pairs. VDSL2 is an access technology that exploits the existing infrastructure of copper wires that were originally deployed for POTS.

Recommendation ITU-T G.993.2 specifies only discrete multi-tone (DMT) modulation and incorporates components from ITU-T G.993.1 (VDSL), ITU-T G.992.3 (ADSL2), and ITU-T G.992.5 (ADSL2 plus).

Whilst POTS uses approximately the lowest 4 kHz and ADSL2plus uses approximately 2 MHz of the copper wire spectrum, VDSL2 is defined to allow the use of up to 30 MHz of the spectrum.

VDSL2 can be deployed from central offices, from fibre-fed cabinets located near the customer premises, or within buildings (Figure 1.3-1).

The availability of bandwidth up to 30 MHz allows G.993.2 transceivers to provide reliable high data rate operation on short loops. The use of the US0 band (upstream band #0, located in the lowest frequencies of the VDSL2 signal spectrum) and means to train echo cancellers and time-domain equalizers (TEQs, to handle the more severe signal distortion in the lowest frequencies) also allows this system to provide reliable operation on loops up to approximately 2500 metres of 26 AWG (0.4 mm) copper wires.

Recommendation ITU-T G.993.2 defines a wide range of settings for various parameters (such as bandwidth and transmitter power) that could potentially be supported by a transceiver. Therefore, ITU-T G.993.2 specifies profiles to allow transceivers to support a subset of the allowed settings and still be compliant with the Recommendation. The specification of multiple profiles allows vendors to limit implementation complexity and develop implementations that target specific service requirements. Some profiles are better suited for asymmetric data rate services, whereas other profiles are better for symmetric data rate services.

The annexes of ITU-T G.993.2 include bandplans and power spectral density (PSD) masks that address region-specific requirements. Moreover, it defines upstream power back-off (UPBO) to mitigate far-end crosstalk (FEXT) caused by upstream transmissions on shorter loops to longer loops. As do other Recommendations in the ITU-T G.99x series, ITU-T G.993.2 uses Rec. ITU-T G.994.1 to initiate the transceiver training sequence.

1.3.2.1 Reference models

The functional model of VDSL2, which includes functional blocks and interfaces of the VTU-O (VDSL Terminal Unit at the ONU (or central office, exchange, cabinet, etc.; i.e., operator-end of the loop)) and VTU-R (VTU at the remote site (i.e., subscriber-end of the loop)) is presented in Figure 1.3-2. The model illustrates the most basic functionality of VDSL2 and contains both an application-invariant section and an application-specific section. The application-invariant section consists of the physical medium dependent (PMD) sub-layer and physical media specific part of the transmission convergence sub-layer (PMS-TC). The application-specific parts related to the user plane are confined to the transport protocol specific transmission convergence (TPS-TC) sub-layer and application interfaces.

The management protocol specific TC (MPS-TC) is intended for management data transport. The VDSL2 management entity (VME) supports management data communication protocols. Management plane functions at higher layers are typically controlled by the operator's network management system (NMS) and are not shown in Figure 1.3-2. The NTR-TC supports transport of the 8 kHz network timing reference (NTR) to the VTU-R. The ToD-TC supports distribution of accurate time-of-day to the VTU-R. The NTR-TC and the ToD-TC contain the timing related aspects of the VTU.

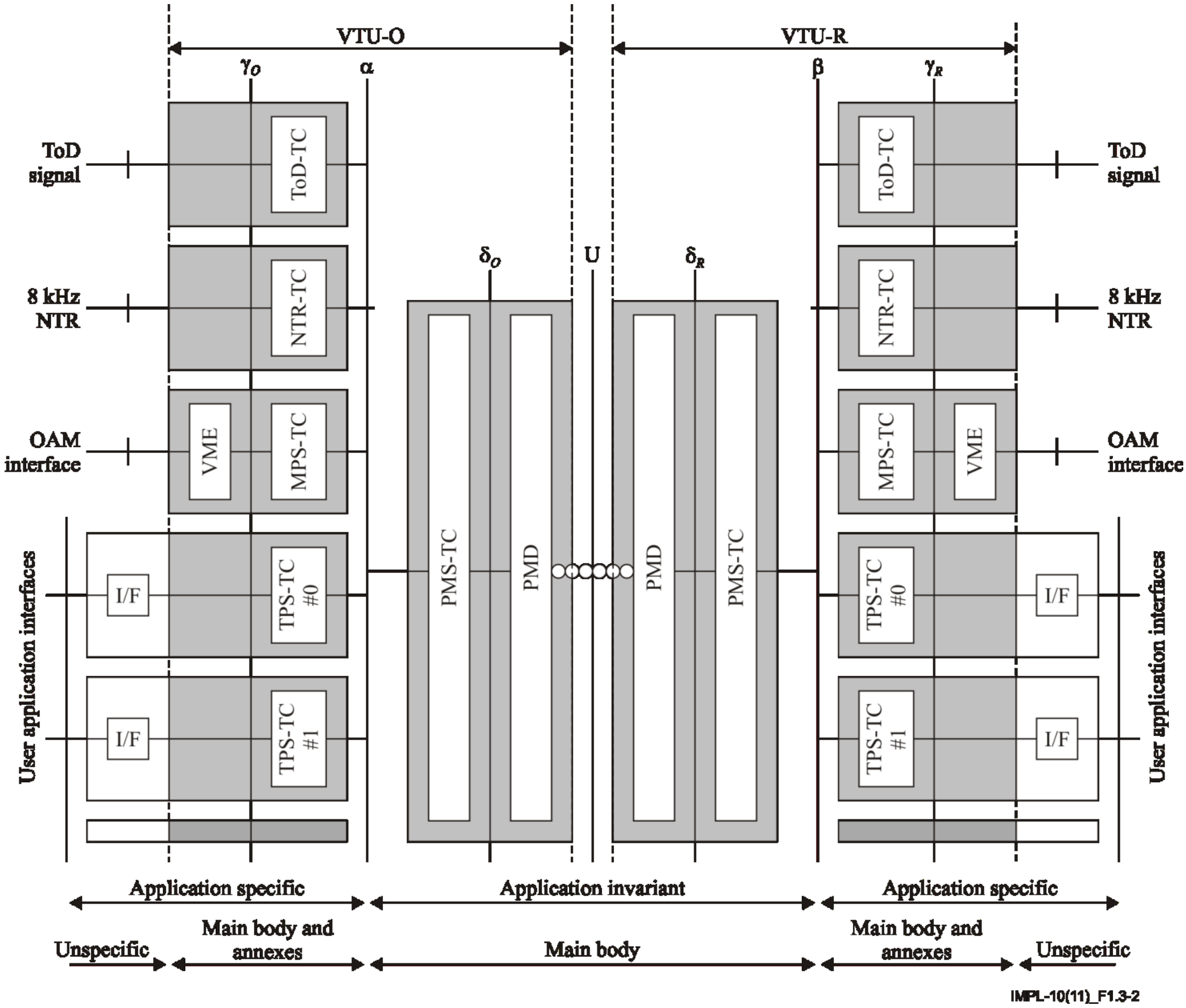


Figure 1.3-2 – VDSL2 and VTU functional model

The principal functions of the PMD are symbol timing generation and recovery, encoding and decoding, and modulation and demodulation. The PMD may also include echo cancellation and line equalization.

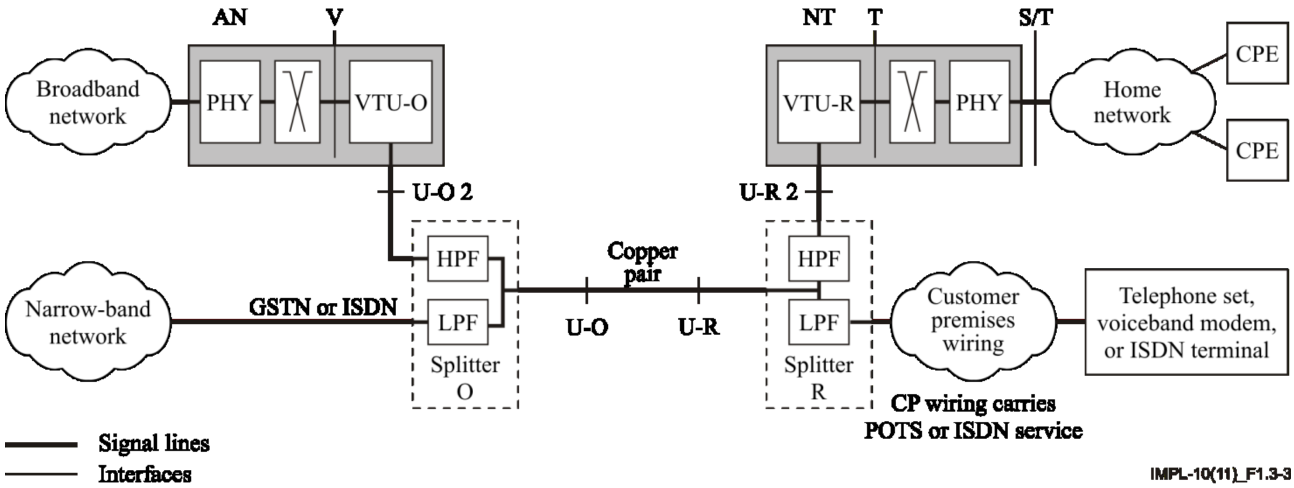
The PMS-TC sub-layer contains framing and frame synchronization functions, as well as forward error correction (FEC), error detection, interleaving and de-interleaving, scrambling and descrambling functions. Additionally, the PMS-TC sub-layer provides an overhead channel that is used to transport management data (control messages generated by the VME).

The TPS-TC is application specific and is mainly intended to convert applicable data transport protocols into the unified format required at α and β interfaces and to provide bit rate adaptation between the user data and the data link established by the VTU. Depending on the specific application, the TPS-TC sub-layer may support one or more channels of user data. There are three types of user data TPS-TCs defined in VDSL2:

- Type 1: STM transport (STM-TC);
- Type 2: ATM transport (ATM-TC); and
- Type 3: Ethernet and generic packet transport (PTM-TC).

The application reference model for remote deployment with POTS or ISDN service facilitated by a splitter is shown in Figure 1.3-3. The application model for splitterless remote deployment is shown in Figure 1.3-4. An optional low-pass filter may be included to provide additional isolation between the VTU-R and narrow-band network CPE such as telephone sets, voice band modems, or ISDN terminals.

The location of the filters (HPF and LPF) in application models presented in Figures 1.3-3 and 1.3-4 is functional only; the physical location and specific characteristics of splitters and the filter may be regionally specific. The filters at the CPE side shown in Figure 1.3-3 may be implemented in a variety of ways, including splitters, in-line filters and filters integrated with VTU devices, and filters integrated with narrow-band network CPE.



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NOTE – One or both of the high-pass filters, which are part of the splitters, may be integrated into the VTU. If so, the U-O2 and U-R2 interfaces become the same as the U-O and U-R interfaces, respectively.

Figure 1.3-3– Generic application reference model for remote deployment with splitter

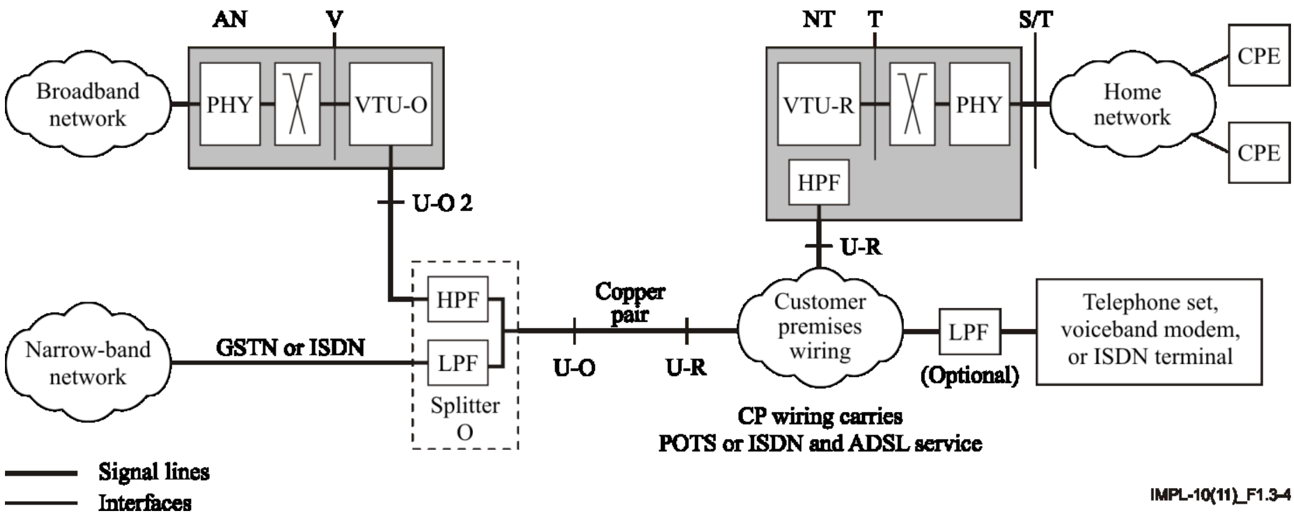

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Figure 1.3-4 – Generic application reference model for splitterless remote deployment

VDSL2 operating in the splitterless remote deployment mode is highly likely to suffer severe service impairments due to the topology and uncertain quality of the in-premises wiring. Star topology wiring practices, in particular, will lead to deep notches in the frequency response of the transmission path due to multiple signal reflections. In addition, poor balance, routing close to sources of electrical noise, and exposure to strong radio signals can all lead to high levels of RFI.

NOTE – HPF is to filter off the POTS/ISDN so modem gets only VDSL2. The LPF is to filter off the VDSL2 so the phone only gets POTS/ISDN. The central LPF also blocks the RFI ingress and the impulse noise present on the home wiring from affecting the VDSL2 signal. Indeed, the splitterless position of LPF could make the VDSL2 signal (more) vulnerable to RFI ingress, impulse noise, and bridged taps present on the home wiring.

1.3.2.2 Profiles

VDSL2 defines a wide range of configurations for various parameters that could potentially be supported by a VDSL2 transceiver. Profiles are specified to allow transceivers to support a subset of the allowed configurations. The specification of multiple profiles allows vendors to limit implementation complexity and develop implementations that target specific service requirements.

The eight VDSL2 profiles are referred to as 8a, 8b, 8c, 8d, 12a, 12b, 17a, and 30a. The number refers to the transmission signal bandwidth in MHz. Table 1.3-1 lists the requirements of each profile, related to the other parameters with significant impact on implementation complexity. VDSL2 implementations may support more than one profile. The active profile is selected during initialization.

Table 1.3-1 – VDSL2 profiles

Parameter value for profile							
8a	**8b**	**8c**	**8d**	**12a**	**12b**	**17a**	**30a**
Maximum aggregate downstream transmit power (dBm)							
+17.5	+20.5	+11.5	+14.5	+14.5	+14.5	+14.5	+14.5
Maximum aggregate upstream transmit power (dBm)							
+14.5	+14.5	+14.5	+14.5	+14.5	+14.5	+14.5	+14.5
Sub-carrier spacing (kHz)							
4.3125	4.3125	4.3125	4.3125	4.3125	4.3125	4.3125	8.625
Support of upstream band zero (US0)							
Required	Required	Required	Required	Required	Not Required	Not Required	Not Supported
Minimum bidirectional net data rate capability (MBDC) (Mbit/s)							
50	50	50	50	68	68	100	200
Aggregate interleaver and de-interleaver delay (octets)							
65536	65536	65536	65536	65536	65536	98304	131072
Maximum interleaving depth (D_{max})							
2048	2048	2048	2048	2048	2048	3072	4096
Parameter $(1/S)_{max}$ downstream (number of RS code words per symbol)							
24	24	24	24	24	24	48	28
Parameter $(1/S)_{max}$ upstream (number of RS code words per symbol)							
12	12	12	12	24	24	24	28

1.3.2.3 Duplexing method and bandplan construction

VDSL2 transceivers use frequency division duplexing (FDD) to separate upstream and downstream transmissions. Overlapping of the upstream and downstream passbands is not allowed. The allocation of the upstream and downstream frequency bands is defined by the bandplan, which is specified by band-separating frequencies. The VDSL2 signal can potentially utilize the frequency range up to 30 MHz, although the maximum frequency used by a modem to transmit data depends on the selected bandplan and the profile.

NOTE – In the frequency-division duplexing (FDD) technique the downstream and the upstream directions operate at different sub-carrier frequencies. Using this technique the effects of the NEXT could, in principle, be eliminated, because the NEXT interfering signals are in frequency band different from the useful one.

Figure 1.3-5 shows the 30 MHz-wide bandplans defined for VDSL2. One bandplan (NA998E30) is for use in North America. Four bandplans are for use in Europe (EU997E30, EU998E30, EU998ADE30, and EUHPE30). One bandplan (JA998E30) is for use in Japan. ITU-T G.993.2 also defines truncated versions of these bandplans (e.g., truncated to 12 or 17 MHz) and variants depending on the type of US0 (e.g., up to 138 or 276 kHz). The first downstream band is referred to as DS1, the first upstream band is US1, the second downstream band is DS2, etc. Up to 4 downstream and four upstream bands may be defined. The lowest and highest US0 frequencies and lowest DS1 frequency are defined in ITU-T G.993.2 but not shown to scale in Figure 1.3-5.

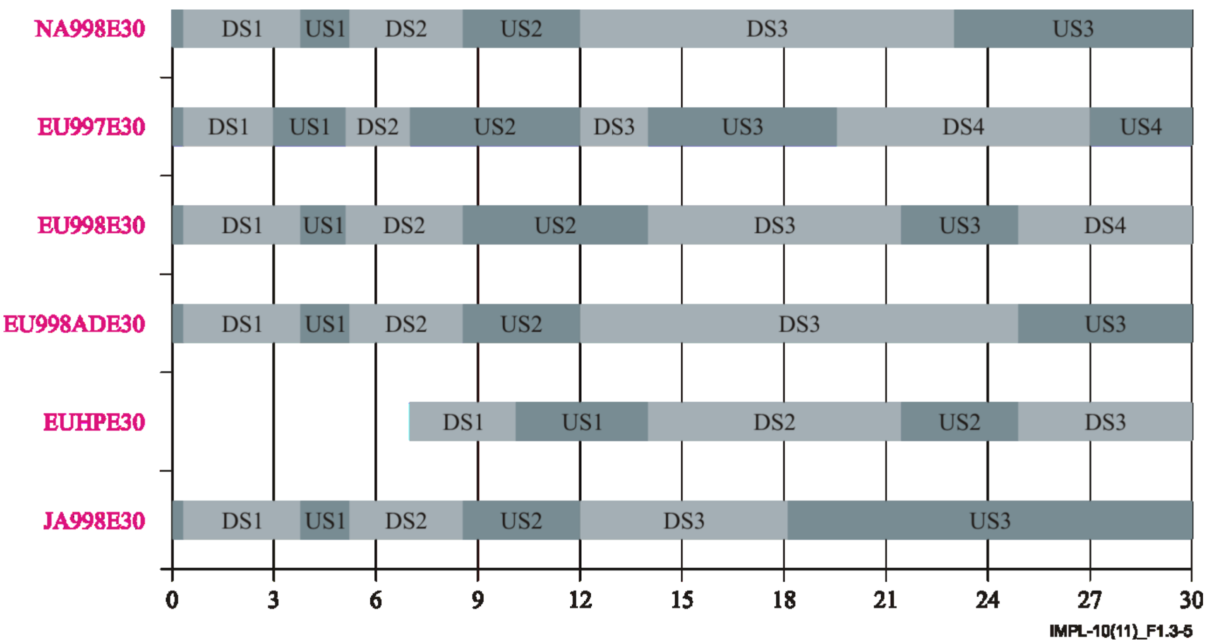


Figure 1.3-5 – VDSL2 bandplans up to 30 MHz

For optimal performance, all VDSL2 lines in the same cable should use the same bandplan to avoid excessive crosstalk. The choice of VDSL2 bandplan is typically under control of the national regulatory authority.

1.3.2.4 Power spectral density (PSD)

A VDSL2 modem confines the PSD of its transmit signal to be within the transmit PSD mask. The transmit PSD mask is the lesser, at every frequency, of the limit PSD mask specified in the ITU-T G.993.2, and a MIB PSD mask specified by the service provider, which is provided to the modems via the MIB.

In some deployment scenarios, an operator may choose to force VDSL2 modems to transmit at levels lower than those specified by the Limit PSD masks. The MIB PSD mask is an additional tool that allows operators to shape the VTU-O and VTU-R transmit PSD masks.

Further reduction of the transmit PSD (below the transmit PSD mask) is provided through transmit power cut-back (PCB) and transmit power back-off (DPBO for downstream and UPBO for upstream) mechanisms. This section provides a simplified description of these mechanisms. For a detailed description, see ITU-T G.997.1 and ITU-T G.993.2.

1.3.2.4.1 Transmit power cut-back (PCB)

Transmit power cut-back is the reduction of the transmitted PSD using the PSD ceiling mechanism. The PCB is dependent on the service (bearer) requirements, such as net data rates, INP (impulse noise protection), delay and on the desired SNR margin. The PCB also accommodates the dynamic range of the far-end receiver.

During channel analysis phase of initialization, the VTU-R communicates an initial upstream PSD ceiling value to the VTU-O. The VTU-O then communicates an updated upstream PSD ceiling value to the VTU-R. The VTU-R then uses this updated value to determine the upstream transmit PSD.

Similarly, during channel analysis phase of initialization, the VTU-O communicates an initial downstream PSD ceiling value to the VTU-R. The VTU-R then communicates an updated upstream PSD ceiling value to the VTU-O. The VTU-O then uses this updated value to determine the downstream transmit PSD.

1.3.2.4.2 Downstream power back-off (DPBO)

A DPBO mechanism is defined to allow the network operator to shape the downstream transmit PSD at the remote cabinet location. The mechanism is used to reduce crosstalk from VDSL2 deployed at the remote cabinet into ADSL from the exchange on pairs in the same binder.

The set of line configuration parameters and the procedure to generate a VDSL2 downstream MIB PSD mask is defined in ITU-T G.997.1. These parameters are provided through the CO-MIB and are typically under control of the national regulatory authority. The configuration parameters are the following:

- Assumed exchange PSD mask (DPBOEPSD): the PSD mask that is assumed to be permitted at the exchange. Typically set to e.g., the ADSL2plus transmit PSD mask defined in ITU-T G.992.5.
- E-side electrical length (DPBOESEL): distance between the exchange and the remote cabinet location, expressed as the loss (in dB) of an equivalent length of hypothetical cable at a reference frequency.
- E-side cable model (DPBOESCM): a cable model in terms of three scalars DPBOESCMA, DPBOESCMB and DPBOESCMC that are used to describe the frequency dependent loss of E-side cables using the formula:

$$ESCM(f) = \left(DPBOESCMA + DPBOESCMB \cdot \sqrt{f} + DPBOESCMC \cdot f\right) \cdot DPBOESEL$$

- Minimum usable signal (DPBOMUS): the assumed minimum usable receive PSD mask at the remote cabinet location for exchange based service (typically a value of about -100 dBm/Hz). The Maximum usable frequency (MUF) is defined as the highest frequency for which the MIB PSD Mask is greater than DPBOMUS.

- DPBO span minimum frequency (DPBOFMIN): the minimum frequency from which the DPBO is applied.
- DPBO span maximum frequency (DPBOFMAX): the maximum frequency at which DPBO may be applied.

The "Predicted attenuated exchange PSD Mask" (*PEPSD(f)*) is defined as the *DPBOEPSD(f)* lowered by *ESCM(f)*. The Maximum usable frequency (MUF) is defined as the highest frequency for which the *PEPSD(f)* is greater than DPBOMUS.

Over the frequency range DPBOFMIN to min(DPBOFMAX, MUF), a modified PSD mask is applied to the VTU-O, defined as the lower of the MIB PSD mask and the *PEPSD(f)*.

1.3.2.4.3 Upstream power back-off (UPBO)

Upstream power back-off (UPBO) is performed by the VTU-R to improve spectral compatibility between VDSL2 systems on loops of different lengths deployed in the same binder. UPBO is applied to all upstream bands except US0.

The VTU-R estimates the electrical length of its loop, kl0, and uses this value to calculate the UPBO PSD mask at the beginning of initialization. The VTU-R then adapts its transmit signal to conform to the mask UPBOMASK(kl0, f) during initialization and showtime, while also remaining below the upstream MIB PSD mask and PSD limits determined by the upstream PCB (power cut back) mechanism.

Two methods for upstream power back-off method are defined:

- the reference PSD UPBO method: loops are configured such that the predicted upstream receive PSD level at the remote cabinet is equal for all loops;
- the equalized FEXT UPBO method (optional): loops are configured such that the predicted upstream FEXT level at the remote cabinet is equal for all loops.

With the reference PSD UPBO method, the UPBOMASK is calculated as:

$$\mathrm{UPBOMASK}(kl_0, f) = -a - b\sqrt{f} + kl_0\sqrt{f} + 3.5 \quad [\mathrm{dBm/Hz}]$$

With the equalized FEXT UPBO method and for loops with $kl_0 < kl_{0\_REF}$, this UPBOMASK(kl_0,f) is increased proportionally to the reduced FEXT coupling length with:

$$10\log_{10}\left(\frac{kl_{0\_REF}}{kl_0}\right) \quad [\mathrm{dB}].$$

The parameters *a, b* (which may differ for each upstream band) and kl_{0_REF} are provided by the network operator through the CO-MIB and are typically under control of the national regulatory authority.

1.3.2.5 Physical media specific transmission convergence (PMS-TC) sub-layer

1.3.2.5.1 Functional model

The PMS-TC functional models are presented in Figure 1.3-6 applicable to single latency mode and dual latency mode. Up to two bearer channels of transmit user data originated by various TPS-TCs, management data originated by the MPS-TC, and NTR data are incoming via the α/β interface. The incoming user data and the overhead data are multiplexed into one or two latency paths.

Three different modes are allowed:

- single latency mode: support of one latency path, only latency path #0 is enabled.

- dual latency mode: support of two latency paths (optional), both latency paths #0 and #1 are enabled.
- single latency with robust overhead channel (ROC mode): support of a single latency path for data with a second overhead-only latency path (optional), latency path#1 is enabled for user data and latency path #0 is enabled for the ROC.

NOTE – In the previous sub-sections on ADSL and VDSL, fast and interleaved paths have been quoted, where a bearer channel allocated to the fast path has minimum delay and only a bearer channel allocated to the interleaved path has configurable maximum delay. For ADSL2, ADSL2plus and VDSL2 there are two latency path (L0 and L1), where bearer channels are allocated to either L0 or L1, each bearer channel with independently configurable maximum delay.

The multiplexed data in each latency path (including an overhead-only latency path, if present) is scrambled, encoded using Reed-Solomon forward error correction coding, and interleaved. The interleaved buffers of data of both latency paths are multiplexed into a bit stream to be submitted to the PMD sub-layer.

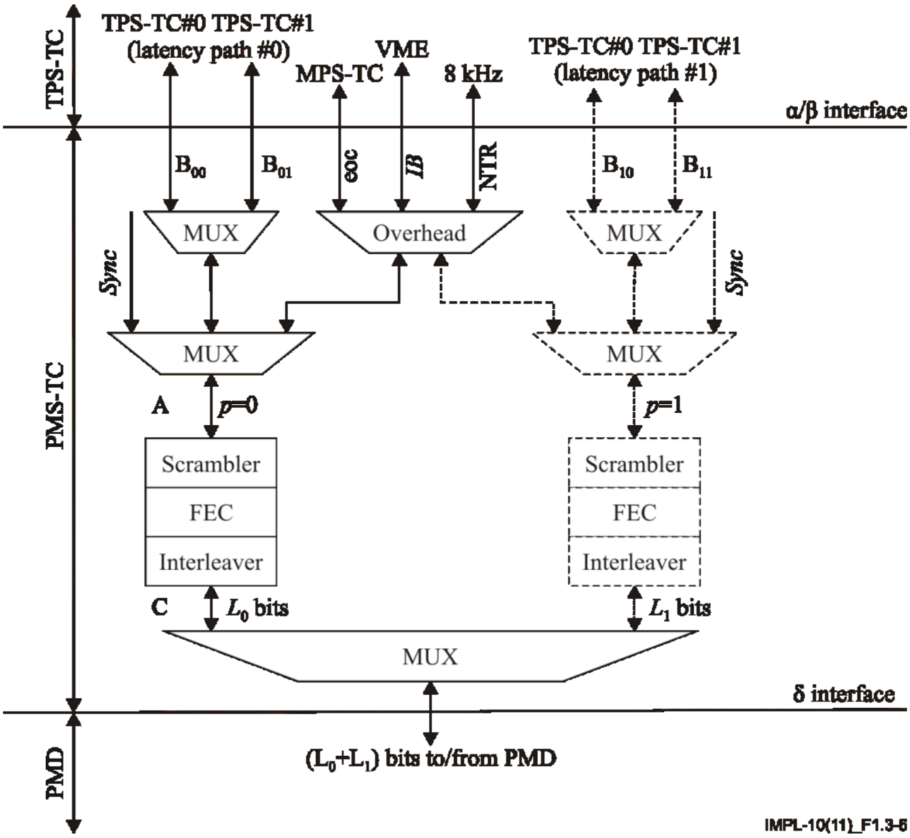


Figure 1.3-6 – PMS-TC functional model applicable to single latency mode and dual latency mode

1.3.2.5.2 Scrambler, FEC and interleaving

A scrambler is used to reduce the likelihood that a long sequence of zeros will be transmitted over the channel. The scrambler is self-synchronizing such that descrambling can occur without requiring a particular alignment with the scrambled sequence. The scrambling algorithm is represented by the equation below:

$$x(n) = m(n) + x(n-18) + x(n-23)$$

where:

- $m(n)$ is the input bit of data at the sample time n. All arithmetic is modulo 2;

- $x(n)$ is the output bit of data at the sample time n.

A standard byte-oriented Reed-Solomon (RS) code is used for forward error correction (FEC). FEC provides protection against random and burst errors. A Reed-Solomon code word contains $N_{FEC} = K+R$ bytes, comprised of R check bytes appended to the K data byte. Both K and R are programmable parameters. Valid values for the number of check bytes R in the code word are 0, 2, 4, 6, 8, ... , 16. Valid values for N_{FEC} are all integers from 32 to 255 inclusive.

A FEC code word consists of q interleaver blocks (with q=1 to 8) of I bytes (i.e., $N_{FEC} = q \times I$). Each interleaver block is interleaved through convolution with depth D (with D and I co-prime). Interleaving is provided in all supported latency paths to protect the data against bursts of errors by spreading the errors over a number of Reed-Solomon code words. The aggregate interleaver/de-interleaver delay is $(D-1) \times (I-1)$ octets. Values of D and I are chosen within the limits determined by the VDSL2 profile.

A method to dynamically change the interleaver depth during transmission is defined for VDSL2. This method is optional. Support is indicated during initialization. If a change of the interleaver depth is to be accompanied by a corresponding change of the data rate in the particular latency path [e.g., SRA (seamless rate adaptation)], the change of D is coordinated with the corresponding change of parameter L_p (for L_p see next section).

Parameter $1/S$ defines the total number of Reed-Solomon code words decoded within a single data symbol. The range of $1/S$ values is profile dependent. Beyond the mandatory values of $(1/S)_{max}$ determined by the profile, optional extended (valid) values of $(1/S)_{max}$ for different profiles are specified in Table 1.3-2.

Table 1.3-2 – Optional extended values of $(1/S)_{max}$

Parameter value for profile							
8a	**8b**	**8c**	**8d**	**12a**	**12b**	**17a**	**30a**
Parameter $(1/S)_{max}$ downstream (number of RS code words per symbol)							
64	64	64	64	64	64	64	32
Parameter $(1/S)_{max}$ upstream (number of RS code words per symbol)							
32	32	32	32	64	64	64	32

1.3.2.5.3 Impulse noise protection

INP_p (impulse noise protection for latency path p) is defined as the number of consecutive DMT symbols or fractions thereof, as seen at the input to the de-interleaver, for which errors can be completely corrected by the error correcting code, regardless of the number of errors within the errored DMT symbols.

The receiver selects framing parameters such that for each bearer channel the actual INP (INP_act_n) is at least the minimum INP configured by the network operator through the CO-MIB (INP_min_n), regardless of any vendor-discretionary techniques including, for example, the use of erasure decoding. The actual impulse noise protection INP_act_n of bearer channel #n is always set to the INP_p of the underlying PMS-TC path function.

When the Reed-Solomon decoder in the receiver does not use erasure decoding, the INP_p is computed as:

$$INP\_no\_erasure_p = \frac{8 \times D_p \times \left\lfloor \frac{R_p}{2 \times q_p} \right\rfloor}{L_p} = \frac{S_p \times D_p \times \left\lfloor \frac{R_p}{2 \times q_p} \right\rfloor}{N_{FECp}} \text{ DMT symbols}$$

p latency path

D_p interleaver depth

R_p the number of redundancy octets in the RS code word

q_p the number of interleaver blocks in the RS code word

L_p the number of bits from latency path p transmitted in each data symbol.

S_p the number of data symbols over which the RS code word spans

N_{FECp} the RS code word size

where parameters D_p, R_p, L_p, and q_p are selected such that $INP\_act_n \geq INP\_min_n$. When erasure decoding is used, INP_p might not equal $INP\_no\_erasure_p$.

From the above equation it follows that the resilience to impulse noise is directly proportional to the relative FEC overhead (R/N) and the delay [about (S*D)/(4*q) ms] selected. The operator has to carefully trade-off the configuration of INP_min and delay_max, since requiring a low delay and high INP resilience will result in a selection of high relative RS overhead and hence low user data rate.

If INP_min=2 is configured by the operator, then an impulse noise (e.g. from light switch or dimmer) of up to 250 microsec will affect maximum 2 consecutive DMT symbols and hence not cause errors on the DSL.

1.3.2.5.4 Delay

When the interleaver is disabled (interleaver depth = 1), the one-way delay between α and β interfaces (Figure 1.3-2) does not exceed 2 ms. The actual delay in milliseconds introduced by the interleaver to latency path p is computed as:

$$delay_p = \frac{S_p \times (D_p - 1)}{q_p \times f_s} \times \left(1 - \frac{q_p}{N_{FECp}}\right) = \frac{8 \times (D_p - 1) \times \left(\frac{N_{FECp}}{q_p} - 1\right)}{L_p \times f_s} \text{ ms}$$

where f_s is the data symbol rate in ksymbols/s.

NOTE – For the meaning of the other symbols see the previous subsection.

The interleaver delay in milliseconds for the specific bearer channel n is constrained by the value of $delay\_max_n$ defined by the network operator in the CO-MIB.

From the above equation it follows that the delay is directly proportional to the interleaver depth (D) and inversely proportional to the number of bits carried in one symbol (L_p). To adapt to changing line characteristics, the online reconfiguration using the embedded operations channel allows for changing the L value. In order to not let the delay increase with lower L values, the online reconfiguration also includes reconfiguration of the interleaver depth. This is a feature that is not present in ADSL2 and ADSL2plus.

1.3.2.5.5 Bit error ratio

The bit error ratio (BER), referenced to the output of the α or β interface of the receiver, does not exceed 10^{-7} for any of the supported bearers. The modem implements appropriate initialization and reconfiguration procedures to assure this value.

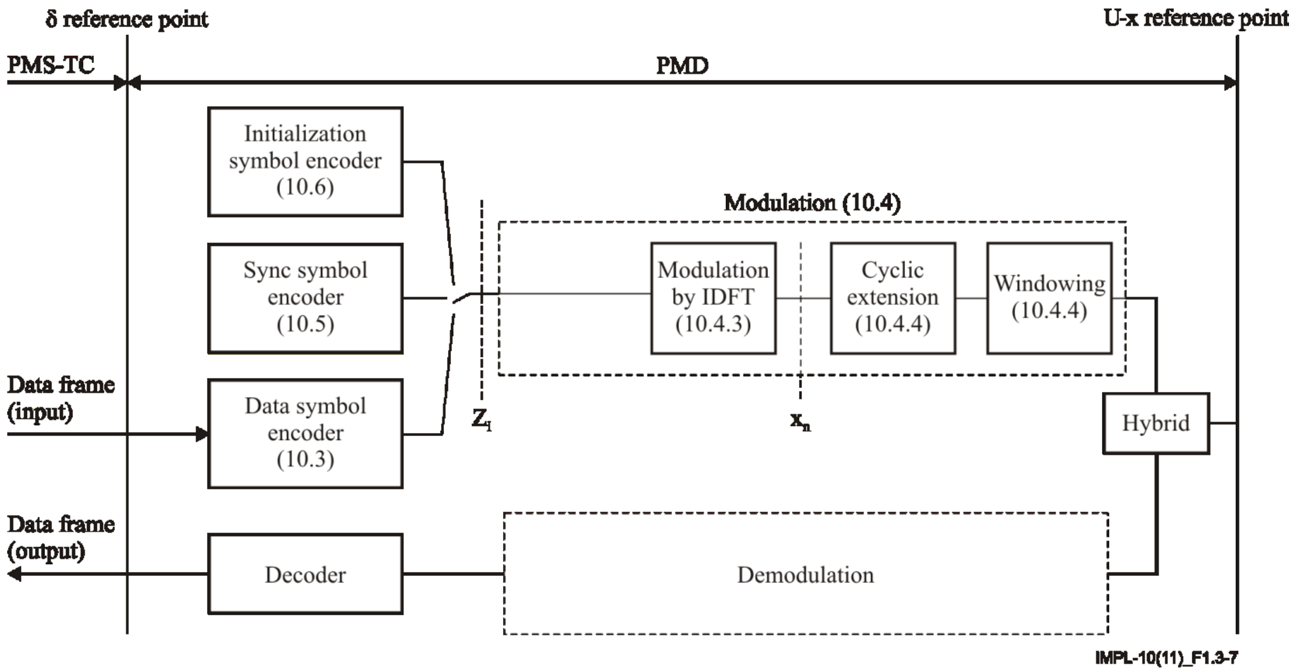
1.3.2.6 Physical media-dependent function

1.3.2.6.1 Functional model

The functional model of the PMD sub-layer is presented in Figure 1.3-7. In the transmit direction, the PMD sub-layer receives input data frames from the PMS-TC sub-layer via the δ interface. Each data frame contains an integer number of data bits equal to $L_0 + L_1$ (i.e., the number of bits carried in one symbol for latency path #0 and #1 respectively) to be modulated onto one DMT symbol. Prior to modulation, the incoming bits are encoded by the symbol encoder. The encoder divides the incoming bit stream into small groups of bits, where each group is assigned to modulate a specific subcarrier of the DMT signal. Each group is further encoded by the trellis encoder and mapped to a point in a signal constellation. The set of constellation points modulates the sub-carriers of the DMT symbol using an inverse discrete Fourier transform (IDFT). The number of bits assigned to each sub-carrier is determined during the initialization procedure based on the SNR of the sub-carrier and specific system configuration settings. After the IDFT, the resulting symbol is cyclically extended and windowed (see subsection 1.3.2.6.3), and sent towards the transmission medium over the U interface.

In the receive direction, the signal incoming from the transmission medium via the U interface is demodulated and decoded to extract the transmitted data frame. The data frame obtained from the decoder (denoted "Data frame (output)" in Figure 1.3-7) is sent to the PMS-TC sub-layer via the δ interface.

The transmit PMD function uses the DMT superframe structure shown in Figure 1.3-8. Each DMT superframe is composed of 256 data frames, numbered from 0 to 255, followed by a single sync frame. The content of the sync frame is dependent on whether timing for on-line reconfiguration is being signalled. The data frames are modulated onto 256 data symbols, and the sync frame is modulated onto a sync symbol. The sync symbol provides a time marker for on-line reconfiguration.



NOTE – The numbers quoted in brackets refer to clauses of ITU-T G.993.2.

Figure 1.3-7 – Functional model of PMD sub-layer

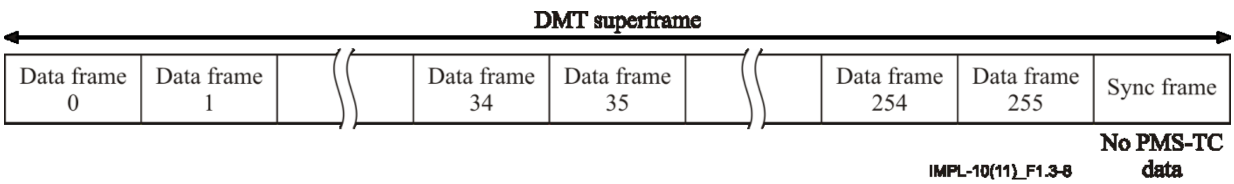


Figure 1.3-8 – DMT superframe structure

The duration of a superframe depends on the sub-carrier spacing and value of the cyclic extension. When the sub-carrier spacing is 4.3125 kHz and the mandatory cyclic extension value is used (5/64), the duration of a superframe is 64.25 ms.

1.3.2.6.2 Symbol encoder for data symbols

The symbol encoder for data symbols is shown as part of the transmit PMD function in Figure 1.3-7. The symbol encoder for data symbols consists of the following functions:

- Tone ordering;
- Trellis coding;
- Constellation mapping.

NOTE – Except for some differences in terminology related to carrier sets, Tone ordering, Trellis coding and Constellation mapping are the same in VDSL2 and in ADSL2.

During initialization, the receive PMD function calculates the numbers of bits and the relative gains to be used for every sub-carrier in the MEDLEY set (either MEDLEYus or MEDLEYds, depending on the transmission direction), as well as the order in which bits are assigned to sub-carriers (i.e., the tone ordering). The calculated bits and gains and the tone ordering are sent back to the transmit PMD function during the channel analysis & exchange phase of initialization. The number of sub-carriers in MEDLEYus and MEDLEYds is denoted by NSC_{us} and NSC_{ds}, respectively.

NOTE – MEDLEY set is a subset of the SUPPORTEDCARRIERS set. It is determined during the channel discovery phase and contains the sub-carriers that will be used for transmission of initialization signals after the channel discovery phase. SUPPORTEDCARRIERS set is the set of sub-carriers allocated for transmission in one direction, as determined by the bandplan.

Block processing of Wei's 16-state 4-dimensional trellis code is optional to improve system performance. If trellis coding is not used, data bytes from the data frame buffer are extracted according to a reordered bit allocation table b'_i. If trellis coding is used, data bytes from the data frame buffer are extracted according to a reordered bit allocation table b'_i. The (even number of) 1-bit sub-carriers in bit allocation table b_i are paired to form 2-dimensional constellation points in bit allocation table b'_i as input to the trellis encoder. Because of the 4-dimensional nature of the code, the extraction is based on pairs of consecutive b'_i, rather than on individual ones, as in the non-trellis-coded case. Furthermore, due to the constellation expansion associated with coding, the bit allocation table, b'_i, specifies the number of coded bits per tone, which can be any integer from 2 to 15. Given a pair (x, y) of consecutive b'_i, $x + y - 1$ bits (reflecting a constellation expansion of 1 bit per 4 dimensions, or one half bit per tone) are extracted from the data frame buffer and encoded into two binary words v and w (containing x and y bits respectively), which are used to look up two constellation points in the encoder constellation table.

For a given subcarrier, the encoder selects an odd-integer point (X, Y) from the square-grid constellation based on the b bits of either binary words v or w. For example, for $b = 2$, the four constellation points are labelled 0, 1, 2, 3 corresponding to $(v_1, v_0) = (0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$, respectively. Figure 1.3-9 shows example constellations for $b = 2$ and $b = 4$.

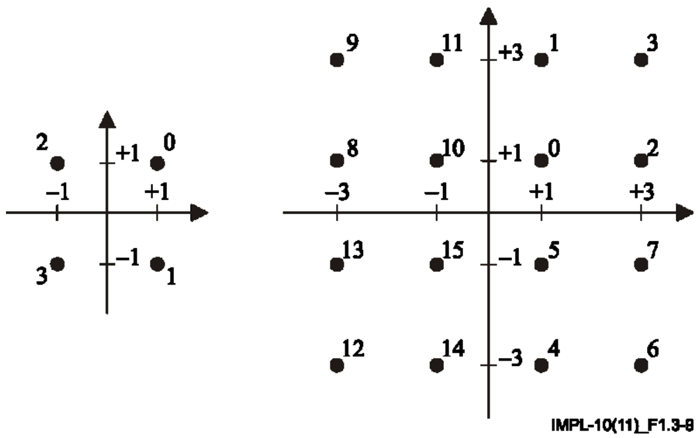


Figure 1.3-9– Constellation labels for $b = 2$ and $b = 4$

Figure 1.3-10 shows the constellation for the case $b = 5$.

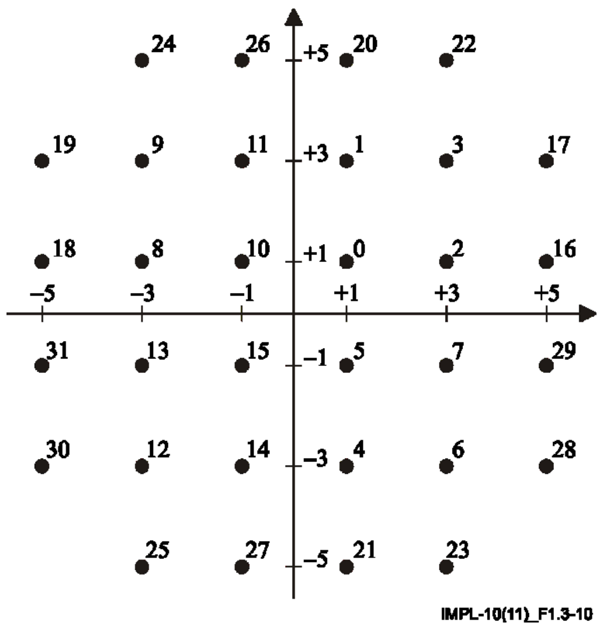


Figure 1.3-10 – Constellation labels for *b* = 5

Each constellation point (X_i, Y_i), corresponding to the complex value $X_i + jY_i$ at the output of the constellation mapper, is scaled by the power-normalization factor $\chi(b_i)$, the gain adjuster g_i, and a frequency-domain spectrum shaping coefficient tss_i to result in a complex number Z_i, defined as:

$$Z_i = g_i \times tss_i \times \chi(b_i) \times (X_i + jY_i)$$

The values (X, Y) are scaled such that all constellations, regardless of size, have the same average power. The required scaling, $\chi(b_i)$, is a function only of the constellation size.

The frequency-domain transmit spectrum shaping (tss_i) are intended for frequency-domain spectrum shaping. The tss_i values provide flexibility to meet the transmit PSD mask and are selected by the transmitter. They are defined both upstream and downstream.

The gain g_i values are selected by the receiver and intended for fine gain adjustment within a range from −14.5 dB and +2.5 dB, which may be used to equalize the SNR margin for all sub-carriers. The values of g_i are assigned during initialization, and may also be updated during showtime via an OLR procedure.

1.3.2.6.3 Modulation

Sub-carrier spacing is the frequency spacing, Δf, between the sub-carriers. The sub-carriers are centred at frequencies $f = i \times \Delta f$. The index of highest supported sub-carrier is bandplan-dependent. Valid values of sub-carrier spacing are 4.3125 kHz and 8.625 kHz, both with a tolerance of ±50 ppm. Sub-carrier spacing is profile dependent (see Table 1.3-1).

The IDFT is used to modulate the output of the symbol encoder onto the DMT sub-carriers. It converts the *NSC* (number of sub-carriers in MEDLEY set) complex values Z_i generated by the symbol encoder (frequency domain representation) into $2N$ real values x_n ($n = 0, 1, \ldots, 2N - 1$), which is a time domain representation. The conversion is performed with a $2N$ point IDFT, with $N - 1 \geq MSI$, as:

$$x_n = \sum_{i=0}^{2N-1} \exp\left(j \cdot 2 \cdot \pi \cdot \frac{n \cdot i}{2 \cdot N} \right) \cdot Z_i \qquad \text{for } n = 0 \text{ to } 2N - 1$$

The valid values of N are $N = 2^{n+5}$, where n can take integer values from 0 (64-point IDFT) to 7 (8192-point IDFT). The values of N used for upstream and downstream are exchanged during initialization.

In order to generate real values of x_n, the input values Z_i, where $i = 0, 1, ..., N - 1$ and $Z_0 = 0$, shall be further augmented so that the vector Z_i has a Hermitian symmetry:

$$Z_i = \mathrm{conj}\,(Z_{2N-i}) \quad \text{for } i = N + 1 \text{ to } 2N - 1$$

The transmit DMT symbol are constructed from the IDFT samples x_n using the following rules.

The last L_{CP} samples of the IDFT output x_n are prepended to the $2N$ output IDFT samples x_n as the cyclic prefix (CP). The first L_{CS} samples of x_n are appended to the block of $x_n + L_{CP}$ samples as the cyclic suffix (CS). The first β samples of the cyclic prefix and last β samples of the cyclic suffix are used for shaping the envelope of the transmitted signal (windowing). The values of the window samples are vendor discretionary. Figure 1.3-11 summarizes all of the operations that are performed by the transmitter to construct the DMT symbol.

The cyclic extension (CE) length is defined as $L_{CE} = L_{CP}+L_{CS} - \beta$. The values L_{CP}, L_{CS} and β are set in order to satisfy the equation $L_{CE} = (L_{CP}+L_{CS} - \beta) = m \times N/32$, where valid values of m are integers between 2 and 16, inclusive. Support for the value of $m = 5$ is mandatory. Partitioning between the CS and CP is vendor discretionary. The specific settings of the CE and CP are exchanged during initialization.

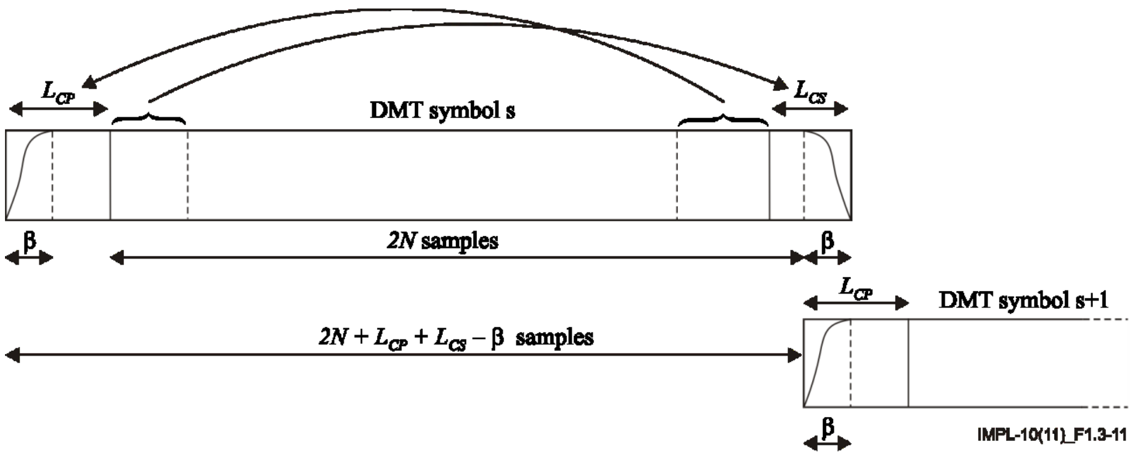


Figure 1.3-11– Cyclic extension, windowing and overlap of DMT symbols

For a given setting of the CE (cyclic extension) length and window length β, the DMT symbols will be transmitted at a symbol rate equal to:

$$f_{DMT} = \frac{2N \times \Delta f}{2N + L_{CP} + L_{CS} - \beta} = \frac{2N \times \Delta f}{2N + L_{CE}}$$

If the CE length corresponds to $m = 5$, this results in symbol rates of 4 ksymbols/s for $\Delta f = 4.3125$ kHz and 8 ksymbols/s for $\Delta f = 8.625$ kHz, independent of the sampling rate used.

The data symbol rate is equal to:

$$f_s = \frac{2N \times \Delta f}{2N + L_{CP} + L_{CS} - \beta} \times \frac{256}{257}$$

The VTU-R may select one or more sub-carriers to use for timing recovery, called "pilot tones". Pilot tones are selected separately for initialization and showtime. The VTU-O transmits on the selected sub-carriers the value of 00 using 4-QAM modulation during every data symbol.

1.3.2.7 Operations, administration and maintenance (OAM)

1.3.2.7.1 OAM functional model

The functional model of the OAM operation and communication over the VDSL2 link is presented in Figure 1.3-12. The external OAM interface adapter (EIA) provides the interface to the NMS (network management system) (Q interface), and the interface with the MIB. The MIB contains all of the management information related to the VDSL2 link. It may be implemented to serve an individual VDSL2 line or to be shared between several lines.

The VME collects the OAM data from and delivers it to all of the VTU transmission entities, thus providing all internal OAM functions for the modem. It also supports all interactive management functions between the VTU-O and the VTU-R using two OAM-dedicated communication channels:

- Indicator bits (IB) channel; and
- Embedded operations channel (EOC).

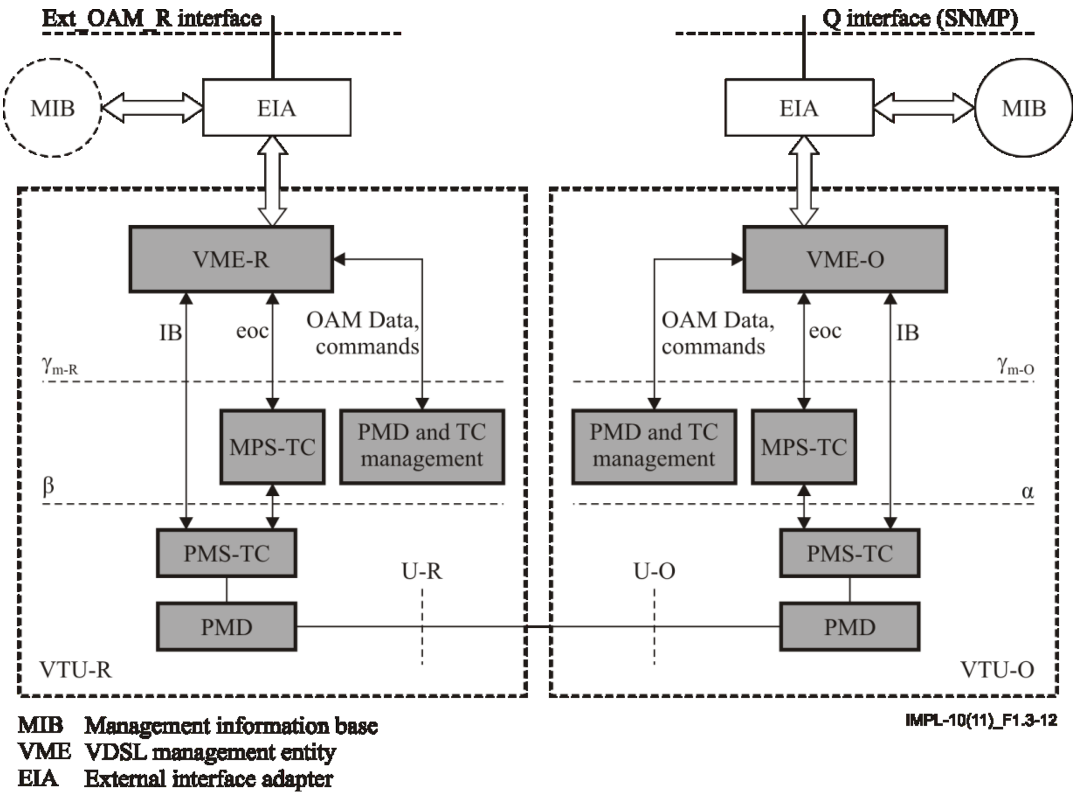


Figure 1.3-12 – Functional model of OAM of the VDSL2 link

To communicate management data, the VME uses EOC messages (details in clause 11.2.3 of ITU-T G.993.2) and IB (details in clause 11.2.4 of ITU-T G.993.2). The EOC messages and IB form a complete set of management data exchanged between the VTU-O and VTU-R, which includes the management data from all data-transmission sub-layers of the VTU and the management data incoming from the EIA, including messages sent to the VTU-R. The latter are referred to as a "clear EOC".

1.3.2.7.2 Indicator bits and embedded operations channel

The indicator bits (IB) channel is shared for communication between the peer OAM entities of the PMD, PMS-TC and TPS-TC. It is intended to transfer time-sensitive primitives (those requiring an immediate action) from the far end. The IB channel operates in a unidirectional mode, i.e., the upstream and downstream directions of the IB channel operate independently, and there are no acknowledgements or retransmissions in the protocol. The IB are specified in clause 11.2.4 of ITU-T G.993.2.

The embedded operations channel (EOC) is shared for communication between the peer OAM entities of the PMD, PMS-TC, TPS-TC and VME (system-related OAM data, such as power-related primitives). The EOC is mostly intended to exchange management data that is not time critical. It is used to transport clear EOC messages sent to the VTU-R and MIB elements specified in Recommendation ITU-T G.997.1, to set and query parameters, and to invoke management procedures at the far-end VTU. In particular the EOC provides exchange of the PMD, PMS-TC, TPS-TC and system-related primitives, performance parameters, test parameters, configuration parameters and maintenance commands.

Table 1.3-3– High priority commands and responses

Command type and assigned value	Direction of command	Command content
On-line reconfiguration (OLR)	From the receiver of either VTU to the transmitter of the other	All the necessary PMD and PMS-TC control parameter values for the new configuration

Table 1.3-4– Normal priority commands and responses

Command type and assigned value	Direction of command	Command content
Diagnostic	From VTU-O to VTU-R	Request to run the self-test, or to update test parameters, or to start and stop transmission of corrupt CRC, or to start and stop reception of corrupt CRC
	From VTU-R to VTU-O	Request to update test parameters
Time	From VTU-O to VTU-R	Set or read out the time
Inventory	From either VTU to the other	Identification request, auxiliary inventory information request, and self-test results request
Management Counter Read	From either VTU to the other	Request to read the counters
Clear EOC	From either VTU to the other	Clear EOC command as defined in ITU-T G.997.1
Power Management	From either VTU to the other	Proposed new power state
Non-standard Facility (NSF)	From either VTU to the other	Non-standard identification field followed by vendor proprietary content

The EOC command and response types are specified in Table 1.3-3 (high priority commands), Table 1.3-4 (normal priority commands) and Table 1.3-5 (low priority commands).

Table 1.3-5 – Low priority commands and responses

Command type and assigned value	Direction of command	Command content
PMD Test Parameter Read	From either VTU to the other	The identification of test parameters for single read, or for multiple read, or for block read
INM facility	From VTU-O to VTU-R	Set or readout the INM data
Non-Standard Facility (NSF) Low Priority	From either VTU to the other	Non-standard identification field followed by vendor proprietary content

1.3.2.7.3 OAM primitives

Among the standard OAM primitives, VDSL2 specifies only anomalies and defects (for the definition of primitives, anomalies and defects see subsection 1.2.1.8 of this Technical paper). The system uses the corresponding failure specifications of ITU-T G.997.1.

Two line-related near-end anomalies are defined:

- Forward error correction interleaved (*fec-p*) anomaly;
- Cyclic redundancy check interleaved (*crc-p*) anomaly.

Three line-related near-end defects are defined:

- Loss-of-signal (*los*) defect;
- Severely errored frame (*sef*) defect;
- Loss of margin (*lom*).

For STM transport, various payload types can be used. These payload types and path related anomalies are not specified in ITU-T G.993.2.

For ATM transport, three near-end path related anomalies are defined for each path separately:

- No cell delineation (*ncd-n*) anomaly;
- Out of cell delineation (*ocd-n*) anomaly;
- Header error control (*hec-n*) anomaly.

For ATM transport, one near-end path related defect is defined for each path separately:

- Loss of cell delineation interleaved (*lcd-n*) defect.

For PTM, three near-end path related anomalies is defined for each path separately:

- TC_out_of_sync (*oos-n*) anomaly;
- TC_CRC_error (*crc-n*) anomaly;
- TC_coding_violation (*cv-n*) anomaly.

One other power related near-end primitive is defined:

- Loss-of-power (LPR).

For each of the near-end anomalies, defects and primitive, a related far-end anomaly, defect or primitive is defined. The far-end anomalies and defects are directly observable through indicator bits or their count or status may be read via overhead commands (for STM and ATM) or via the IEEE 802.3 OAM channel (for PTM). The ATU-R reports the LPR primitive through the indicator bits.

1.3.2.7.4 Test parameters

The test parameters are measured by the PMD transmit or receive function and are reported on request to the near-end VME. Test parameters can be used to identify possible issues with the physical loop and to check for adequate physical media performance margin at acceptance and after repair verification, or at any other time following the initialization of the VDSL2 system.

The following test parameters are passed on request from the receive PMD function to the near-end VME:

- Channel characteristics function [H(*f*)] per sub-carrier (CCF-ps);
- Quiet line noise PSD [QLN(*f*)] per sub-carrier (QLN-ps);
- Signal-to-noise Ratio [SNR(*f*)] per sub-carrier (SNR-ps);
- Loop attenuation per band (LATN-pb);
- Signal attenuation per band (SATN-pb);
- Signal-to-noise ratio margin per band (SNRM-pb);
- Signal-to-noise ratio margin for the Robust Operation Channel (SNRM-ROC);
- Attainable net data rate (ATTNDR);
- Far-end actual aggregate transmit power (ACTATP);
- Far-end actual impulse noise protection (INP_act);
- Far end actual impulse noise protection of the ROC (INP_act-ROC).

The following test parameter shall be passed on request from the transmit PMD function to the near-end VME:

- Near-end actual aggregate transmit power (ACTATP).

The purposes of making the above information available are:

- H(f) can be used to analyse the physical copper loop condition;
- QLN(f) can be used to analyse the crosstalk;
- SNR(f) can be used to analyse time-dependent changes in crosstalk levels and loop attenuation such as due to moisture and temperature variations;
- The combination of H(f), QLN(f) and SNR(f) can be used to help determine why the data rate is not equal to the maximum data rate for a given loop.

1.3.2.7.5 Impulse noise monitoring procedure

Figure 1.3-13 shows the impulse noise monitoring (INM) functional block diagram.

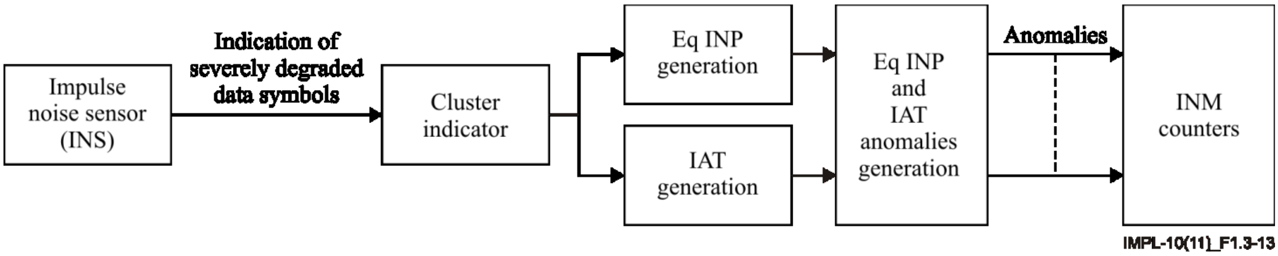


Figure 1.3-13 – Impulse noise monitor functional block diagram

The impulse noise sensor (INS) indicates whether a data symbol is severely degraded or not. A data symbol is considered to be severely degraded when it would lead to severe errors on the gamma interface (see Figure 1.3-2) when there would be no impulse noise protection (i.e., RS only used for coding gain).

The cluster indicator indicates short groups of severely degraded data symbols as clusters. The cluster can contain a single severely degraded data symbol, a group of consecutive severely degraded data symbols, or several groups of one or more consecutive severely degraded data symbols with gaps between the groups.

The cluster indicator identifies the largest group of consecutive data symbols, starting and ending with a severely degraded data symbol, containing severely degraded data symbols, separated by gaps smaller than or equal to INMCC (the cluster continuation parameter).

In the Eq INP generation block, the "equivalent INP" of the cluster is generated. For each cluster, the following characteristics shall be determined:

- The impulse noise cluster length (INCL), defined as the number of data symbols from the first to the last severely degraded data symbol in the cluster.
- The impulse noise cluster degraded data symbols (INCD), defined as the number of severely degraded data symbols in the cluster.
- The impulse noise cluster number of gaps (INCG), defined as the number of gaps in the cluster, with gap as defined above.

An equivalent INP (INP_eq) is defined, with a relation to INCL, INCD and INCG depending on the configured mode of operation. Anomalies are generated for several values of INP_eq. The counters of these anomalies represent the INP_eq histogram.

In the IAT generation block, the inter-arrival time (IAT) is generated as the number of data symbols from the start of a cluster to the start of the next cluster. Anomalies are generated for several ranges of inter arrival time. The counters of these anomalies represent the IAT histogram.

1.3.2.8 Link activation methods and procedures

The VDSL2 link state and activation/deactivation procedures diagram is illustrated in Figure 1.3-14.

Figure 1.3-14 has two link states (L0 and L3), and also contains the procedures that allow the modem to change from one link state to another. The link states are shown in rounded boxes, whilst the procedures are shown as rectangular boxes.

L3 is the state where the modem is provisioned through a management interface for the service desired by the operator. In this state, the modem does not transmit any signal. In the L3 link state, a VTU may determine to use the initialization procedure. A VTU that receives a higher layer signal to activate uses the initialization procedure. A VTU that detects the signals of the initialization procedure at the U reference point, if enabled, responds by using the initialization procedure. If disabled, the VTU remains in the L3 link state.

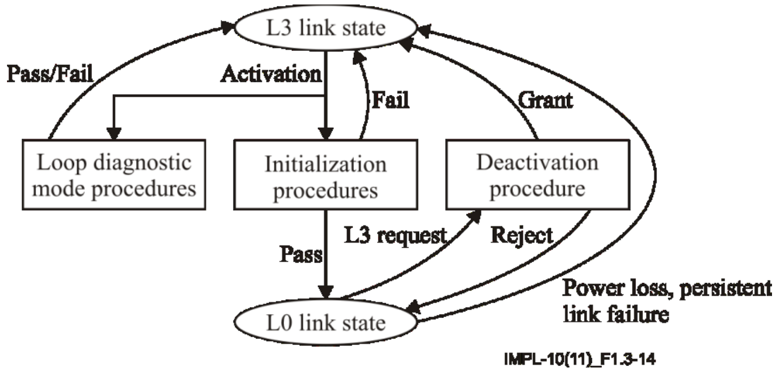


Figure 1.3-14 – VDSL2 link state and activation/deactivation procedures diagram

L0 is a state achieved after the initialization procedure has completed successfully. In this state, the link transports user information with standard performance characteristics. The modem returns to L3 state upon guided power removal (L3 request), power loss or persistent link failures during showtime.

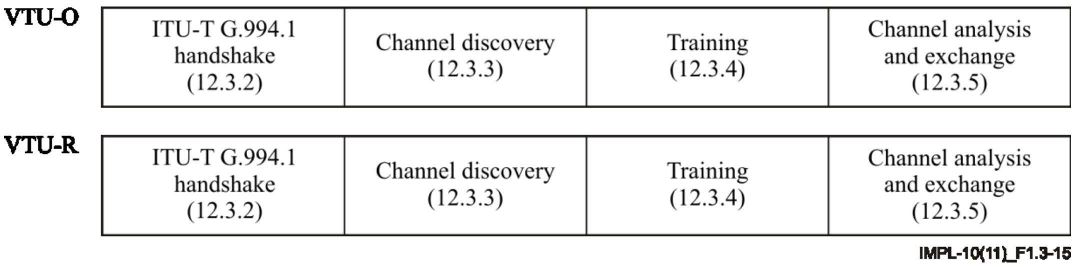
1.3.2.9 Initialization procedure

Initialization of a VTU-O/VTU-R pair includes the following main tasks:

- Definition of a common mode of operation (profile, bandplan and initial values of basic modulation parameters);
- Synchronization (sample clock alignment and symbol alignment);
- Transfer from the VTU-O to the VTU-R of transmission parameters, including information on the PSD masks to be used, RFI bands (e.g., amateur radio bands) to be protected, and target data rates in both transmission directions;
- Channel identification;
- Noise identification;
- Calculation of framer, interleaver, and coding parameters, as well as the bit loading and gain tables;
- Exchange of modem parameters (including RS (Reed-Solomon) settings, interleaver parameters, framer settings, bit loading and gain tables).

The common mode of operation is negotiated during the ITU-T G.994.1 handshake phase. Information such as the PSD mask, locations of RFI bands to be notched, and target data rates are initially available at the VTU-O through the CO-MIB.

The time line in Figure 1.3-15 provides an overview of the initialization procedure, which contains four phases. Following the initial ITU-T G.994.1 handshake phase (see Section 1.4.2), upstream power back-off is applied and a full duplex link between the VTU-O and the VTU-R is established during the channel discovery phase to set the PSDs of the transmit signals and the main modulation parameters. During the training phase, any time-domain equalizers (TEQs) and echo cancellers may be trained, and the timing advance is refined. During the channel analysis & exchange phase, the two modems measure the characteristics of the channel and exchange parameters to be used in showtime.



NOTE – The numbers in brackets refer to clauses of ITU-T G.993.2

Figure 1.3.15 – Overview of initialization procedure

The transition to the next phase of initialization occurs after all tasks in a phase have been completed. A time-out period is defined for each phase to avoid suspension of the initialization procedure. Violation of the time-out or an inability to complete a task results in abortion of the activation process (unsuccessful activation).

Exchange of information between the VTU-O and VTU-R during all phases of initialization, excluding the ITU-T G.994.1 handshake phase, is performed using the messaging protocol over the special operations channel (SOC).

NOTE – The SOC provides a bidirectional communication of messages between the VTU-O and the VTU-R to support initialization, fast start-up, and loop diagnostic procedures.

1.3.2.10 Loop diagnostic mode procedures

The built-in loop diagnostic function enables the immediate measurement of channel conditions at both ends of the loop without dispatching maintenance technicians to attach test equipment to the loop. The resulting information helps to isolate the location (inside the premises, near the customer end of the loop, or near the network end of the loop) and the sources (crosstalk, radio frequency interference, and bridged taps) of impairments.

If selected by either VTU, the loop diagnostic mode is entered after completion of the ITU-T G.994.1 handshake phase. The sequence of stages in the loop diagnostic mode is the same as for initialization up to the channel analysis & exchange phase, where the test parameters are exchanged. However, the test parameters for the quiet line noise (QLN) and the channel characteristics function are measured and exchanged during the channel discovery phase.

1.3.2.11 Types of on-line reconfiguration

The types of on-line reconfiguration (OLR) defined for VDSL2 include bit swapping, seamless rate adaptation (SRA), and SOS.

Bit swapping reallocates bits and power (i.e., margin) among the allowed sub-carriers without modification of the higher layer features of the physical layer. Bit swapping reconfigures the bit and gain (b_i, g_i) parameters without changing any other PMD or PMS-TC control parameters. After a bit swapping reconfiguration, the number of bits modulated on a symbol for each latency path is unchanged, and the net data rate for each bearer channel is unchanged.

Because bit swapping is used autonomously to maintain the operating conditions of the modem during changing environment conditions, bit swapping is a mandatory capability. The procedure for bit swapping is implemented using Type 1 OLR messages through the EOC.

Seamless rate adaptation (SRA – optional) is used to reconfigure the number of bits modulated on a symbol for each latency path. Hence, at least one bearer channel will have a new net data rate after the SRA. The procedure for SRA is implemented using Type 3 OLR messages through the EOC. Interleaver reconfiguration (within SRA) allows one to dynamically change the interleaver depth D_p on one or more latency paths.

SOS provides the receiver with a means to rapidly perform a bit loading reduction in a specified part of the frequency spectrum. This can be used in case of sudden noise increases. During initialization, the modems may define a number of SOS tone groups in both the upstream and downstream directions. An SOS request reduces the bit loading on all tones in a group by the same number of bits (multiple groups can be changed in a single command). The SOS request can also explicitly reconfigure the framing parameters L_p and the interleaver depth D_p in each of the latency paths.

For a wideband sudden noise increase, it is a goal that VTUs improve the data transmission within 1 second after the SOS trigger to achieve a BER≤1E-7. The desired data rate after this time is at least 80% of the data rate that would be obtained if the VTU were to (re-) initialize in the high noise condition using the same Transmit PSD level. Sudden noise increases of up to 30 dB may occur in real networks.

1.3.2.12 Network timing reference TPS-TC

Transport of an 8 kHz Network Timing Reference (NTR) from the VTU-O to the VTU-R is supported in order to support isochronous services that require the same exact timing reference at both sides of the VDSL2 line to operate the higher layers of the protocol stack. The VTU-O indicates to the VTU-R the presence of NTR transport during initialization.

NTR transport is facilitated by the NTR-TC. At the VTU-O the NTR-TC encodes the incoming NTR signal transitions into the NTR byte to be transported over the VDSL2 link in the NTR field of the VDSL2 overhead frame. At the VTU-R the NTR-TC extracts the NTR field from the VDSL2 overhead frame and reconstructs the NTR signal. The NTR field carries the phase offset between the 8 kHz NTR and an 8 kHz Local Timing Reference (LTR) derived by dividing the VDSL2 sampling clock. The NTR field is set to ZERO if the VTU-O locks its sampling clock to the NTR frequency.

NOTE – The LTR frequency, being proportional to the VDSL2 sampling clock, will have the same ±50 ppm frequency variation. The NTR fields support an NTR with a maximum variation of ±40 ppm.

1.3.2.13 Time-of-day transport

Transport of Time-Of-Day (ToD) from the VTU-O to the VTU-R is defined to support services that require accurate ToD at both sides of the VDSL2 line to operate the higher layers of the protocol stack. The VTU-O indicates the presence ToD transport during initialization.

NOTE 1 – Exchange of network time management information from VTU-R to VTU-O related to the quality of the ToD frequency and/or time recovery at the VTU-R is for further study.

NOTE 2 – Exchange of relevant clock information from AN to CPE to support the ToD interface output from CPE is for further study. For PTP, this information includes source traceability, number of hops, and leap seconds.

NOTE 3 – The γ-O to γ-R ToD accuracy requirements are for further study, but expected to be in the order of 100/200 nsec.

Figure 1.3-16 shows the system reference model identifying the key elements in support of time-of-day transport across a VDSL2 link. The VTU-O receives a time-of-day signal from the master clock across the γ-O interface and the VTU-R outputs a time-of-day signal across the γ-R interface to slave clock external to the VTU-R that is synchronous in frequency, phase and time to the master clock. A master clock source external to the VTU-O provides a time-of-day signal to the VTU-O across the γ-interface. The details of the time-of-day signal are for further study.

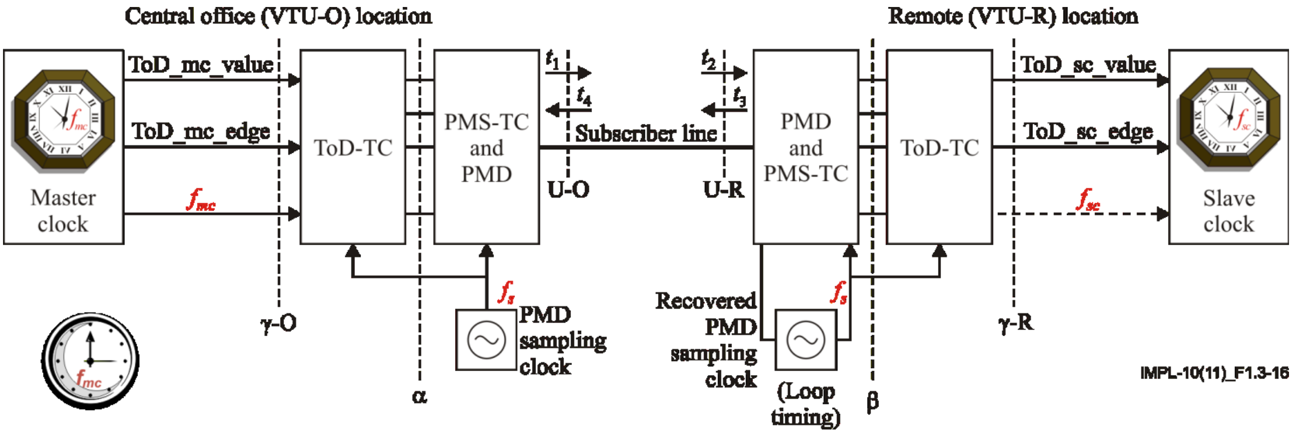


Figure 1.3-16 – End-to-end system reference model for time-of-day transport in VDSL2

The ToD-TC in the VTU-O and that in the VTU-R implement functionality with the objective of synchronizing the RTC-R to the RTC-O in frequency, phase and time. Two methods are defined to achieve this objective:

- Frequency synchronization through locking the PMD sampling clock with the ToD frequency (f_{mc}): the VTU-R achieves frequency synchronization through loop timing and performs phase/time synchronization through the processing of time stamps at reference samples, or
- Frequency synchronization using ToD phase difference values: the VTU-R achieves frequency synchronization through processing of ToD phase difference values (i.e., phase of t1 event relative to ToD) and performs phase/time synchronization through the processing of time stamps (of events t1, t2, t3, and t4) at the reference samples.

The frequency synchronization method adopted in the VTU-O is communicated to the VTU-R during initialization.

The block diagram in Figure 1.3-17 shows a functional model of the required processing in the VTU-O ToD-TC. The ToD-TC receives the time-of-day signals from the master clock and assigns time stamps to reference samples per the Real-time Clock (RTC-O), that is, synchronous with the external master clock time base.

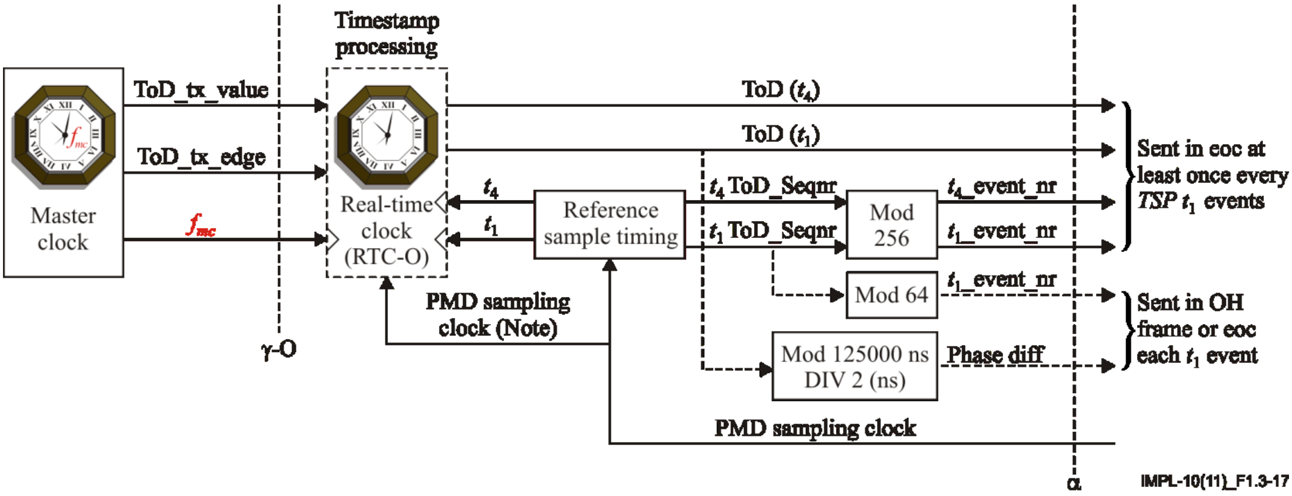
The time-of-day (phase) synchronization of the RTC-R to the RTC-O, is done in the ToD-TC in the VTU-R. The computation of the offset value (τ) is computed from the reported time stamps using the following equation:

$$\tau = \frac{\left(ToD(t_2) - ToD(t_1)\right) - \left(ToD(t_4) - ToD(t_3)\right)}{2}$$

The above computation of the offset value is based on the assumption that the downstream and upstream propagation delays between the U-C and U-R reference points are approximately identical. Any asymmetry in the propagation delay between the U-C and U-R reference points will result in an error in calculation of the offset value whose magnitude is approximately:

$$|error| = \left|\frac{(upstream\_propagation\_delay) - (downstream\_propagation\_delay)}{2}\right|$$

To limit this error, the use of the lowest upstream frequencies (US0) may need to be disabled.



*NOTE – Use of the PMD sampling clock for implementation of the RTC-O is vendor discretionary

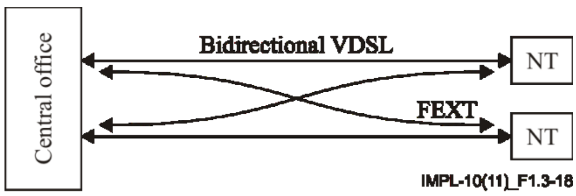
Figure 1.3-17 – Functional reference model for ToD-TC in the VTU-O

1.3.3 VDSL2 with vectoring

(For further information see Recommendation ITU-T G.993.5.)

Vectoring is a transmission method that employs the coordination of line signals for reduction of crosstalk levels and improvement of performance. The degree of improvement depends on the channel characteristics. Vectoring may be for a single user or for multiple-users' benefit.

The scope of vectoring, specified in ITU-T G.993.5, is specifically limited to the self-FEXT (far-end crosstalk) cancellation in the downstream and upstream directions. ITU-T G.993.5 defines a single method of self-FEXT cancellation, in which FEXT generated by a group of near-end transceivers and interfering with the far-end transceivers of that same group is cancelled (Figure 1.3-18). This cancellation takes place between VDSL2 transceivers, not necessarily of the same profile. Vectoring is intended to be implemented in conjunction with ITU-T G.993.2. Multi-pair digital subscriber line (DSL) bonding may be implemented in conjunction with vectoring.



NT = Network termination

Figure 1.3-18 – FEXT generated by a group of near-end transceivers

Vectoring provides means of reducing self-FEXT generated by the transceivers in a multi-pair cable or cable binder (see the following Note). Self-FEXT cancellation techniques are particularly beneficial with short cable lengths (< 1 km) and limited near-end crosstalk (NEXT), background noise, and FEXT from systems which are not a part of the vectored group (alien noise). The level of non-self-FEXT noise sources relative to that of self-FEXT sources determines the degree to which self-FEXT reduction can improve performance. Another significant factor is the degree to which the self-FEXT cancelling system has access to the disturbing pairs of the cable. Maximum gains are achieved when the self-FEXT cancelling system has access to all of the pairs of a cable carrying broadband signals. For multi-binder cables, significant gains are possible when the self-FEXT cancelling system has access to all of the pairs of the binder group(s) in which it is deployed and has the ability to cancel at least the majority of dominant self-FEXT disturbers within the binder. When multiple self-FEXT cancelling systems are deployed in a multi-binder cable without binder management, gains may be significantly reduced.

NOTE – A cable binder group is a bundle of pairs (e.g. there are binder groups of 25-50-100 pairs). The pairs within a binder group remain adjacent to each other for the length of the cable. As a result, the crosstalk of pairs within a binder group is somewhat greater than the crosstalk between pairs in different binder groups. However, the copper loop may consist of multiple cable sections and copper pairs may be in the same binder only for a part of the loop length (i.e., binder integrity may not be preserved from CO to NT).

1.3.3.1 Reference model

A reference model for a vectored system is illustrated in Figure 1.3-19. In a vectored system, the access node (AN), located at a central office (CO) or remote terminal (RT) or other location transmits to and receives from a number of network terminations (NTs). The common element of all forms of vectoring is coordinated transmission (downstream vectoring) or coordinated reception (upstream vectoring) of signals from lines in the vectored group at the AN. Thus, the signals may be represented as a vector where each component is the signal on one of the lines. This coordination is made possible through an interface between a VTU-O (here called VTU-O-1) and all other VTU-Os (here called VTU-O-*n*, *n*=2…*N,* where *N* denotes the number of lines in the vectored group), which is here called ε-1-*n* to indicate that the coordination takes place between line 1 and line *n*.

Coordinated management of the lines is performed by the network management system (NMS), passing management information to the management entity (ME) through the Q-interface. Both the NMS and the ME are defined in ITU-T G.997.1. Inside the AN, the ME further conveys the management information for a particular line (over an interface here called ε-m) to the vectoring control entities (VCEs) of the vectoring group that line belongs to. Each VCE controls a single vectored group, and controls VTU-O-*n* (connected to line *n* in the vectored group) over an interface here called ε-c-*n*. Pre-coder data are exchanged between VTU-O-*n*1 and VTU-O-*n*2 over an interface here called ε-*n*1-*n*2.

Figure 1.3-19 shows the reference model for a vectored system (only line 1 out of a vectored group of *N* lines is shown). The PHY blocks represent the physical layer of the AN interface towards the network and of the NT interface towards the customer premises (CP). These blocks are shown for completeness of the data flow but are out of scope of ITU-T G.993.5 and therefore of this Technical paper. The L2+ blocks represent the Ethernet Layer 2 and above functionalities contained in the AN and NT. These blocks are shown for completeness of the data flow but are out of scope of VDSL2 and vectoring, except for the encapsulation (at NT) and de-capsulation (at AN) of the backchannel (see next section).

A vectored VDSL2 system improves its performance from the use of joint signal processing in the downstream direction (coordinated transmission), or from the use of joint signal processing in the upstream direction (coordinated reception) which allows cancelling of self-FEXT (i.e., FEXT generated by the lines of the vectored group). The noise sources which are external to the group of vectored pairs in the vectored system reduce the benefits of FEXT cancellation and reduce the performance enhancement provided by a vectored system. Example noise sources are alien crosstalk from lines operated by another service provider, interference from AM broadcast channels and interference from amateur radio transmitters above the AM broadcast band (Hamming, HAM).

For relatively short lines and high-bandwidth systems such as VDSL2, self-FEXT is the limiting factor for downstream data rates. In upstream there may be UPBO (upstream power back-off) and there is typically a higher noise floor in the access node as compared to CPE, so that upstream vectoring improves performance but not as much as in downstream.

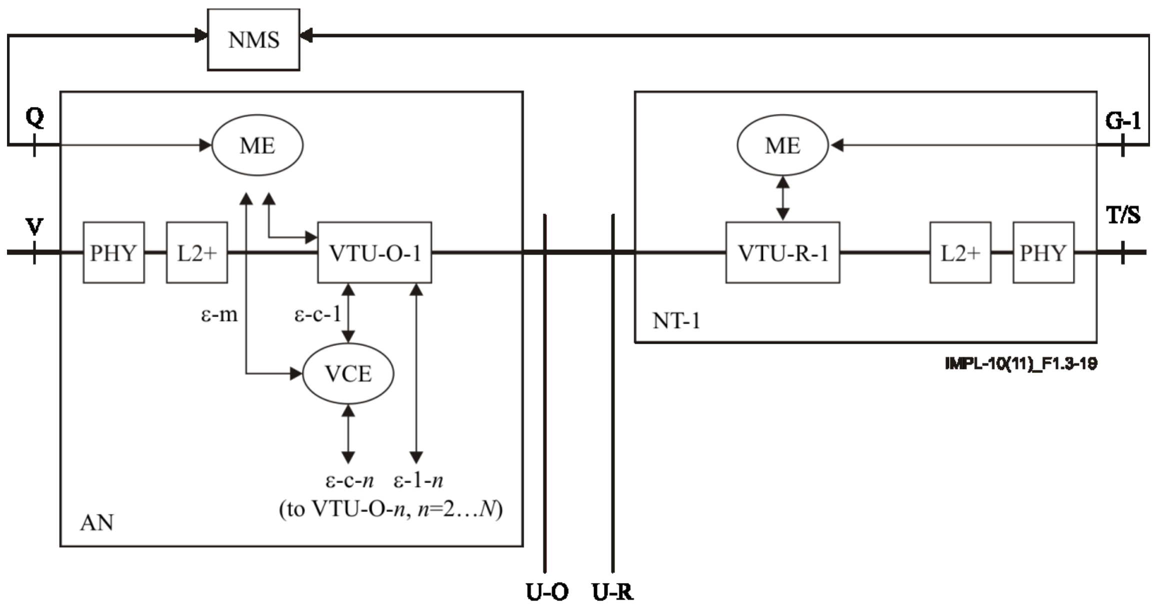


Figure 1.3-19 – Reference model for a vectored system (shown for line 1 in a vectored group of *N* lines)

Vectoring defines multi-line pre-coding at the AN to mitigate FEXT in the downstream direction, based on "pre-subtraction" or "pre-compensation" of the FEXT, while meeting transmitted power constraints. To accommodate for such pre-coding, the ITU-T G.993.2 PMD layer is modified as shown in Figure 1.3-20 (adapted from Figure 1.3-7, with differences shown shaded). Figure 1.3-20 shows the VTU-O functional model for line 1 out of a vectored group of *N* lines. For each line in the vectored group, the PMD sub-layer includes an N×1 pre-coder. Over the vectored group, the *N* pre-coders for each of the *N* lines constitute the FEXT cancellation pre-coder shown in Figure 1.3-21.

The VTU-R functional model of PMD sub-layers is as shown in Figure 10-1 of ITU-T G.993.2, with an addition of vectoring-related control signals applied to the Sync symbol encoder and initialization symbol encoder to provide pilot sequence modulation on sync symbols, similar to those shown in Figure 1.3-20.

Upstream vectoring is mainly a receiver function at the CO-side, and therefore its implementation is vendor discretionary.

ITU-T G.993.5 only defines the VTU-R transmitter requirements to facilitate upstream FEXT cancellation at the CO-side (e.g., transmission of upstream pilot sequence with timing and content under VCE control).

NOTE – In upstream all pairs end in the same place and upstream vectoring is based on post-compensation. Downstream all pairs end in different boxes and vectoring is based on pre-compensation. Pre-compensation requires CPE to send feedback information about the observed residual crosstalk signal, whereas post-compensation does not. Hence for interoperability, downstream vectoring requires more standardization than upstream vectoring.

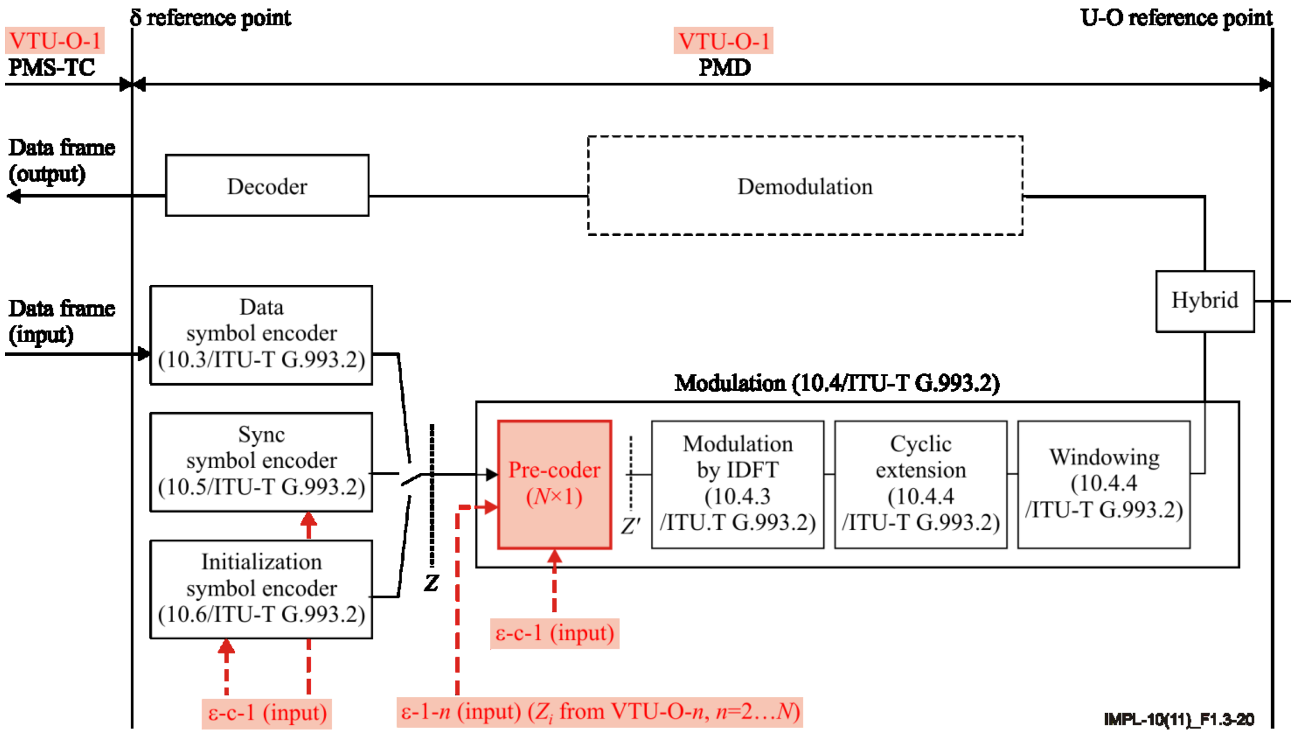


Figure 1.3-20 – VTU-O functional model of PMD sub-layer using N×1 pre-coder for downstream vectoring (shown for line 1 in vectored group of N lines)

1.3.3.2 Downstream vectoring

Figure 1.3-21 shows the functional model for the inclusion of downstream FEXT cancellation pre-coding at the AN for all lines in the vectored group, as a generalization of Figure 1.3-20 from a signal processing perspective. The model shows only the portion of an array of the downstream symbol encoders (which represent the data, sync or initialization symbol encoders shown in Figure 1.3-18) and the modulation by the IDFT functional blocks of the VTU-Os, with the FEXT cancellation pre-coder inserted between the symbol encoders and the modulation by the IDFT blocks.

The vectoring control entity (VCE) of the vectored group learns and manages the channel matrix per vectored sub-carrier, which reflects the channel characteristics of the managed group of lines. In the functional model in Figure 1.3-21, the channel matrix for each vectored sub-carrier is of size $N \times N$ where N is the number of lines in the vectored group.

From the channel matrix, a FEXT pre-coder matrix may be derived and used to compensate the FEXT from each line in the vectored group. In the functional model in Figure 1.3-21, this is shown by a matrix of FEXT cancellation pre-coders per vectored sub-carrier of size $N \times N$. This FEXT cancellation pre-coding matrix may be "sparse" (i.e., contain many coefficients set to 0). In typical cases, several of the pre-coder coefficients may be set to 0 for implementation reasons, or because the crosstalk coefficients are negligibly small. Knowing the transmit symbols on each disturbing channel, the pre-coder pre-compensates the actual transmit symbol such that at the far-end receiver input, the crosstalk is significantly reduced.

The channel matrix and the resulting FEXT cancellation pre-coder matrix are assumed to be entirely managed inside the AN. An information exchange between the VTU-O and VTU-R is required in each vectored line to learn, track, and maintain the channel matrix and associated FEXT cancellation pre-coder matrix (referred to as the backchannel). The actual algorithms for processing this information to obtain the channel matrix and to generate the FEXT cancellation pre-coder are vendor discretionary. Depending on the implementation, it may be possible for the VCE to directly determine the FEXT cancellation pre-coder matrix and therefore only have an implicit learning of the channel matrix.

Under VCE control, all VTU-Os in the vectored group use the same sub-carrier spacing and symbol rate, and start transmission of DMT symbols at the same time on all of the lines in the vectored group. The VTU-Os have the capability to transmit sync symbols at time positions determined by the VCE. The VCE may configure all VTU-Os in the vectored group to transmit downstream sync symbols at the same time positions or use different time positions for one or more VTU-Os in the vectored group.

The VTU-Os have the capability to modulate a VCE-specified downstream pilot sequence on the downstream sync symbols. The downstream pilot sequence is vendor discretionary, determined by the VCE, and is a binary string of length *Npilot_ds*. The valid values of *Npilot_ds* are all powers of 2 in the range from 8 to 512. The pilot sequence is cyclically repeated after *Npilot_ds* bits.

The modulation of a pilot sequence on the tones of sync symbols is defined as whether the sync frame bits modulated on the sync symbol are set to all ZEROs (if the pilot sequence bit is ZERO) or set to all ONEs (if the pilot sequence bit is ONE) (i.e., a 1-bit control per sync symbol).

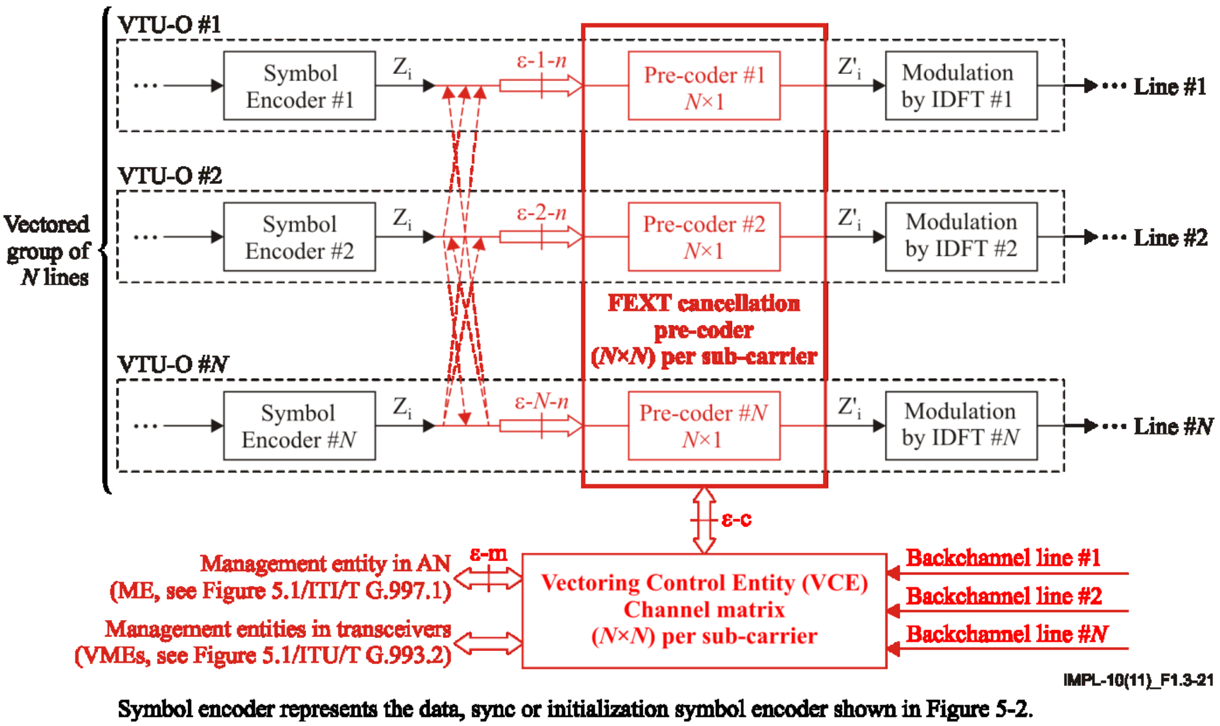


Figure 1.3-21 – Vectored group functional model of PMD sub-layer using $N \times N$ pre-coder for downstream vectoring

The VTU-R sends normalized error samples to the VCE of the vectored group, through the backchannel. During initialization, the VCE communicates to the VTU-R the backchannel encapsulation method to use (Layer 2 Ethernet encapsulation or EOC encapsulation). The VTU-R converts the received time domain signal into frequency domain samples, resulting in a complex value Z for each of the received sub-carriers. The subsequent constellation de-mapper associates each of these complex values Z with a constellation point, represented by a value $\hat{C}$. Figure 1.3-22 shows the computation of a normalized error sample E for a particular sub-carrier in a particular sync symbol. The normalized error sample represents the error between the received complex data sample Z normalized to the 4-QAM constellation point and the corresponding decision constellation point $\hat{C}$ associated with the received sync symbol in a VTU-R and referred to the input of the constellation descrambler.

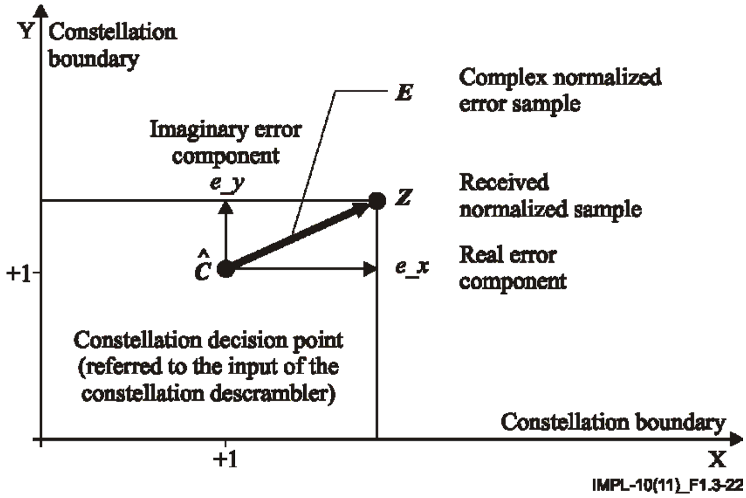


Figure 1.3-22 – Definition of the normalized error sample *E*

Through the EOC, the VCE communicates to the VTU-O a set of control parameters for error sample reporting (frequency bands to report any error sample data compression parameters for control of the backchannel data rate).

1.3.3.3 Upstream vectoring

Under VCE control, all VTU-Rs in the vectored group use the same sub-carrier spacing and symbol rate. The VTU-Rs have the capability to transmit sync symbols at time positions assigned by the VCE and communicated to the VTU-R during initialization. The time position of upstream sync symbols is defined by an offset between upstream and downstream sync symbol positions.

The VTU-Rs have the capability to modulate a VCE-specified upstream pilot sequence on all sub-carriers of the upstream sync symbols. The upstream pilot sequence is vendor discretionary, determined by the VCE, with length *Npilot_u*s and sent to the VTU-R at initialization. The valid values of *Npilot_us* are all powers of 2 in the range from 8 to 512. The pilot sequence is cyclically repeated after *Npilot_u*s bits. The time position of the upstream pilot sequence is determined by the VCE and communicated to VTU-R during the initialization by special markers.

The modulation of a pilot sequence on the sync symbols is defined as whether the sync frame bits modulated on the sync symbol are set to all zeros (if the pilot sequence bit is zero) or set to all ONEs (if the pilot sequence bit is one) (i.e., a 1-bit control per sync symbol).

The implementation at the CO-side is vendor discretionary, apart from the required ability to convey sync symbol timing and upstream vectoring control parameters from the VCE to the CP-side.

1.4 Common aspects of xDSL

1.4.1 Relationship among the DSL systems

Editors: Miguel Peeters and Massimo Sorbara

(For further information, see Recommendation ITU-T G.995.1.)

All xDSL transmission systems provide high speed data transmission on twisted wire pairs in the access network. Symmetric DSLs, specifically HDSL and SHDSL generally target business related services. Alternatively, asymmetric DSLs such as ADSL and VDSL generally target residential customers in support of triple-play services, i.e. simultaneous transmission of voice (analogue), data, and video. The type of applications, data rates, symmetric or asymmetric transmission, loop plant coverage, and modulation method are what differentiate one DSL system from the other.

The DSL systems have been specified by the ITU-T in several Recommendations, as shown in Figure 1-1 within the Introduction to this Chapter.

1.4.1.1 HDSL and SHDSL systems

(For further information see Section 1.1 of this Technical paper and Recommendations ITU-T G.991.1 and ITU-T G.991.2.)

The driving application for HDSL (high bit rate digital subscriber line) is the provisioning of digital services to end customers via the local loop plant with the goal to offer faster service provisioning times and eliminate or significantly reduce the use of repeaters in the access network.

First generation HDSL addresses the provisioning of a T1 (bit synchronous 1.544 Mbit/s in accordance with ITU-T G.703 and ITU-T 704) signal on two twisted wire pairs for application in North America; the bit rates on each wire pair operate at 784 kbit/s which transported half of the 64 kbit/s time slots in each wire pair plus 16 kbit/s of overhead that contain an 8 kbit/s embedded operations channel and an 8 kbit/s for framing overhead. For Europe, the same HDSL core transceivers operating at 784 kb/s each would be used to provision an E1 (bit synchronous 2.048 Mbit/s in accordance with ITU-T G.703/704) signal on three twisted wire pairs. Alternatively, a two pair option is defined for transport of bit synchronous 2.048 Mbit/s signals, where the bit rate on each wire pair is 1168 kbit/s that includes half of the payload 64 kbit/s time slots, transport of the two reserved 64 kbit/s signalling time slots in each wire pair, plus 16 kbit/s for EOC (Embedded Operation Channel) and framing overhead.

Upstream and downstream transmission on each wire-pair is provided in the same frequency spectrum and the upstream and downstream transmissions are separated using the echo-cancellation method. Another common aspect of HDSL is that the transceiver unit at the customer premises location is generally considered to be network owned equipment. Hence, the HDSL equipment at the customer premises location is powered from the central office (or exchange office) location across the phantom circuit formed by the multiple wire pairs connecting HDSL equipment. The redundancy offered by the multiple wire architecture allows sustaining of partial rate service in the event that service on one of the wire pairs should fail.

A new generation of symmetric DSL addresses business access applications delivering fractional (n x 64 kbit/s) T1 or E1 related services of symmetric user data rates from 192 to 2312 kbit/s on a single wire pair. This new generation is indicated as symmetric high-rate DSL (SHDSL) and it is defined in ITU-T G.991.2. Included in SHDSL is operational support for second generation HDSL (HDSL2) that defines transmission of 1.544 Mbit/s T1 service and of 2.048 Mbit/s E1 service each provisioned on a single wire pair. Optional multi-pair transmission configurations are also defined. ITU-T G.991.2 has also defined optional transport of ATM (asynchronous transfer mode) or PTM (packet transfer mode) payloads.

Unlike HDSL, the SHDSL customer premises transceiver unit is typically locally powered at the customer premises location. Similar to HDSL, the SHDSL systems support an 8 kbit/s EOC for enabling operation and maintenance of the bit synchronous access service. The protocols for the EOC operation are defined in ITU-T G.991.1 and ITU-T G.991.2.

In summary ITU-T G.991.1 (HDSL) and ITU-T G.991.2 (SHDSL) are related in that both address transmission of symmetric user data over metallic copper wires, support T1 and E1 services and other business applications on one-two-three pairs of metallic copper wires and do not support the use of analogue splitting technologies for coexistence with either POTS or ISDN. However, SHDSL is different from HDSL in that it supports a range of user data rates from 192-2312 kbit/s over a single twisted copper wire pair, while HDSL supports only 2048 and 1544 kbit/s user data over two-three copper pairs.

1.4.1.2 ADSL and splitterless ADSL

(For further information see Section 1.2 of this Technical paper and Recommendations ITU-T G.992.1 and ITU-T G.992.2.)

ADSL targets "triple-play" service applications to residential customers, i.e. simultaneous transmission of voice (analogue), data, and video. The asymmetric connection in the access network is provisioned to provide higher speed data in the downstream direction (toward the customer) and relatively lower speed data in the upstream direction (toward the central office). ADSL is defined to transmit high speed data on the same wire pair supporting analogue voice service, using frequency spectra above the voice band. HDSL and SHDSL each provide symmetric data transmission but without analogue voice.

ADSL systems, as specified in ITU-T G.992.1 operate in frequencies up to 1.1 MHz. The relatively narrow bandwidth of ADSL makes is suitable for high speed data (Internet access and possibly one channel of video) with maximum loop coverage (i.e. loop length). The ADSL systems support a minimum of 6.144 Mbit/s downstream and 640 kbit/s upstream data rate.

Splitterless ADSL, as specified in ITU-T G.992.2, is based on modifications to ADSL to meet the key objectives of lower equipment complexity, lower power consumption, splitterless operation and easy customer self-installation. Splitterless ADSL systems support a maximum of 1.536 Mbit/s downstream and 512 kbit/s upstream data rate.

The data rates for both ADSL and Splitterless ADSL are asymmetrical. ADSL has higher downstream to upstream asymmetry ratio than Splitterless ADSL. In some respects, ADSL and splitterless ADSL are closely related, while there are other aspects that differentiate them. The close relation of the two lies in the use of the same core DMT (discrete multi-tone) line code and its associated parameters. Moreover, splitterless ADSL has been developed with considerations for possible interoperability with ADSL. The differentiation is that splitterless ADSL, as said above, is based on modifications to ADSL to meet the key objectives of lower equipment complexity, lower power consumption, and splitterless operation easy customer self-installation.

From the loop plant coverage perspective, SHDSL, ADSL and splitterless ADSL, as compared w HDSL, have shorter loop length coverage. The length of HDSL may be increased through the use of regenerators. Regenerators are not specified for ADSL.

1.4.1.3 ADSL2, splitterless ADSL2 and ADSL2Plus

(For further information see Section 1.2 of this Technical paper and Recommendations ITU-T G.992.3, ITU-T G.993.4 and ITU-T G.993.5.)

ADSL2, as specified in ITU-T G.992.3, and Splitterless ADSL2, as specified in ITU-T G.992.4, are the second generation versions of ADSL and Splitterless ADSL respectively. ADSL2plus, as specified in ITU-T G.992.5, is an extended bandwidth version of ADSL2.

The ADSL2 systems support a minimum of 8 Mb/s downstream and 800 kb/s upstream data rate. Splitterless ADSL2 systems support a maximum of 1.536 Mb/s downstream and 512 kb/s upstream data rate. The ADSL2plus systems support a minimum of 16 Mb/s downstream and 800 kb/s upstream data rate. The data rates for ADSL2, splitterless ADSL2 and ADSL2plus are asymmetrical. ADSL2plus has higher downstream to upstream asymmetry ratio than ADSL2. ADSL2 and ADSL2plus may be used for both business and home applications. The large downstream bandwidth in ADSL2 is suitable for facilitating some of the IPTV broadcast applications, where ADSL2plus is suitable for facilitating multichannel IPTV. Splitterless ADSL2's main focus is simplified installations.

1.4.1.4 VDSL and VDSL2

(For further information, see section 1.3 of this Technical paper and Recommendations ITU-T G.993.1 and ITU-T G.993.2.)

VDSL (very high speed digital subscriber line), as specified in ITU-T G.993.1, provides for transceivers that may support both asymmetric and symmetric operations at much higher data rates (52 Mbit/s downstream and 2.3 Mbit/s upstream) when compared to HDSL/SHDSL for symmetric date rates and to the ADSL family for asymmetric data rates.

The VDSL2, as specified in ITU-T G.993.2, is a second generation version of VDSL. VDSL2 based transceivers would be able to coexist with underlying narrow-band POTS or ISDN services, as is the case with ADSL. Network operators would also be able to choose to provide VDSL2 on access lines without any narrow-band services. Recommendation ITU-T G.993.2 for VDSL.2 systems defines various profiles to allow vendors to limit implementation complexity and develop implementations that target specific service requirements. The eight VDSL2 profiles are commonly referred to as 8a, 8b, 8c, 8d, 12a, 12b, 17a, and 30a. The 8.x profiles define a minimum aggregate of downstream and upstream data rates of 50 Mbit/s, where the 12.x, 17a, and 30a profiles define a minimum aggregate of 68, 100 and 200 Mbit/s respectively. Actual data rates will be up to these values, depending on loop characteristics and noise conditions.

VDSL2, defining wider bandwidth signals, enables transmission of multiple video channels in addition to high speed Internet access, but the loop range is reduced; hence, for greater loop coverage, VDSL2 may be more likely provisioned, as said above, from a fibre fed remote cabinet. In the Fibre-To-The-Exchange (FTTEx) type of deployment, VDSL ITU-T G.993.x transceivers would provide less loop plant coverage than the ITU-T G.991.x (HDSL) and ITU-T G.992.x (ADSL) transceivers. The coverage can however be increased using, as said above, a type of deployment where the VDSL systems are used in the terminal segment of the local loop (e.g. from the cabinet to the customer premises, FTTCab) (see Figure 1.3-1).

Unlike HDSL, the customer premises equipment for ADSL and VDSL are locally powered from the customer premises location. As done for HDSL and SHDSL, both ADSL and VDSL support an embedded operations channel (EOC) for providing operations and maintenance control of the provisioned services. However, for both ADSL and VDSL, the operations and maintenance procedures are defined in Recommendation ITU-T G.997.1.

1.4.2 Common technical aspects

Editor: Massimo Sorbara

1.4.2.1 Handshake procedures for DSL systems

(For further information see Recommendation ITU-T G.994.1.)

Handshake procedures for DSL Systems, as specified in ITU-T G.994.1, provide a common mode of automatic selection and operation of the SHDSL, ADSL and VDSL based equipment. Handshake messages, signals, and procedures take place before any signals specific to a particular DSL system are exchanged. The use of the handshake procedures specified in ITU-T G.994.1 is an integral part of the ITU-T G.991.2, ITU-T G.992.x and ITU-T G.993.x. HDSL does not support ITU-T G.994.1. It is expected that the handshake procedures of ITU-T G.994.1 will be used in future DSL Recommendations and future revisions of current DSL Recommendations. ITU-T G.994.1 has no implications for ITU-T G.997.1 and ITU-T G.996.1 (see below).

1.4.2.2 Physical Layer OAM of DSL systems

(For further information see Recommendation ITU-T G.997.1.)

Another common technical aspect of DSL systems is the physical layer operations, administration, and maintenance (PLOAM) procedures. For ADSL and VDSL systems, the PLOAM procedures are defined in Recommendation ITU-T G.997.1. In particular, it contains the specification of the OAM communications channel protocol that includes a bit-oriented clear EOC and message-oriented clear EOC, the data link layer, and the SNMP (simple network management protocol) protocol; it also defines a management information base (MIB) that is used for operator configuration of ADSL and VDSL modems and for reporting of any performance monitoring or loop diagnostic information. Finally, ITU-T G.997.1 provides definition of all reporting parameters that include performance monitoring, alarm and failure conditions.

It is noted that the PLOAM methods and procedures for HDSL (ITU-T G.991.1) and SHDSL (ITU-T G.991.2) are defined in their own respective Recommendations and NOT covered by ITU-T G.997.1.

1.4.2.3 Test procedures for DSL systems

(For further information see Recommendations ITU-T G.996.1 and ITU-T G.966.2.)

Another common technical aspect of DSL systems is the functional and performance testing of the various transceivers. Recommendation ITU-T G.996.1 defines general laboratory test setup and measurement procedures for evaluating the performance of DSL systems. Although the document is written with specific cross-reference to ADSL and splterless ADSL, the general procedures apply to all HDSL, SHDSL, ADSL, and VDSL transceivers, but the parameters need to be adjusted to the specific transceiver under test and the corresponding test environment. ITU-T G.996.1 covers only the transceiver performance tests in the environments of cross-talk (both near-end and far-end crosstalk), impulse noise, radio frequency interference (RFI) and interference analogue telephone transients (specific to ADSL and VDSL only). Specifications are provided for the specific test loops and noise models. Only test procedures are defined in ITU-T G.996.1; the performance objectives and pass/fail conditions of specific test are defined in the Broadband Forum in separate performance and functional test plans for each of the specific DSL transceivers (e.g. TR-100 – ADSL performance testing, TR-105 – ADSL functionality testing, TR-114 – VDSL performance testing, and TR-115 – VDSL functionality testing).

As part of the operations and maintenance capabilities, the ADSL and VDSL transceivers each have the capability of performing some performance monitoring and reporting of test data. Recommendation ITU-T G.996.2 specifies line testing procedures for use on DSL lines. Specifications are provided for single-ended line testing (SELT), dual-ended line testing (DELT), and metallic line testing (MELT). Moreover physical medium dependent (PMD) and processing functions for SELT, DELT and MELT are described.

1.4.2.4 Implementation of a DSL system

(For further information see Recommendation ITU-T G.999.1.)

Finally, another common (though different in scope) technical aspect deals with the implementation of a DSL systems. Specifically, the interconnection of multiport PHY devices with higher level network devices. Recommendation ITU-T G.999.1 defines a point-to-point interface between a LINK layer device, such as a network processor, and a PHY device supporting multiple DSL lines, such as VDSL2, ADSL2, and SHDSL.

The LINK/PHY interface specification in ITU-T G.999.1 defines the framing structure for transporting N data streams between a LINK layer device and a multi-port PHY device, where each stream is specific to a single port in the LINK device and a corresponding port in the PHY device. An optional Ethernet encapsulation mode is also defined to allow use of Ethernet capable switching devices for routing of specific streams within the system.

1.4.3 Bonded DSL

Editor: Massimo Sorbara

(For further information see Recommendation ITU-T G.998.1, ITU-T G.998.2 and ITU-T G.998.3.)

There are numerous deployment situations where either additional loop reach is need for a targeted service rate or additional speed is needed for a given loop distance. One way to achieve either of these objectives is to distribute the data stream across multiple DSL lines operating at lower speed but enabling a greater distance and combine the multiple streams at the receiving end to reconstruct the original higher rate data stream. The ITU-T defines three methods for bonding of data streams across multiple DSL links. Figure 1.4-1 below shows a general reference model for bonded DSL links.

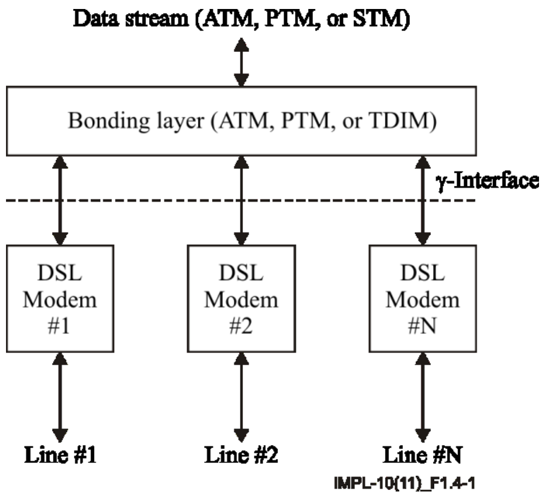


Figure 1.4-1 – General Reference Model for Bonded DSLs

The three methods of bonding are the following:

(1) ATM bonding defined in Recommendation ITU-T G.998.1,

(2) Ethernet bonding, defined in ITU-T G.998.2, and

(3) Time Division Inverse Multiplexing, defined in ITU-T G.998.3.

ITU-T G.998.1 defines the procedures for transporting a single ATM payload stream across multiple DSL lines to a single end user. The protocol allows for bonding of 2 to 32 pairs. The data rate variations across the wire pairs in the bonded group must be within a ratio of 4 to 1 (fastest to slowest). The protocol is independent of the PHY so any DSL modems may be used in the group of bonded links. The Bonding block connects to the individual DSL modems via the γ-interface (Figure 1.4-1) over which ATM cells are transported. For proper operation with ATM bonding, each DSL modem must operate with the ATM-TC. Finally the protocol operates within a maximum one-way delay of 2 ms on a DSL link.

ITU-T G.998.2 defines the procedures for transporting a single Ethernet payload stream across multiple DSL line to a single end user. The specification points to portions of clause 61 of IEEE Standard 802.3 as a normative reference and identifies the requirements for multi-pair bonding. Each Ethernet packet received by the bonding block is fragmented into multiple 65 octet PTM blocks. These fragmented 65 octet PTM blocks of data are distributed across the γ-interface to the various DSL links in the bonded group and recombined at the far end of the line into the original packet. Each DSL modem must operate with PTM-TC block in the TPS-TC layer. The data rate variations across the wire pairs in the bonded group must be within a ratio of 4 to 1 (fastest to slowest). The protocol is independent of the PHY so any DSL modems may be used in the group of bonded links.

ITU-T G.998.3 defines a time-division inverse multiplexing (TDIM) for the purpose of various service data streams (Ethernet, ATM, TDM) over multiple DSL links and to retrieve the original stream at the far-end from these physical links. This protocol defines a new TPS-TC for DSL transceivers that should be placed above the PMS-TC (at the alpha/beta-interface) of existing or future DSL transceivers. Practically, the exact same result can be obtained by stacking the new TPS-TC defined in ITU-T G.998.3 on top of the Clear Channel or STM TPS-TC as defined in existing DSL Recommendations.

1.4.4 Impulsive noise protection for DSL

Editor: Frank Van der Putten

(For further information see Recommendation ITU-T G.998.4.)

This Section describes the techniques, specified in Recommendation ITU-T G.998.4, to provide enhanced protection against impulse noise or to increase the efficiency of providing impulse noise protection (INP) beyond those defined in the existing digital subscriber line (DSL) Recommendations ITU-T G.992.3, ITU-T G.992.5, and ITU-T G.993.2.

Impulse noise is a noise event of limited duration that can degrade one or more transmitted symbols. Unlike the various types of continuous noise found on DSLs, impulse noise has a short duration and may repeat, either randomly or periodically. Impulse noise that does not appear to repeat periodically, but occur as unpredictable events is termed SHINE (Single High Impulse Noise Event). Impulse noise caused by noise from electrical mains that repeats at a constant period related to the local AC power frequency is termed REIN (repetitive electrical impulse noise).

Impulse noise protection techniques are, in general, techniques used by a DSL transceiver to protect against the effects of impulse noise on the transmitted signal. ITU-T G.992.3, ITU-T G.992.5, and ITU-T G.993.2 specify techniques to ameliorate impulse noise effects. Among these methods are the use of forward error correction (FEC) coding and interleaving.

NOTE – Interleaving is a reordering of transmitted bytes over a block of L code words so that adjacent bytes in the transmitted data stream are not from the same code word. Bytes are reordered at the receiver. Errors caused by impulsive disturbances in a DSL are concentrated in a burst of bits/bytes. The duration of the burst can exceed the correctable number of errors of the code. Thus, interleaving distributes the consequent bit/bytes errors of the burst over a longer period in time. Specifically with a long interleaving, the receiver deinterleaver leaves no deinterleaved data segments containing more errors than can be corrected. Since impulsive noise tends to occur with relatively long interarrival times, the errors in the burst can be distributed into adjacent code words that have no such errors. (From Thomas Starr, *et al.*, "Understanding DSL technique", Prentice Hall, 1999.)

ITU-T G.998.4 specifies a physical layer retransmission method for enhancing INP and is implemented in conjunction with one of the following Recommendations, referred as "associated Recommendations": ITU-T G.992.3 (ADSL2), ITU-T G.992.5 (ADSL2plus), or ITU-T G.993.2 (VDSL2).

1.4.4.1 Reference model

The basic principle of the impulsive noise protection technique, adopted for the xDSL in ITU-T G.998.4, is shown in Figure 1.4-2 and can be shortly described as follows. The DTU (data transfer unit) frames are sent from the transmitter (e.g. in the downstream direction) to the receiver. The receiver sends back to the transmitter (through the retransmission request channel, RRC) an acknowledgement when the DTU frame is received correct, while the acknowledgement is not sent if the DTU is received with impairments, e.g. due to impulse noise. When the acknowledgement of a DTU is not received from the transmitter, this DTU is retransmitted taking it from the retransmission queue, if the constraint of the maximum delay is met. A DTU can be retransmitted several times if the constraint of the maximum delay is satisfied. The technique defined in ITU-T G.988.4 allows the retransmission of all the DTUs.

Figure 1.4-2 shows the functional reference model for the case where retransmission is enabled in both transmission directions.

In the forward direction, only one bearer channel (#0) is active. Octets from the bearer channel are encapsulated in data transfer units. DTUs are stored in a retransmission queue after transmission. A DTU multiplexer will select either a new DTU or a DTU from the retransmission queue for transmission over the α2-reference point.

The PMS-TC (physical media specific transmission convergence) contains two latency paths and a retransmission request channel (RRC). Latency path 0 (L0) contains only overhead data, while latency path 1 (L1) contains only DTUs (i.e., octets coming over the α2-reference point). The RRC carries acknowledgments for received DTUs. The latency paths are scrambled and encoded using a Reed-Solomon code. The RRC is encoded using an extended Golay code. The output bits from the latency paths and the RRC are multiplexed into a data frame that is transferred to the PMD over the δ-reference point.

NOTE – A binary Golay code is a type of error-correcting code used in digital communications. The extended binary Golay code encodes 12 bits of data in a 24-bit word in such a way that any triple-bit error can be corrected and any quadruple-bit error can be detected.

If retransmission is enabled in a single direction, the functional reference model is identical to the one described in Figure 1.4-2, with the exception that there is no RRC. The functional reference model in the return direction for the TPS-TC (transmission protocol-specific transmission convergence) is identical to the TPS-TC functional model in the applicable associated Recommendation (ITU-T G.992.3, ITU-T G.992.5 or ITU-T G.993.2). The PMS-TC consists of one latency path and the RRC. The functional model of the latency paths is identical to that in the applicable associated Recommendation (ITU-T G.992.3, ITU-T G.992.5 or ITU-T G.993.2). The RRC is multiplexed with the output of the latency paths into a data frame that is transferred to the PMD over the δ-reference point.

A DTU consists of a one-byte sequence identifier (SID), one-byte timestamp (TS), W CRC bytes (W represents the number of CRC bytes), V padding bytes and an integer number of 53-byte ATM cells. Four framing modes are defined, each with a different number of CRC bytes (i.e., different value for W).

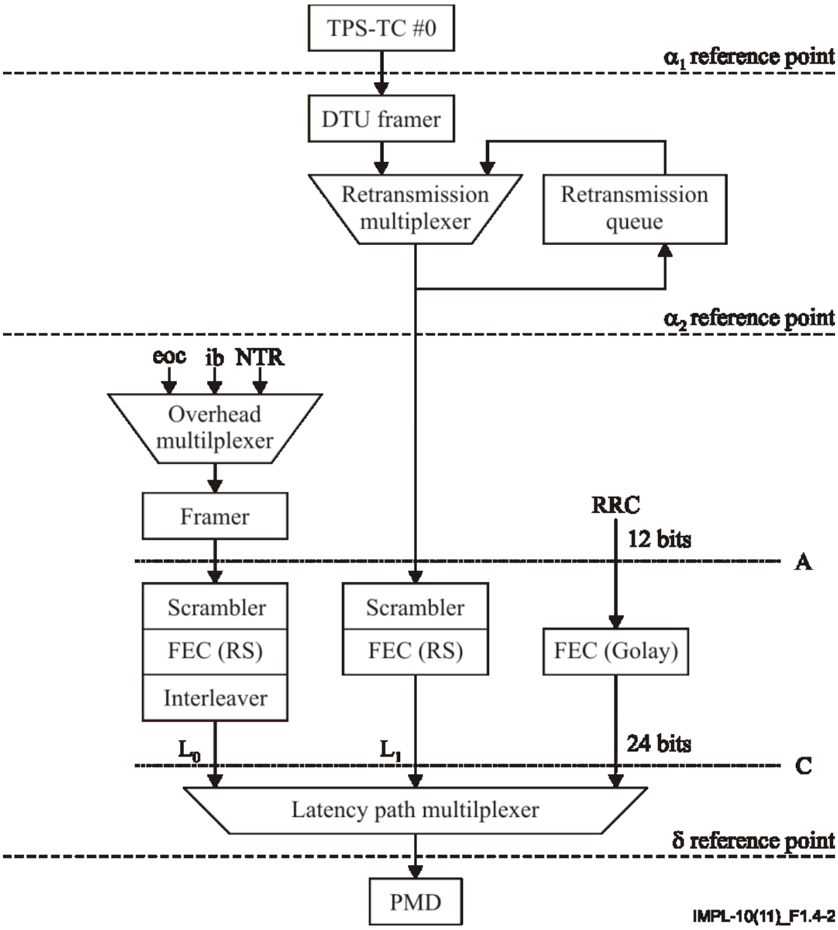


Figure 1.4-2– Reference model when retransmission is enabled in both directions

Every time a DTU is transferred across the α2-reference point, the retransmission multiplexer selects the kind of DTU to be transferred. The DTU is either a new DTU taken from the DTU framer or a previously transmitted DTU taken from the retransmission queue. The control of the selection is done by a transmitter retransmission state machine based on the content of the RRC and on the requirements of INP, and delays configured on the bearer transported in the latency path.

In the transmitter any DTU that is not acknowledged is retransmitted if the constraint of the maximal delay is met. The exact time when a DTU is retransmitted is implementation specific but the transmitter ensures that at least a number of retransmissions of the same DTU are possible without violating the maximal delay constraint.

The retransmission return channel is used to acknowledge the DTUs.

1.4.4.2 Roundtrip

The roundtrip is the time between the transmission of a DTU and the reception of the acknowledgement that the DTU has (not) been correctly received by the receiver. While waiting for the acknowledgement, the transmitter stores the DTU in the transmit queue for possible retransmission.

The combination of the roundtrip and the transmit queue size is of particular importance since the maximum net data rate (NDR) that can be achieved is approximately given by the following relationship:

$$\text{Maximum NDR} = (\text{Transmit queue size in bits}) / (\text{Roundtrip in seconds})$$

The roundtrip is typically in the order of a few milliseconds. With a roundtrip of 4 msec and a transmit queue size of 8001 octets, ADSL2 allows a maximum downstream NDR to 16 Mbit/s. With a roundtrip of 2 msec and a transmit queue size of 32k octets (i.e., equal split over 128k octets over transmitter and receiver and downstream and upstream direction), VDSL2 profile 30a allows a maximum downstream and maximum upstream NDR of 128 Mbit/s.

1.4.4.3 Operation, administration and maintenance management function

As for the operation, administration and maintenance (OAM) management function, ITU-T G.998.4 defines the following terms:

- **Expected throughput** (*ETR*): the rate available in Showtime at the α/β-reference point (see Figure 1.3-2), assuming full protection against an impulse noise environment corresponding to the Impulse Noise environment as described by parameters in the MIB.
- **Net data rate** (*NDR*): the data rate at the α/β-reference point of the bearer channel mapped in latency path #1, assuming that no retransmissions occur.
- **Error-free throughput rate** (*EFTR*): is defined as the average bit-rate, calculated during a 1 second time window, at the β1-reference point, of bits originating from DTU's that have been detected to contain no error at the moment of crossing the β1-reference point. The 1 second time windows that are consecutive and non-overlapping. As a result of this definition, $EFTR \leq NDR$.
- **SHINEratio**: the loss of rate in a 1 second interval expressed as a fraction of NDR due to a SHINE impulse noise environment expected by the operator to occur at a probability acceptable for the services.

NOTE – The alpha and beta are the functional reference points at network side and at user side respectively, α1 and β1 are the same reference points.

Chapter 2
Optical access networks (PON, point-to-point and OMCI)

Introduction

Editor: Frank J. Effenberger

Optical fibre is capable of delivering bandwidth intensive integrated voice, data and video services at distances beyond 20 km in the access network. Various configurations can be imagined for the deployment of the optical fibre in the local access network. The most well-known are fibre-to-the-home (FTTH), fibre-to-the-building (FTTB) and fibre-to-the-curb (FTTC).

In the FTTH approach the optical fibre in the local access network can be used in a point-to-point topology, with a dedicated fibre running from the local exchange to each end-user subscriber. While this is a simple architecture, in most cases it is cost prohibitive due to the fact that it requires significant outside plant fibre deployment as well as connector termination space in the local exchange. Considering N subscribers at an average distance L km from the central office, a point-to-point design requires 2N transceivers and N * L total fibre length (assuming single fibre is used for bidirectional transmission).

To reduce fibre deployment, it is possible to deploy a remote switch (concentrator) close to the customer (FTTC, FTTB). This reduces fibre consumption to only L km (assuming negligible distance between the switch and customers), but actually increases the number of transceivers to 2N+2 since there is one more link added to the network. In addition, a curb-switched architecture requires electrical power as well as backup power at the curb unit. Currently, one of the highest costs for local exchange carriers is providing and maintaining electrical power in the local loop. Moreover, as the service is given over the existing copper subscriber lines, the maximum speed achievable with very high speed digital subscriber line (VDSL) systems is limited with respect to that of fibre-based systems.

An alternative solution to the two above is to replace the hardened active curb-side switch with an inexpensive passive optical component. Passive optical network (PON) is a technology viewed by many network operators as an attractive solution to minimize the amount of optical transceivers, central office terminations and fibre deployment. A PON is a point-to-multipoint optical network with no active element in the signal path from source to destination. The only interior elements used in a PON are passive optical components such as fibre, splices and splitters. Access networks based on single-fibre PON require only N+1 transceivers and L km of fibre. The general structure of a PON network is shown in Figure 2-1.

At the network side there is an optical line termination (OLT), which is usually installed at the local central office. The OLT is the interface between all the users connected to the given PON and the metro network. Such users have access to the services offered by the network, through the network terminal (NT), and to the optical network through the ONU optical network unit/optical network termination (ONU/ONT).

The OLT and the ONUs are connected via an optical distribution network (ODN), which in many cases has a point-to-multipoint configuration with one or more splitters. Typical splitting factors include 1:16 / 1:32 / 1:64 or more.

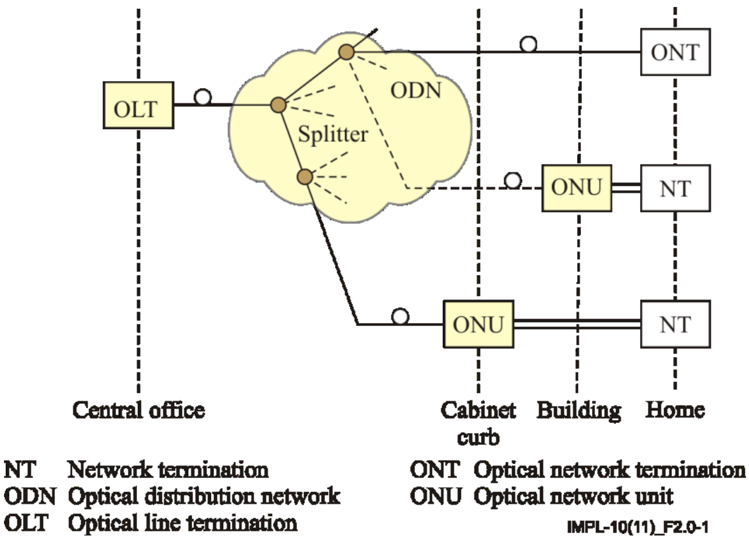


Figure 2-1 – General structure of a PON

PON splitters can be placed near the OLT or at the user sites, depending on the availability of fibres in the ODN, and/or on the ODN deployment strategy adopted by network operators.

The PON shown in Figure 2-1 is completely passive and the maximum distance between the OLT and the ONU is typically limited to 20 km at nominal split ratios. However, there are also solutions that include deployment of active elements in the network structure (e.g., optical amplifiers) when it is necessary to achieve a longer reach (e.g., up to 60 km) or to reduce the number of central office sites (central office concentration), or to connect a larger number of users to a single OLT port (e.g., where higher power budget is required due to a higher split ratio). Such solutions are typically referred to as “long-reach PON”.

As shown in Figure 2-1, a PON can be deployed in a FTTH architecture, where an ONU/ONT is provided at the subscriber's premises, or in FTTB, FTTC or fibre-to-the-cabinet (FTTCab) architectures, depending on local demands. In the latter cases, the optical link is terminated at the ONU, and the last stretch to the subscriber's premises is typically deployed as part of the copper network using, for example, existing xDSL lines. Various types of xDSL family technologies, e.g., VDSL2, are typically used.

In the upstream channel (from subscriber to the OLT), access to a shared fibre channel is guaranteed by the use of the time division multiple access (TDMA) mechanism, where a certain bandwidth is assigned to each ONU/ONT by the OLT. In the downstream channel (from the OLT to the subscribers), there is only one transmitter located at the OLT, and data to individual ONUs/ONTs is transmitted using time division multiplexing (TDM). Figure 2-2 shows the use of these techniques in downstream and upstream channels.

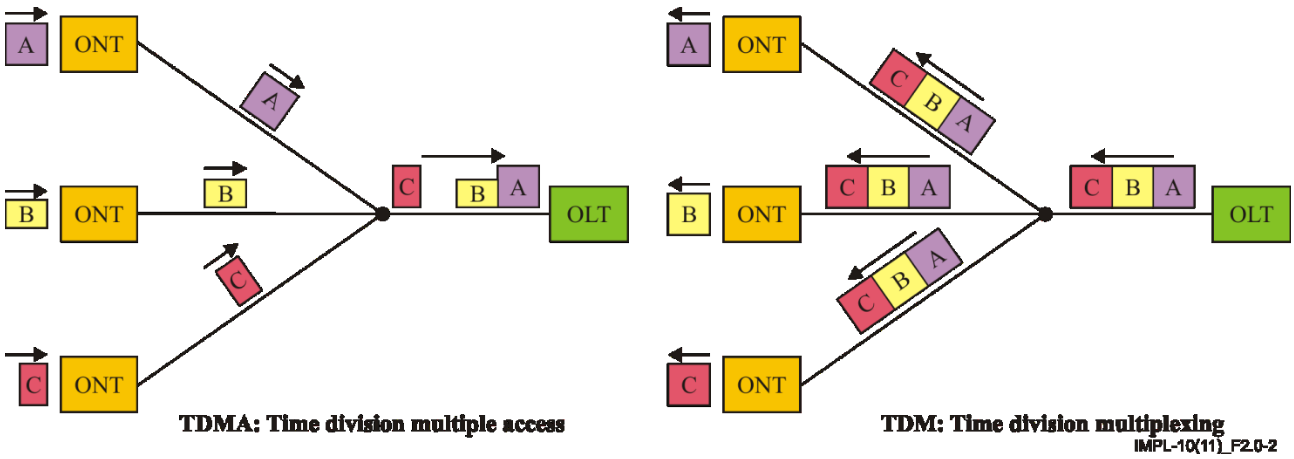


Figure 2-2 – TDM/TDMA technique

The downstream channel works in continuous mode, i.e., the cells/packets to be sent to the different ONTs are queued with no time gap between them. Idle cells/packets are generated by the OLT when necessary, in order to assure a continuous data flow in the downstream direction. This allows the ONTs to recover their own clock from the downstream data flow. The upstream channel works in burst mode instead, and when the cells/packets reach the OLT receiver, they have different amplitude, because the branches of the ODN have very likely different lengths and attenuation. A suitable guard time is guaranteed between consecutive cells/packets by the media access control (MAC) protocol. In case of poor upstream traffic, the OLT receiver must be able to cope with the reception of a cell/packet after a relatively long period of "silence". Moreover, the length of the upstream cells/packets is not fixed, thanks to the dynamic bandwidth assignment (DBA) algorithm, which assigns more bandwidth to the ONTs that have more upstream traffic to be transmitted at a particular moment. In the downstream direction, an ONT can receive more cells/packets than another one, but this is not reflected in Figure 2-2, for the sake of simplicity.

Based on the supported upstream and downstream data rate, there are three main categories of PON: the Broadband PON (B-PON), the Gigabit-capable PON (G-PON) and the 10 Gigabit PON (XG-PON).

In order to reduce the need for dual fibre ODNs, the aforementioned PON systems can take advantage of the wavelength division multiplexing (WDM) technique, where downstream and upstream channels are transmitted at different wavelengths on the same optical fibre, e.g., 1260-1360 nm for the upstream and 1480-1500 nm for the downstream. It is also possible to add another optical signal, to for example, carry radio-frequency-video signals in the bandwidth 1530-1580 nm (called the enhancement band).

Table 2-1 – Downstream and upstream data rates

Type	Downstream (max.)	Upstream (max.)
BPON	Standard:1.2 Gbit/s In service: 622 Mbit/s	Standard: 622Mbit/s In service: 155 Mbit/s
G-PON	2.5 Gbit/s	Standard: 2.5 Gbit/s In service: 1.2 Gbit/s
XG-PON	10 Gbit/s	2.5 Gbit/s

Several versions of PON are at present specified in ITU-T: B-PON (ITU-T G.983.x series), G-PON (ITU-T G.984.x series), XG-PON (ITU-T G.987.x series). These three PON architectures have the same infrastructure, design and installation. The main difference among the three solutions is related to downstream and upstream data rates, as shown in Table 2-1.

More specifically the ITU-T Recommendations that describe passive optical networks are diagrammed in Figure 2-3.

In this figure there is also Recommendation ITU-T G.982, entitled “Optical access networks to support services up to the ISDN primary rate or equivalent bit rates”. ITU-T G.982 can be considered obsolete and it is quoted here mainly for historical reasons, because it is the mother of all technical choices that are at the basis of B-PON (e.g., topology architecture and wavelength allocation).

As described above there have been three major series of ITU-T Recommendations developed: the arrows show the approximate evolution of the technical content subject areas as the multiple series were developed. In some cases, large subject areas were split into multiple ITU-T Recommendations in the next series, while in others new features were merged into the main part of the next series.

The ITU-T G.983.x series described PON systems based on ATM technology (A-PON / B-PON) and consisted of five Recommendations. The first described the base system, including the requirements, architecture, physical interfaces and transmission convergence functions. The following four described features that were added subsequently.

The ITU-T G.984.x series described Gigabit PON systems (G-PON), and consisted of seven Recommendations and one Supplement. The first four defined the base system, with one document each handling requirements, physical layer specifications, transmission convergence layer specifications and management functions. The other four documents contained additional features and enhancements that arose later.

The ITU-T G.987.x series described 10 Gigabit-capable passive optical networks (XG-PON) systems, and consists of five Recommendations. The first provides defined terms and acronyms, and then the following three define the base system, using a similar structure as that used for G-PON, with the exception of ONU management, which is handled by ITU-T G.988 (Section 2.5 of this Technical paper). The sixth document describes reach extension for XG-PON.

In the framework of the optical access networks there are two other ITU-T Recommendations to be quoted: ITU-T G.985 and ITU-T G.986. They do not deal with passive optical networks and therefore are not indicated in Figure 2-3. Both of them describe point-to-point Ethernet-based optical access systems for optical access services. ITU-T G.985 specifies 100 Mbit/s point-to-point systems and ITU-T G.986 specifies 1 Gbit/s point-to-point systems (Section 2.4).

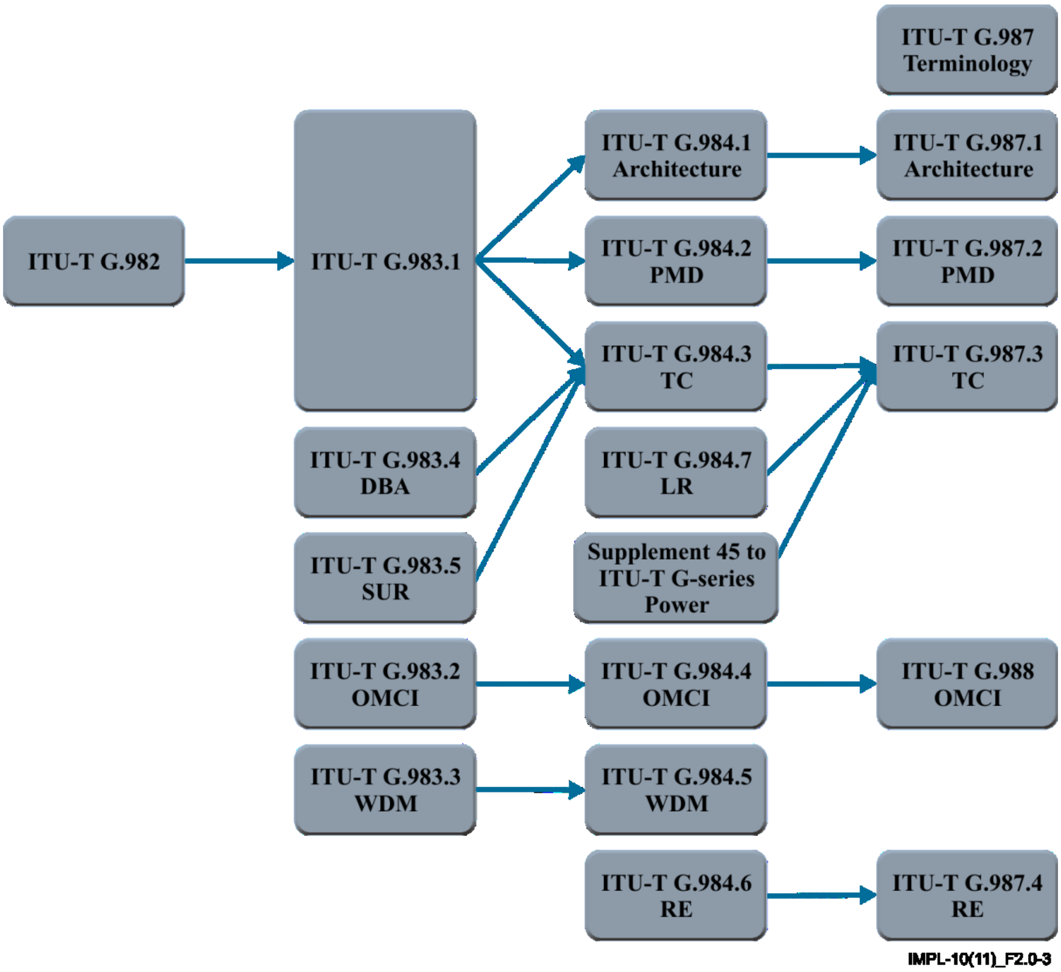


Figure 2-3 – The PON ITU-T Recommendations at a glance

2.1 Broadband passive optical network (B-PON)

Editor: Frank J. Effenberger

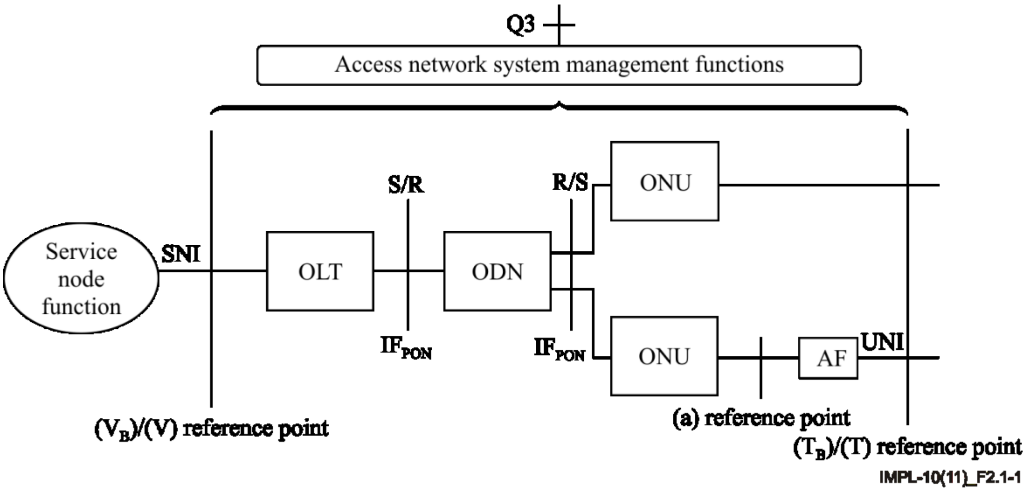
This section describes a flexible optical fibre access network capable of supporting the bandwidth requirements of narrow-band and broadband services. This description, based on the content of ITU-T G.983.1, mainly refers to systems with nominal downstream line rates of 155.52, 622.08 and 1244.16 Mbit/s, and nominal upstream line rates of 155.52 and 622.08 Mbit/s. Both symmetrical and asymmetrical systems are described. In particular this section describes the physical layer requirements and specifications for the physical media-dependent layer and the transmission convergence (TC) layer of an asynchronous transfer mode (ATM)-based B-PON.

2.1.1 Architecture, interfaces, requirements

(For further information see Recommendation ITU-T G.983.1.)

2.1.1.1 Architecture and interfaces of the optical access network

The reference configuration of a B-PON is shown in Figure 2.1-1. The access network lies between the V (service node interface, SNI) and T (user network interface, UNI) reference points. The interfaces of the optical distribution network (ODN) are defined as the S/R (send/receive) and R/S interfaces. Additionally referenced is the Q3 interface, which manages the PON system in general. The Q3 interface is outside the scope of this Technical paper and its description can be found in the ITU-T Q.834 series of Recommendations.



(a)	Reference point – This reference point is added to differentiate the AF from the ONU.
AF	Adaptation function
ODN	Optical distribution network
OLT	Optical line termination
ONU	Optical network unit
R	Point on the optical fibre just before the ONU(downstream)/OLT(upstream) optical connection point (i.e., optical connector or optical splice).
S	Point on the optical fibre just after the OLT(downstream)/ONU(upstream) optical connection point (i.e., optical connector or optical splice).

Figure 2.1-1 – Reference configuration for passive optical networks, including reference points

2.1.1.2 Physical medium dependent layer requirements

The physical layer parameters are specified in Recommendation ITU-T G.983.1 in a large set of tables. The key index to finding the appropriate parameters is Table 2.1-1, which indicates this by downstream and upstream, and nominal bit rate.

Moreover all parameters shall be in accordance with Table 4-a of ITU-T G.983.1 where the parameters of the ODN are specified.

(For further information on the physical layer parameters, see also chapter 9 of the ITU-T Manual on optical fibres, cables and systems.)

Table 2.1-1 – Relation between parameter categories and tables

Transmission direction	Nominal bit rate	Table
Downstream	155.52 Mbit/s	Table 4-b of ITU-T G.983.1 (downstream, 155 Mbit/s)
	622.08 Mbit/s	Table 4-c of ITU-T G.983.1 (downstream, 622 Mbit/s)
	1244.16 Mbit/s	Table 4-d of ITU-T G.983.1 (downstream 1244 Mbit/s)
Upstream	155.52 Mbit/s	Table 4-e of ITU-T G.983.1 (upstream, 155 Mbit/s)
	622.08 Mbit/s	Table 4-f of ITU-T G.983.1 (upstream, 622 Mbit/s)

As said before, the ODN characteristics are given in Table 4-a of ITU-T G.983.1, where, in particular, three classes of attenuation ranges are specified:

- Class A: 5-20 dB
- Class B: 10-25 dB
- Class C: 15-30 dB.

Note that the loss budget and certain parts of Table 4 from ITU-T G.983.1 are overridden by ITU-T G.983.3 amendments, which are discussed in Section 2.1.3.

2.1.1.3 Transmission convergence layer requirements

The TC-layer is the part that adapts the upper data networking protocol into the physical layer. The TC layer requirements for an ATM-PON are described in Table 2.1-2.The basic idea of this system was to reuse the TC layers that had been already defined for ATM systems (i.e., in ITU-T I.432), and then make the minimal modifications necessary to handle the special requirements of PON systems.

Table 2.1-2 – TC layer requirements

Cell rate decoupling	Recommendation ITU-T I.432.1
Head error control calculation error correction	Recommendation ITU-T I.432.1
Maximum number of virtual paths per PON	4096
Minimum addressing capability	64 ONUs

The meaning of the above requirements can be summarized as follows:

- cell rate decoupling allows the signal rate to vary below the ATM cell rate;
- header error control (HEC) covers the entire ATM cell header and is capable of either single bit error correction or multiple bit error detection;
- maximum number of virtual paths per PON determines the maximum number of service flows that are visible and controllable by the PON equipment;
- maximum addressing capability determines the maximum number of ONUs.

2.1.1.3.1 Downstream interface

The transfer capacity for ATM cells includes information cells, signalling cells, operation, administration and maintenance (OAM) cells, unassigned cells and cells used for cell rate decoupling.

The transfer capacity for the 155.52 Mbit/s interface is 149.97 Mbit/s (155.52 * (54:56)).

NOTE – There are 2 physical layer OAM (PLOAM) cells in each downstream frame and 54 byte ATM cells. This explains (54:56).

The transfer capacity for the 622.08 Mbit/s interface is 599.86 Mbit/s.

The transfer capacity for the 1244.16 Mbit/s interface is 1199.72 Mbit/s.

2.1.1.3.2 Upstream interface

In the upstream the physical layer overhead includes the PLOAM cells, the minislots for the MAC channel and the overhead bytes which are added in front of each upstream ATM cell, PLOAM cell or minislot (see Section 2.1.4).

The transfer capacities for the upstream interfaces have upper limits of:

- 147.2 Mbit/s (155.52 * (53:56)) for the 155.52 Mbit/s interface;

  NOTE – In the upstream frame there are 3 bytes added in front of each ATM cell of 53 bytes. This explains (53:56).

- 588.8 Mbit/s for the 622.08-Mbit/s interface.

Some extra bandwidth is allocated by the OLT for the upstream PLOAM channel and MAC channel.

The upstream transfer capacity is shared among the ONUs based on their allocated upstream bandwidth.

2.1.1.3.3 Frame structure

Data are transferred across the PON using the framing format as shown in Figure 2.1-2. The frames are of fixed length, and can carry 56 cells in the downstream and 53 cells in the upstream at the 155 Mbit/s rate. Each downstream frame carries 2 PLOAM cells, which carry all the information necessary for PON control and maintenance. Each upstream cell comprises a 3 byte header and a 53 byte ATM cell.

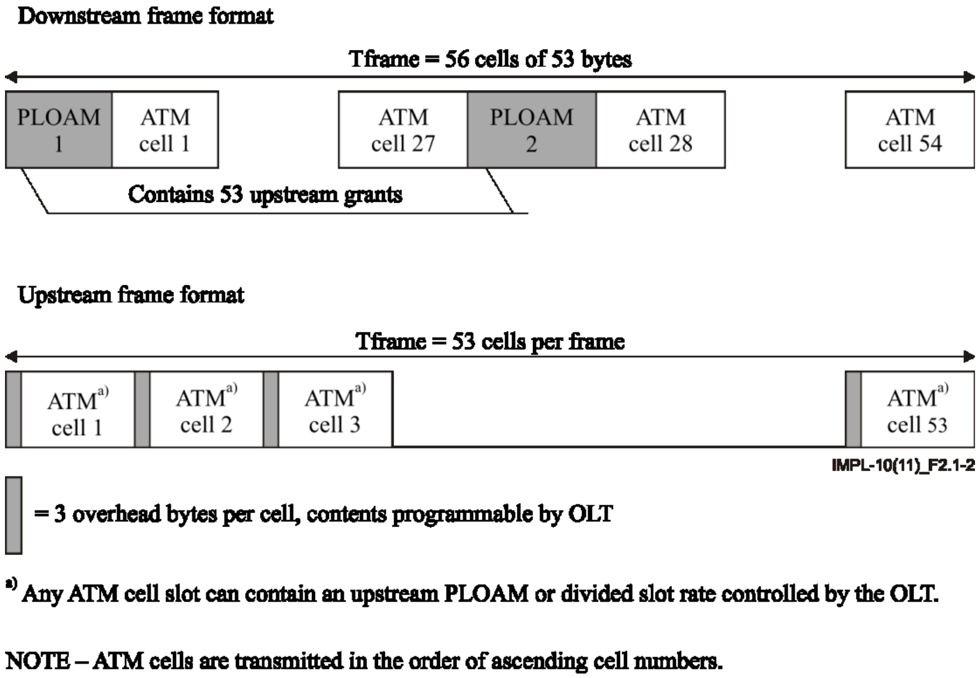


Figure 2.1-2 – Frame format for 155.52/155.52-Mbit/s PON

Recommendation ITU-T I.361 identifies specific patterns for PLOAM flows. The pattern shown in Table 2.1-3 is defined for maintenance of ATM-PONs.

Table 2.1-3 – PLOAM header

	Octet 1	Octet 2	Octet 3	Octet 4	Octet 5
Physical layer OAM cell for ATM-PON	0000 0000	0000 0000	0000 0000	0000 1101	HEC = valid code 0111 0110
NOTE – There is no significance to any of these individual fields from the viewpoint of the ATM layer, as physical layer OAM cells are not passed to the ATM layer.					

The downstream PLOAM cell structure is defined to carry many of the key signals and controls that the PON requires. Each field handles a certain function on the PON. The IDENT field indicates what protocol is being used. The SYNC field provides a reference to an 8 kHz clock signal. The GRANT fields convey which ONU/transmission container (T-CONT) is to transmit in the corresponding upstream slot. The MESSAGE fields carry a transaction-oriented OAM channel. Finally, the BIP presents the byte-wise parity of the downstream signal since the last BIP was sent.

2.1.1.3.4 Churning

Due to the multicast nature of the PON, the downstream signal can be seen by all ONUs at any fibre end. This can be a data privacy concern. To reduce this problem, downstream cells are churned at the TC layer with a churning key sent upstream by the ONU and so remain unknown from any other fibre termination.

The churning is a function applied to the downstream user data from an OLT to its ONUs, which provides the necessary function of data scrambling and offers a low level of protection for data confidentiality. It is installed at the TC layer of the ATM-PON system. The churning is performed for point-to-point downstream connections and churning can only be enabled or disabled per virtual path (VP) at its set-up. The churning key update rate is at least 1 update/second per ONU. If churning is not enough for a security requirement of a provided service, a suitable encryption mechanism should be employed at a higher layer than the TC layer to provide data scrambling.

2.1.1.3.5 Protection switching

Automatic protection switching (APS) at the PON TC layer may be provided as an optional function. The need for APS use depends on the number of users and service reliability requirements. Redundant configurations of dual ODNs or dual ONUs should be considered for business applications. Some control bits for the protection protocol are reserved in the PON Section Trace (PST) message field.

Time required for APS including ranging time for 32 ONUs shall be considered to support plain old telephone service (POTS)and/or Integrated Services Digital Network (ISDN) services; on-going connections should not be disconnected when APS is carried out.

2.1.1.3.6 ONU activation

When an ONU is connected to the PON system, a series of steps must be carried out before the ONU goes into the operational state. This is shown in Fig. 2.1-3. First, the ONU must correctly receive the downstream frame. Next, it must receive the upstream Rx control and upstream overhead messages. It then receives the serial number mask message, which can make the ONU eligible to respond to ranging grants. When the ONU responds to the ranging grant with its serial number, the OLT can identify this new ONU that has joined, and send dedicated messages to it, including the ONU-ID message, and the ranging time message. Once the ONU has been configured with both an ONU-ID and a ranging time, it can pass into the operational state (last step: O8 in Figure 2.1-3). Such an ONU is then further configured with service-specific information.

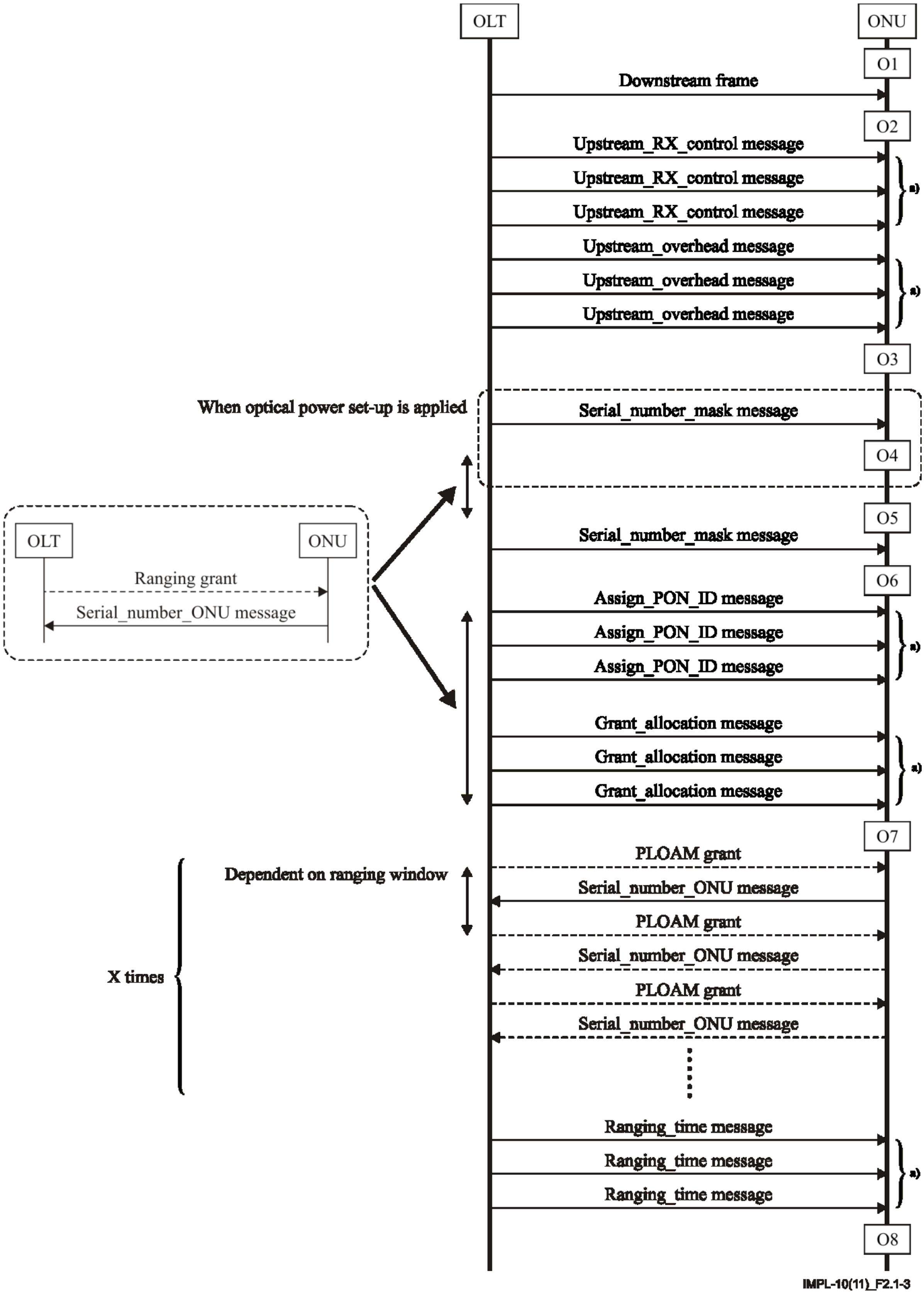


Figure 2.1-3 – Message sequence for ranging

Notes to Figure 2.1-3

NOTE 1 – It is specified that the processing time for each PLOAM message in ONU is within 6 T frames (6*Tframe). ONU can receive PLOAM messages from OLT at any interval.

NOTE 2 – There are two ways to complete optical power set-up. One is that ONU in O3 completes optical power set-up by itself, and the other is that ONU in O4 receives some ranging grants and sends some upstream PLOAM cells. In the latter case, OLT must know beforehand the number of times and timing of sending ranging grants. These values are related to the ranging time and the number of ranging windows. Therefore, the way to complete optical power set-up should be selected by operators according to their service requirements.

NOTE 3 – In O4 and O6, if OLT gives ranging grants to ONU, ONU has to send Serial_number_ONU message to OLT.

NOTE 4 – ONU can move to the next action when it receives at least one message in three consecutive messages at the points indicated by [a)]. The detailed operations are as follows:

- ONU can move to O3 from O2 when it receives at least one Upstream_overhead message.
- ONU can receive Grant_allocation messages when it receives at least one Assigned_PON_ID message.
- ONU can move to O7 from O6 when it receives at least one Grant_allocation message.
- ONU can move to O8 from O7 when it receives at least one Ranging_time message.

NOTE 5 – If an OLT is going to utilize the Rx control field, the OLT will send the Upstream_RX_control message before it tries to use that facility.

NOTE 6 – Serial_number_ONU messages are sent from ONU according to PLOAM grants in O7 X times. X is specified by OLT implementation.

2.1.2 ONT management

(For further information see Recommendation ITU-T G.983.2.)

This section describes the ONT management and control interface (OMCI), defined in Recommendation ITU-T G.983.2 for the B-PON system, to enable multi-vendor interoperability between the OLT and the ONT.

NOTE – These B-PON systems are called ATM-PON in Recommendation ITU-T G.983.1.

2.1.2.1 ONT management and control interface

The OMCI specification addresses the ONT configuration management, fault management and performance management for B-PON system operation and for several services including:

- ATM adaptation layers 1, 2, and 5;
- circuit emulation service;
- Ethernet services, including MAC Bridged LAN, VLAN tagging and filtering;
- Internet protocol routing;
- wireless LAN (IEEE 802.11) service;
- ADSL and VDSL services;
- voice services, including ISDN;
- wavelength division multiplexing, including video;
- PON protection switching;
- dynamic bandwidth assignment;

- enhanced security.

The focus of this OMCI specification is on FTTH and FTTBusiness ONTs.

NOTE – FTTH and FTTBusiness both refer to a fibre structure to the user: a home in FTTH and a business in FTTBusiness.

The protocol necessary to support the capabilities identified for these ONTs, specified in ITU-T G.983.2, also allows optional components and future extensions.

The basic concept of the OMCI is shown in Figure 2.1-4. The generic PON system is shown with users on the left and the core network on the right. The OMCI is a management link between the two black circles in the figure, and allows communication between the OLT and the ONUs/ONTs.

Using this link, the OLT can act as the management proxy for the entire set subtending ONUs. The OLT itself is managed from an element management system over the Q3 interface. In this way, the scalability of the network is enhanced, in that a large number of ONUs (typically 2~8 thousand) can be managed through only the single OLT, and the element manager need only deal with this one OLT. In contrast, a scheme where the ONU is separately managed requires the element manager to communicate with thousands of ONUs as well as the OLT.

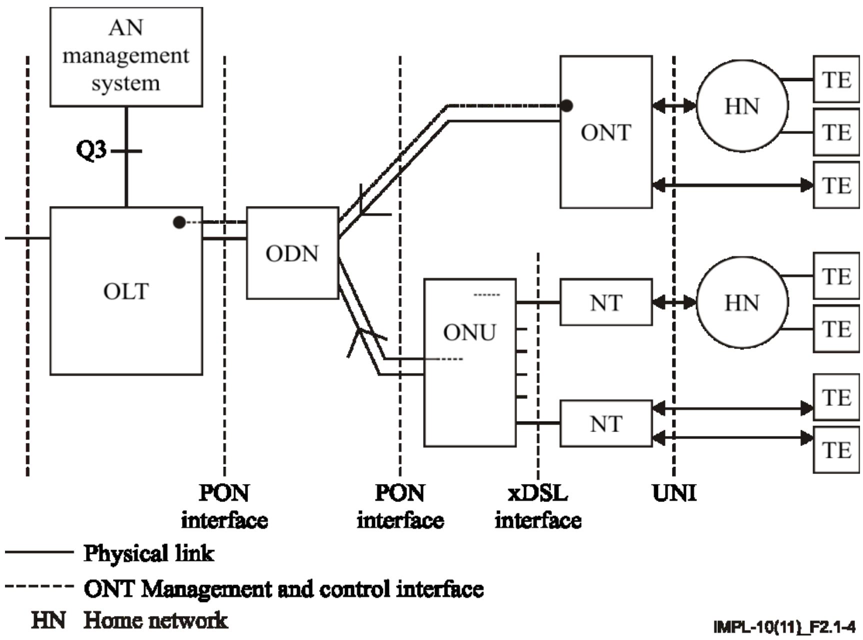


Figure 2.1-4 – OMCI reference model

The OMCI is used by the OLT to control an ONU or ONT. This protocol allows the OLT to:

establish and release connections across the ONT;

manage the UNIs at the ONT;

request configuration information and performance statistics;

autonomously inform the system operator of events such as link failures.

The OMCI protocol runs across an ATM connection between the OLT controller and the ONT controller that is established at ONT initialization. The OMCI protocol is asymmetric: the controller in the OLT is the master and the one in the ONT is the slave. A single OLT controller using multiple instances of the protocol over separate control channels may control multiple ONTs.

The ONT management and control interface requirements are needed to manage the ONT in the following areas:

configuration management;

fault management;

performance management.

2.1.2.2 Managed entities

The protocol-independent management information base (MIB) described in Recommendation ITU-T G.983.2 has been defined in terms of managed entities (ME). The managed entities are abstract representations of resources and services in an ONT.

Three levels are used for indicating the degree of compliance necessary for specific functions and managed entities associated with the OMCI specification:

- requirement (R): entities necessary for operational compatibility;
- conditional requirements (CR): entities necessary when the specified optional function is implemented;
- option (O): entities that may be useful and required by an operator but that are not necessary for operational compatibility.

A small example of the managed entities is listed in Table 2.1-4, which is an excerpt of Table 1 of ITU-T G.983.2. Note that there are over 100 ME types defined in the Recommendation ITU-T G.983.2.

Table 2.1-4 – Managed entities in the OMCI

Managed entity	Required/ Optional	Description	Defined in clause
IEEE 802.1p mapper service profile	O	Used to define mapping of IEEE 802.1 frames to virtual channel connection (VCC) tag protocols (TPs) based on IEEE 802.1p priority bits	7.3.95 of ITU-T G.983.2
IEEE 802.11 general purpose object	CR	Used for IEEE 802.11 interface supported by the ONT	7.3.59 of ITU-T G.983.2
ONT B-PON	R	Used for ONT equipment management	7.1.1 of ITU-T G.983.2

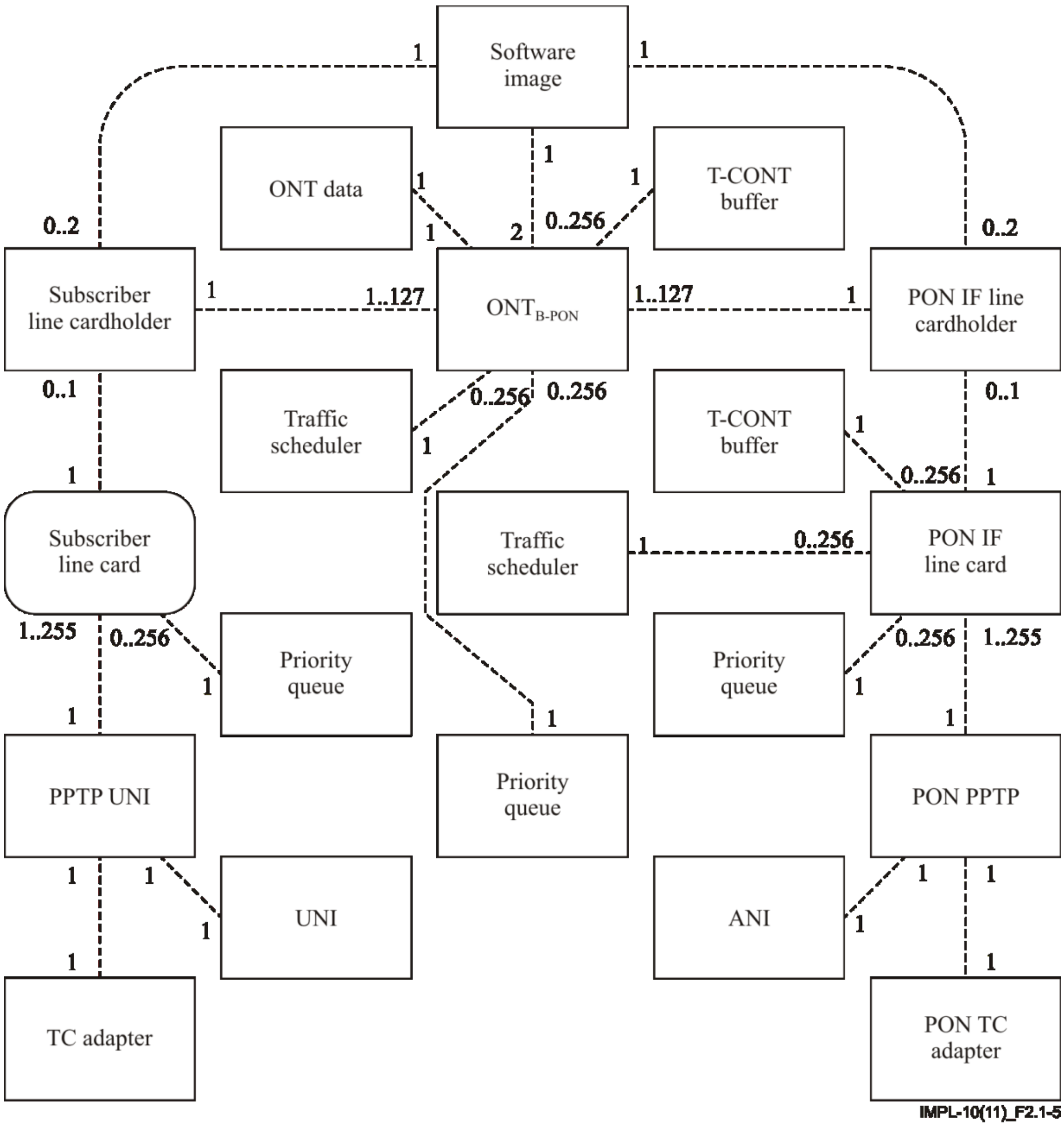
The relationships between the required managed entities are given in Figures 13 to 31 of ITU-T G.983.2. Figure 13 gives the legend of symbols used in these diagrams. Figure 14 is reproduced below in Figure 2.1-5, as an example. This diagram shows the core MEs that represent the ONU as equipment (the line card and line cardholder), and also the quality of service MEs (the priority queues and T-CONT buffers).

The detailed description of all ONT managed entities include:

- the purpose of the entity;
- the relationship(s) that the entity supports with other managed entities;
- the attributes of the entity;
- the management operations that may be performed on the entity;
- the notifications generated by the managed entity.

A managed entity can be created by the ONT autonomously or on explicit request of the OLT via a create command.

Attributes of a managed entity for which no create action exists (i.e., a managed entity which is auto-instantiated by the ONT) can be (R)ead, (W)rite, or (R, W). On the other hand, attributes of a managed entity for which a create action exists (i.e., a managed entity which is instantiated on explicit request by the OLT) can be (R), (W), (R, W), (R, Set-by-create), (W, Set-by-create), or (R, W, Set-by-create). For attributes that are not "Set-by-create", a default value is specified in Recommendation ITU-T G.983.2 which will be assigned to the attribute on instantiation of the managed entity.



ANI	**Access node interface**	**TC**	**Transmission convergence**
IF	**Interface**	**T-CONT**	**Transmission container**
PPTP	**Point-to-point tunneling protocol**		

Figure 2.1-5 – The ME relationships for the core parts of the ONU

The notifications generated by a managed entity stem from the following events: alarms, attribute value changes (AVCs), threshold crossing alerts (TCAs) and test results.

Alarms, TCAs and failures of autonomous self-tests are all reported via "Alarm" messages. AVCs are reported via "Attribute Value Change" messages.

Test results are reported:

via a "Test result" message if the test is invoked by a "Test" command from the OLT;

via an "Alarm" message in the case of failure of an autonomous self-test (in start-up phase).

2.1.2.3 ONU management control channel

Each ONU/ONT Management and Control Protocol packet is encapsulated directly in a single 53-byte ATM cell. The cell format is shown in Figure 2.1-6. Each of these fields serves a function. The ATM header is used to identify this cell as belonging to the ONT management control channel (OMCC) flow. The transaction correlation field is used to track messages and match responses with commands. The message type indicates what kind of operation (get or set, for example) is desired in this message. The device identifier indicates which protocol handler this message should go to (only one is defined for B-PON). The message identifier specifies which ME type (one byte) and entity instance (two bytes) this message is addressing. The message contents contain the particular command data. Lastly, the AAL5 trailer contains the error control of the entire cell payload. The content of all these messages is specified in ITU-T G.983.2.

The OMCC has certain limitations on the sizes of messages that can be carried. While the origins of these limitations are largely historical, they do have an impact on how the ME's and their attributes are defined. For example, the information of some functional entities is spread over several subtending MEs due to the limitation on the number of attributes.

ATM header (5 bytes)	Transaction correlation identifier (2 bytes)	Message type (1 byte)	Device identifier (1 byte)	Message identifier (3 bytes)	Message contents (33 bytes)	AAL 5 trailer (8 bytes)

IMPL-10(11)_F2.1-6

Figure 2.1-6 – ONT management and control protocol cell format

2.1.3 Extended wavelength allocation

(For further information see Recommendation ITU-T G.983.3.)

This section describes the broadband passive optical network (B-PON) system that uses wavelength division multiplexing techniques (WDM). These WDM techniques allow operators to provide additional services without disturbing the basic ATM-PON system.

New wavelength allocations have been specified to distribute ATM-PON signals and additional service signals simultaneously. These new wavelength bands are made available by constraining the current ATM-PON downstream wavelength to a portion of downstream optical spectrum originally specified in ITU-T G.983.1. The new bands have the potential to provide unidirectional and bidirectional services. The new wavelength allocation enables the distribution of video broadcast services or data services, and the general optical characteristics of these services are considered. However, the detailed specifications of these services, such as modulation scheme, signal format, and so on are beyond the scope of this Technical paper.

Moreover new reference points and optical interface parameters of the new WDM and/or optical power splitter/combining functions needed at OLT and/or ONU sites are defined.

The following terms are used:

- basic band: the wavelength region allocated for the ATM-PON downstream capabilities;

- enhancement band: the wavelength region allocated for new additional service capabilities, which include at least video services and dense wavelength division multiplexing (DWDM) services.

Figure 2.1-7 shows the wavelength allocation for the WDM-capable system. The upstream band remained unchanged at 1260 nm to 1360 nm. The water-peak wavelengths (1380nm to 1460nm) were reserved for future standardization (which has not occurred as of 2012). The downstream band was changed significantly. The ATM-PON downstream was narrowed to only 1480 nm to 1500 nm. This left space for the definitions of two new bands. The enhancement band operates in the spectrum around 1550 nm (there are two options given below), and there is a future L-band allocation. Guard bands between the bands are therefore defined.

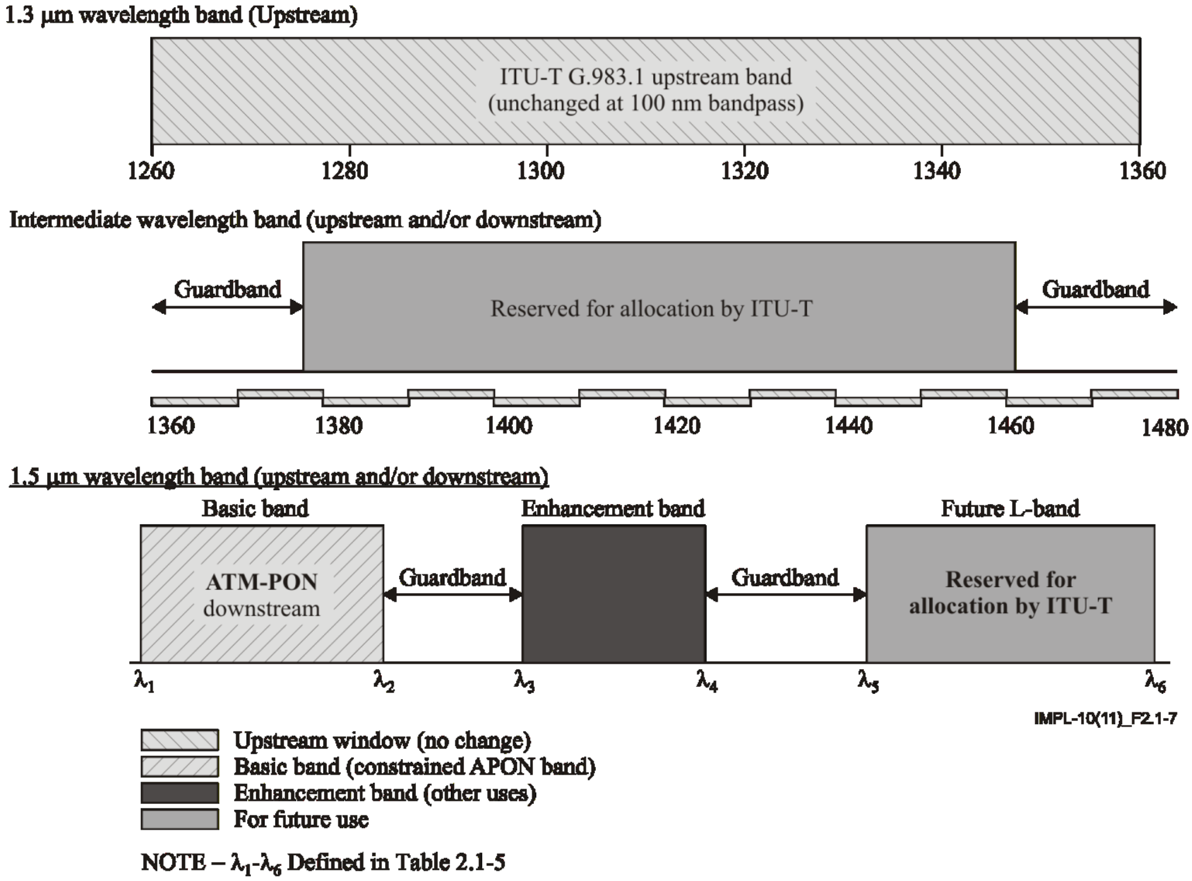


Figure 2.1-7 – Wavelength allocation

There were several possible uses for the enhancement band, and so there were two options given for the spectrum reserved for the enhancement band. These are shown in Table 2.1-5. For enhancements based on digital services (conceptually, multi-channel WDM overlays), the enhancement band is wider. For enhancements based on video broadcast services, the enhancement band is defined to be narrower, and further away from the basic band ATM-PON downstream. This is to enhance the isolation of the optical filters needed to protect the basic-band receiver from the video signal.

There are currently two major applications for the B-PON system. The first is a full-service system with a video overlay. The second is a digital-only system without a video overlay. These two applications are diagrammed in Figure 2.1-8. The two applications lead to slightly differing loss budget requirements. To meet these two sets of requirements, it is necessary to define two OLT optic types, and one ONT optic type. The OLT optic type then determines which application and loss budget will be obtained. The single ONT optic type allows for commonality over both applications, and increases volumes.

Table 2.1-5 – Parameters for wavelength allocation in Figure 2.1-7

<table>
<tr><th>Items</th><th>Notation</th><th>Unit</th><th>Nominal value</th><th>Application examples</th></tr>
<tr><td colspan="4">1.3 µm wavelength band</td><td rowspan="3">For use in ATM-PON upstream</td></tr>
<tr><td>Lower limit</td><td>–</td><td>nm</td><td>1260</td></tr>
<tr><td>Upper limit</td><td>–</td><td>nm</td><td>1360</td></tr>
<tr><td colspan="4">Intermediate wavelength band</td><td rowspan="3">For future use –reserved band including guard bands for allocation by ITU-T</td></tr>
<tr><td>Lower limit</td><td>–</td><td>nm</td><td>1360</td></tr>
<tr><td>Upper limit</td><td>λ1</td><td>nm</td><td>1480</td></tr>
<tr><td colspan="4">Basic band</td><td rowspan="3">For use in ATM-PON downstream</td></tr>
<tr><td>Lower limit</td><td>λ1</td><td>nm</td><td>1480</td></tr>
<tr><td>Upper limit</td><td>λ2</td><td>nm</td><td>1500</td></tr>
<tr><td colspan="4">Enhancement band (Option 1)</td><td rowspan="3">For additional digital service use</td></tr>
<tr><td>Lower limit</td><td>λ3</td><td>nm</td><td>1539</td></tr>
<tr><td>Upper limit</td><td>λ4</td><td>nm</td><td>1565</td></tr>
<tr><td colspan="4">Enhancement band (Option 2)</td><td rowspan="3">For video distribution service</td></tr>
<tr><td>Lower limit</td><td>λ3</td><td>nm</td><td>1550</td></tr>
<tr><td>Upper limit</td><td>λ4</td><td>nm</td><td>1560</td></tr>
<tr><td colspan="4">Future L-band</td><td rowspan="3">For future use –reserved band for allocation by ITU-T</td></tr>
<tr><td>Lower limit</td><td>λ5</td><td>nm</td><td rowspan="2">For further study</td></tr>
<tr><td>Upper limit</td><td>λ6</td><td>nm</td></tr>
<tr><td colspan="5">NOTE 1 – The central frequencies in the enhancement band for the DWDM application shall be based on the frequency grid given in ITU-T G.694.1.
NOTE 2 – The value of isolation between the basic band signal and the enhancement band signal is not decided uniquely, because system configuration varies by regulations, service strategy, and geographic conditions as well as offered services in the enhancement band.
In this discussion, isolation should be interpreted as both the ratio of leaked basic band signal to E-ONU (enhancement band-ONU) or E-OLT from basic band signal and the ratio of leaked enhancement band signal to ONU or OLT from enhancement band signal at WF1 or WF2. (WF1 and WF2 are WDM and/or optical combining/splitting functions, which separate/combine wavelength and/or split/combine optical power for ATM-PON transport service and additional services that are located between the ODN and OLT.) Both types of isolation should be defined separately.
Common use of WDM filters is expected for cost reduction through large volume production. The isolation examples required in typical cases are described in Appendix III of ITU-T G.983.3.
NOTE 3 – Isolation value recommended for between the basic band signal and the enhancement band signals (Option 1) is for further study in ITU-T.
NOTE 4 – Isolation value recommended for between the basic band signal and the enhancement band signals (Option 2) is for further study in ITU-T.
NOTE 5 – Applied filter has appropriate loss characteristics to achieve required isolation. However, loss characteristics outside the 1480-1580 nm range (e.g., in the future L-band) is for further study.</td></tr>
</table>

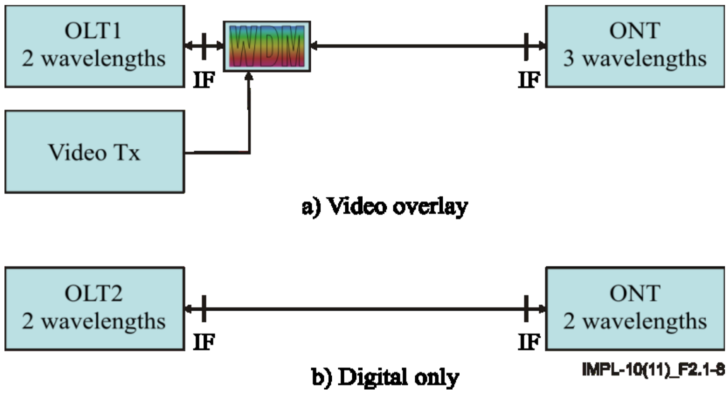


Figure 2.1-8 – B-PON applications

Based on the above wavelength allocation it is possible to look at the loss budget for the upstream and for the downstream links. The starting point is the optical specifications for the industry best practices of optics for the B-PON system which are given in Table 2.1-6. This focused the consideration on a system that had path loss somewhere between class B and class C (hence the so-called "B+" loss budget). And it focused on systems with 622 Mb/s downstream and 155 Mb/s upstream. This table refers to power levels measured at the interface points (IF) shown in Figure 2.1-8; specifically, any WDM filters external to the OLT or ONT equipment are considered part of the ODN. These specifications contained in Amendment 2 to ITU-T G.983.3 are meant to augment similar specifications found in the main body of Recommendation ITU-T G.983.3. All other specifications found elsewhere in the ITU-T G.983.3 still apply.

The link budgets for the two applications are given in Table 2.1-7. These budgets cover all optical components between the OLT and ONT, including non-integrated WDM filters for the multiplex of video overlays and other enhancement band services.

Table 2.1-6 – Optical power levels for the 622 Mbit/s downstream, 155 Mbit/s upstream systems

Items	Unit	Single fibre
OLT1: 622 Mbit/s Tx, 155 Mbit/s Rx		OLT1
Mean launched power MIN	dB	+0
Mean launched power MAX	dB	+3
Minimum sensitivity	dB	–32
Minimum overload	dB	–9
OLT2: 622 Mbit/s Tx, 155 Mbit/s Rx		OLT2
Mean launched power MIN	dB	+1
Mean launched power MAX	dB	+4
Minimum sensitivity	dB	–31
Minimum overload	dB	–6
ONT: 155 Mbit/s Tx, 622 Mbit/s Rx		ONT

Table 2.1-6 – Optical power levels for the 622 Mbit/s downstream, 155 Mbit/s upstream systems

Items	Unit	Single fibre
Mean launched power MIN	dB	–2
Mean launched power MAX	dB	+4
Minimum sensitivity	dB	–28
Minimum overload	dB	–6
NOTE – For the meaning of OLT1 and OLT2, see Figure 2.1-8.		

Table 2.1-7 – Loss budgets for the 622 Mbit/s downstream, 155 Mbit/s upstream systems

Items	Unit	Single fibre
Video overlay system (OLT1-ONT)		
Minimum optical loss at 1490 nm	dB	9
Minimum optical loss at 1310 nm	dB	13
Maximum optical loss at 1490 nm	dB	27
Maximum optical loss at 1310 nm	dB	29
Digital-only system (OLT2-ONT)		
Minimum optical loss at 1490 nm	dB	10
Minimum optical loss at 1310 nm	dB	10
Maximum optical loss at 1490 nm	dB	28
Maximum optical loss at 1310 nm	dB	28

2.1.4 Dynamic bandwidth allocation

(For further information see Recommendation ITU-T G.983.4.)

This section describes enhanced capabilities for flexible optical access networks based on ITU-T Recommendation G.983.1. Specifically, the functions that extend ITU-T Recommendation G.983.1 to enable DBA described here are based on the content of Recommendation ITU-T G.983.4.

The requirements and specifications preserve backward compatibility and interoperability with the current ITU-T G.983.1 systems, including management systems.

The main subjects related to the DBA are the following:

- performances objectives (e.g., bandwidth assignment delay, maximum waiting time);
- application functionality (e.g., dynamic bandwidth assignment for bursty traffic and for ONU/ONT aggregated traffic composed of different traffic classes);

- fairness criteria and protocols (e.g., dynamic bandwidth assignment based on ONU/ONT status reporting, DBA based on OLT monitoring, DBA based on a combination of reporting and monitoring);
- backwards compatibility and interoperability that allows legacy OLTs and ONUs/ONTs to operate in systems where DBA is employed.

The introduction of DBA functionality into B-PON systems will increase efficiency and therefore lower the cost of providing broadband services.

ITU-T G.983.1 specifies a flexible access platform to provide broadband services through passive optical networks. It defines physical and link layer requirements. In particular ITU-T G.983.1 specifies that the upstream traffic from the ONUs/ONTs to the OLT is transferred in a frame of 53 timeslots (cell slots). Each timeslot consists of three bytes of PON layer overhead and an ATM cell or a PLOAM cell. The upstream bandwidth is shared among the associated ONUs/ONTs. The OLT controls each upstream transmission from the ONUs/ONTs on a timeslot-by-timeslot basis. This is accomplished by sending data grants in downstream PLOAM cells. PLOAM data grant cells are sent in the downstream direction to all ONUs/ONTs. The data grants are addressed to specific ONUs/ONTs and contain parameters that include the number of upstream data grants and the timeslots for the grants that are assigned to the individual ONU/ONT. Currently the grants are assigned in a static manner.

ITU-T G.983.4 specifies the two following different DBA mechanisms.

Method one is referred to as "idle cell adjustment". In this approach, the OLT monitors the bandwidth used by each of the ONUs/ONTs. If the utilization exceeds a predefined threshold, then additional bandwidth will be assigned if it is available. In this approach, no bandwidth resources are needed for the ONU/ONT to report status; the OLT infers individual ONU/ONT bandwidth needs from the current utilization. However, a possible drawback of this approach would be a slow reaction to ONUs/ONTs requesting upstream bandwidth, in comparison with implementation ii).

Method two is called "buffer status reporting". ONUs/ONTs using this approach report the status of their buffers by using mini-slots. The OLT reassigns the bandwidth according to the ONU/ONT reports.

One of the key definitions in the development of DBA is that of T-CONTs. T-CONTs are essentially "pipes" that carry ATM virtual paths (VPs) or virtual channels (VCs). Multiplexing of VPs and VCs having different ATM transfer capability/Quality of Service (ATC/QoS) into one T-CONT is programmable, and is dependent on the service model desired from the system operator. But, regardless of that, the PON system and its bandwidth allocation system will handle each T-CONT as if it is a single entity. The T-CONTs can be characterized as having a certain quality of service. There are four types of bandwidth, as shown in Figure 2.1-9. These bandwidth types have a priority relationship, in that the highest priority is served first, and so on. Usable T-CONT types can be defined that combine one or more of these bandwidth types to provide the desired bandwidth sharing behaviour. Each ONU can be configured with multiple T-CONTs, and each T-CONT can be configured to carry multiple service flows (ATM VPs). In this way, the system has a very flexible scheme of QoS control.

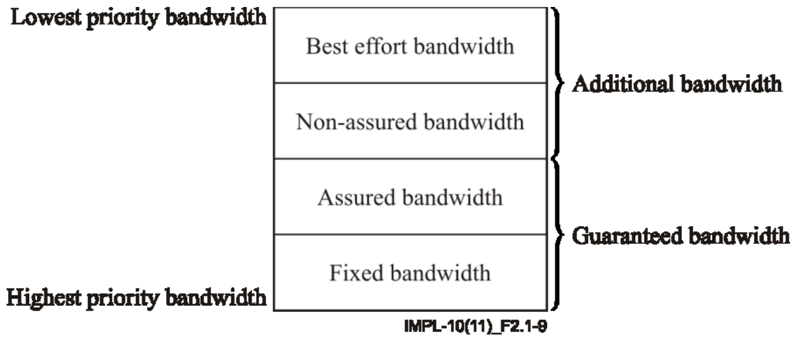


Figure 2.1-9 – Priority of bandwidth for grant allocation

Another important definition is that of the minislots used by the ONU/ONT to report the status (queue length of the T-CONT) of their buffers to the OLT.

An upstream slot can contain a divided_slot. The divided_slot fits into one upstream slot and contains a number of minislots coming from a set of ONUs/ONTs. The OLT assigns one divided_slot grant to this set of ONUs/ONTs for sending their minislots. The format of the divided_slot is shown in Figure 2.1-10.

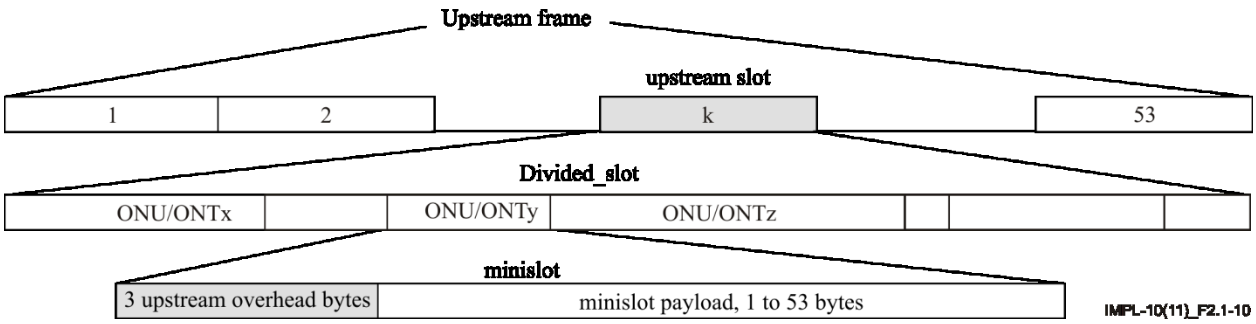


Figure 2.1-10 – Format of divided_slot

The length of the minislot is an integral number of bytes, ranging from a minimum of 5 to a maximum of 56 bytes. Each minislot is composed of the physical layer overhead bytes, one or more T-CONT report bytes, and cyclic redundancy check 8 (CRC-8) trailer.

NOTE – For exceptionally long minislots where the payload is greater than 15 bytes, additional CRC-8s must be inserted.

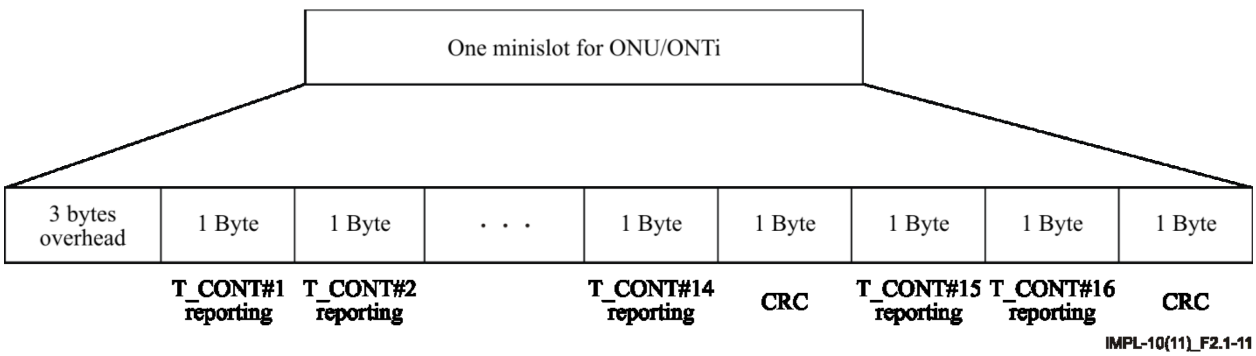


Figure 2.1-11 – The detailed minislot format for one ONU/ONT

The default minislot format is shown in Figure 2.1-11. The report contains a configured number of T-CONT reports, which carry the number of cells in a T-CONT of a specific ONU/ONT. The number of cells is encoded using a compression (lossy) mapping code.

2.1.5 Enhanced survivability

(For further information see Recommendation ITU-T G.983.5.)

This section describes the extended functions for B-PON systems defined in ITU-T G.983.1 to enable protection functions. In particular, it focuses on the protection-configuration types B and C described in Appendix IV of ITU-T G.983.1.

A number of protection features and function choices are discussed, and the necessary specifications in the PON layer to implement these choices are given in ITU-T G.983.5. These specifications include guidelines on performance objectives (e.g., switching and detection time), application functionality (e.g., revertive mode, non-revertive mode, extra traffic support, automatic switching and forced switching), switching criteria and switching protocols (1+1, 1:1, 1:N, bidirectional and unidirectional mechanisms).

These protection enhancements are aimed to the delivery of highly reliable services for a variety of B-PON network scenarios, including fibre-to-the-cabinet (FTTCab) and fibre-to-the-office (FTTO) (see Figure 2-1).

The following B-PON survivability configurations are described.

- Type B protection configuration. In this configuration type (Figure 2.1-12), no equipment redundancy is provided in the ONUs. The protection-capable OLT performs switching if its working PON interface fails or its directly-connected fibre breaks. ITU-T G.983.1 compliant ONUs satisfy type B protection configuration without modification.
- Type C protection configuration. In this end-to-end configuration type (Figures 2.1-13 and 2.1-14), equipment redundancy is provided in both the OLT and ONUs. The protection-capable OLT performs switching if any PON interface in the OLT or ONUs fails or if any fibre in the ODN breaks. ITU-T G.983.5 addresses the modifications to ITU-T G.983.1 necessary to support the type C protection configuration.
  - Mixture of protected and unprotected ONUs in type C configuration. The protection functions shall allow a mixture of protected and unprotected ONUs. In certain fault scenarios, the unprotected ONUs may suffer service disruption while the protected ONUs are recovered.
  - X:N variant of type C protection configuration. In this variant of configuration type C (Figure 2.1-14), equipment redundancy is provided in the OLT (some or all of the line terminals, LTs) and some or all ONUs. This variant allows protected ONUs to be connected to any of the protection LTs, independent of which working LT they belong to. This variant is optional.
- Extra traffic for type C configuration. Extra traffic should be able to be carried over the protection entities while the working entity is active. The extra traffic will not be protected. This option provides effective usage of bandwidth in the protection entities. It must be possible for an operator not to activate this extra traffic option.

The service halt time should be less than 50 ms if the extra traffic option is not used.

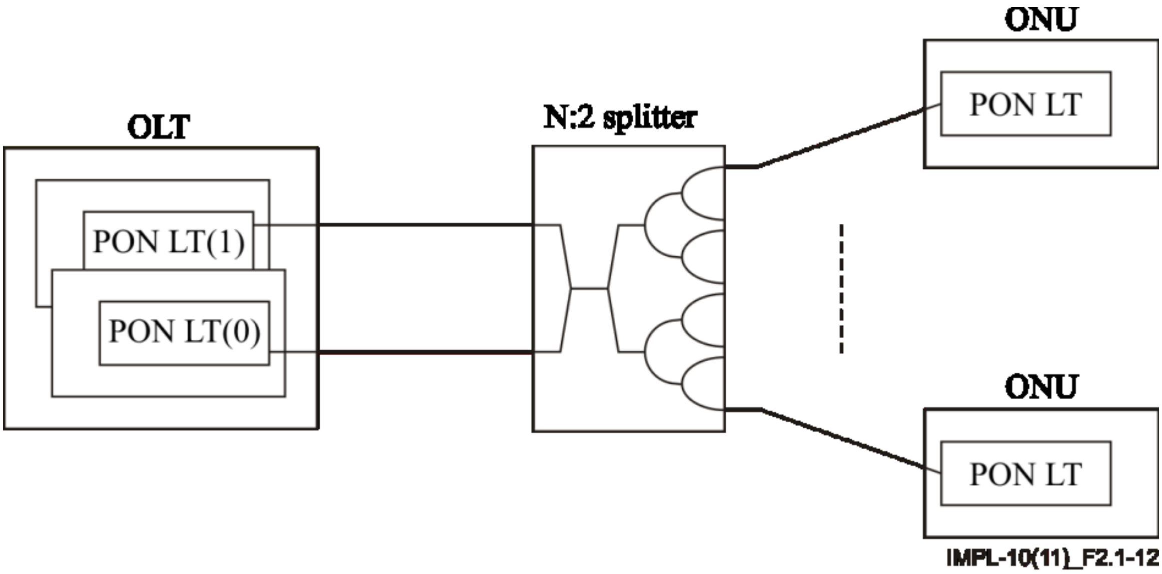


Figure 2.1-12 – Type B: OLT-only protected system

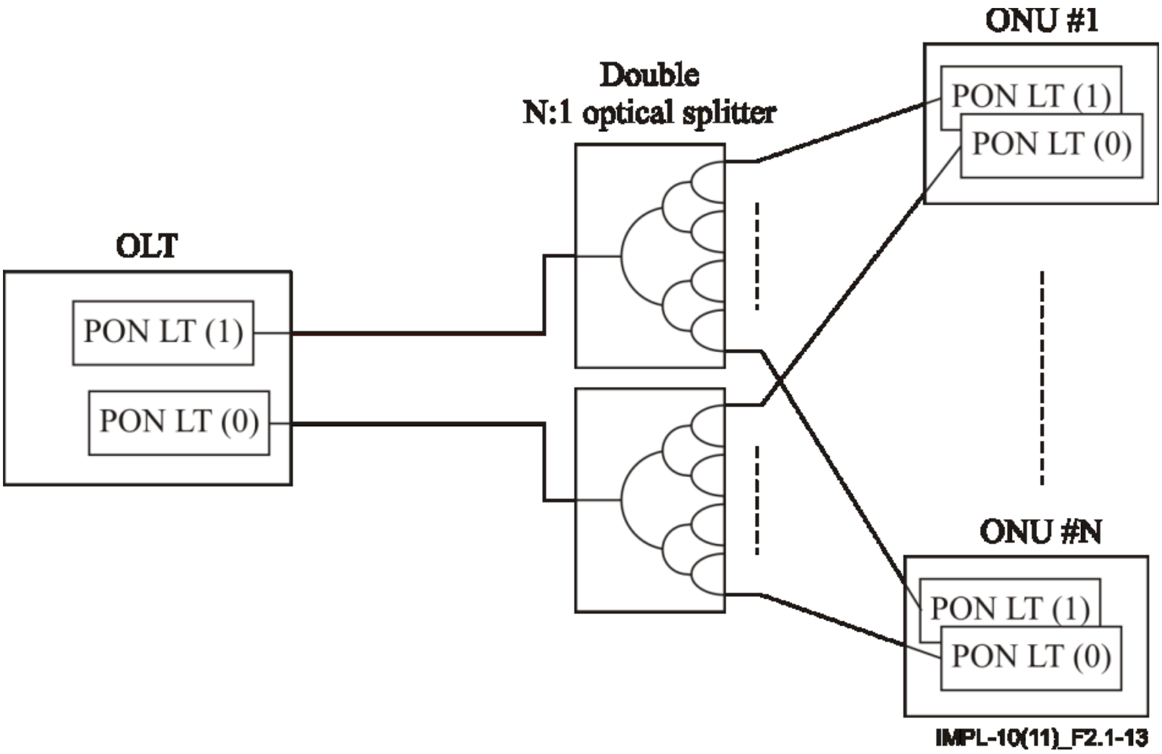


Figure 2.1-13 – Type C: Fully protected system, 1:1 and 1+1

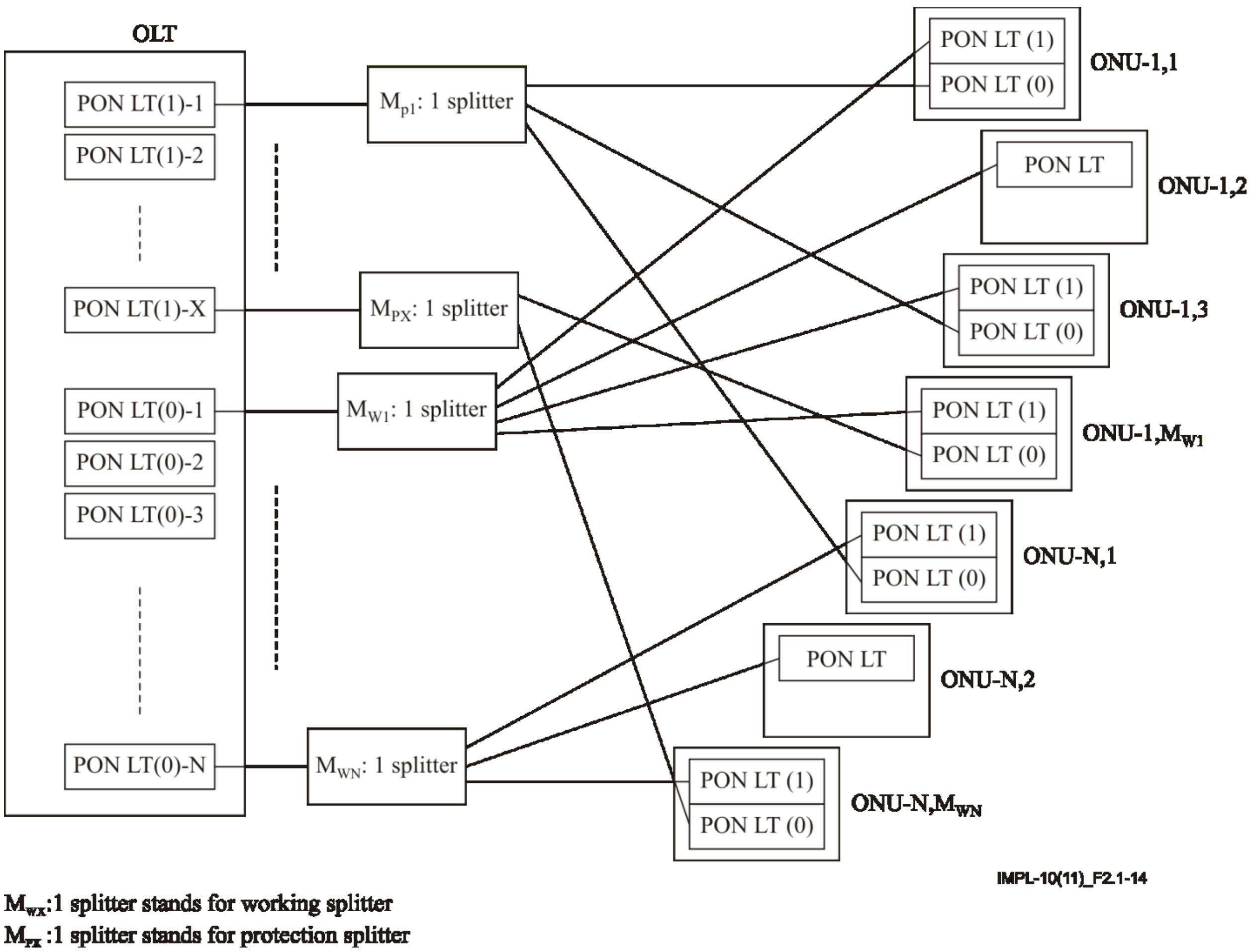


Figure 2.1-14 – Type C: X:N protection system

In the case of a protected system where a redundant PON protects the active PON, protection switching will be activated using specified messages in PLOAM cells or specific PON protocols. This sequence requires that the line numbers of the OLT must exactly match those of the ONU. The line identifier is assigned to a transmitter based on the interconnection scheme between the OLTs and ONUs. The line identifier is periodically sent to both the OLT and ONU to check whether the received line identifier is the same as the equipment's own identifier. This is defined in the PON section trace (PST) message. Each piece of equipment can then verify its continued connection to the intended transmitter. If the received line number differs from the equipment's line number, the equipment generates an alarm, link mismatching (MIS). In case of an unprotected system, link mismatching is optional.

PLOAM messages are described in ITU-T G.983.1. For B-PON survivability, the PST message is redefined to include an additional PLOAM message for survivability. These PST messages are shown in Table 2.1-8.

Table 2.1-8 – PST message definition

Message name	Function	Direction	Trigger	Number of times sent	Effect of receipt
PST message (Broadcast message) (If OLT needs to send the same message to all ONUs, it can send this message)	To check the OLT-ONU connectivity in a redundant configuration and to perform APS Priority level is 1	OLT → ONU	Send it when common message for all ONUs should be sent simultaneously	Same as the individual trigger condition	Same as the individual message (see Note)
PST message (Individual message)	To perform APS Priority level is 1		Send it at a certain rate or when OLT detects the APS trigger to change K1/K2 bytes	1 time/sec or when K1/K2 bytes should be changed	ONU checks K1/K2 bytes and performs APS (see Note)
PST message	To check the OLT-ONU connectivity in a redundant configuration and to perform APS Priority level is 1	OLT ← ONU	Send it at a certain rate or when ONU detects the APS trigger to change K1/K2 bytes	1 time/sec or when K1/K2 bytes should be changed	OLT checks link number with own link number and generates a link mismatch (MIS) if different, or OLT checks K1/K2 bytes and performs APS
NOTE – ONU checks link number with own link number and generates an MIS if different. This is checked by sending either individual or broadcast messages. APS – Automatic protection switching (see Section 2.1.1.3.5). K1/K2 bytes dedicated to the protection switching in the synchronous digital hierarchy (SDH) frames.					

2.2 Gigabit passive optical network (G-PON)

2.2.1 General aspects

Editor: Frank J. Effenberger

(For further information see Recommendation ITU-T G.984.1.)

This section addresses the general characteristics of Gigabit-capable passive optical network (G-PON) systems which guide and motivate the physical layer and the transmission convergence layer specifications. The general characteristics include examples of services, user-network interfaces (UNIs) and service node interfaces (SNIs) that are requested by network operators. Also, this section shows the principle deployment configurations.

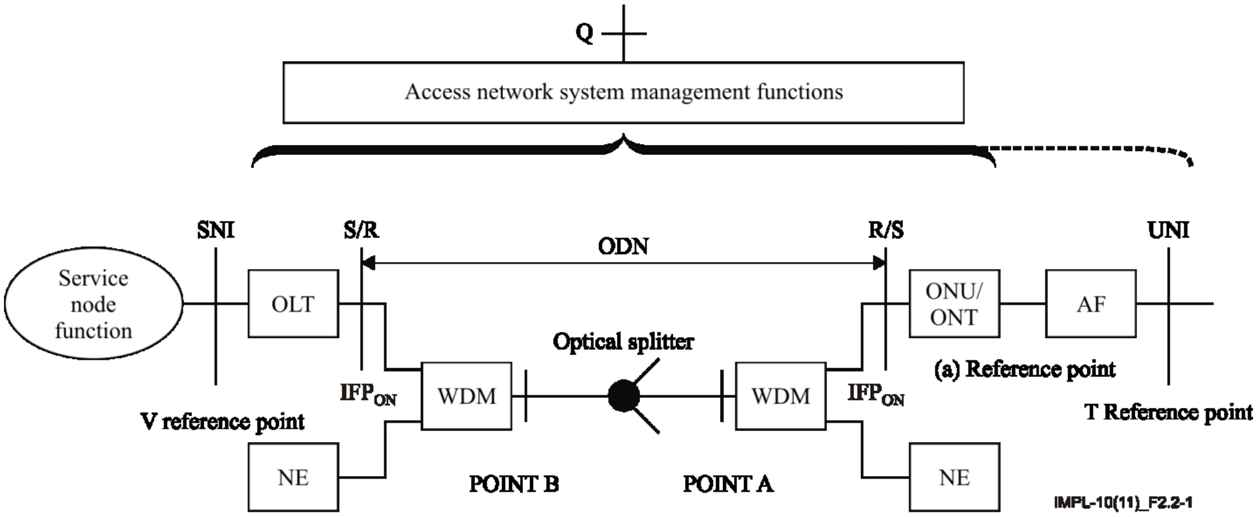
As much as possible, the G-PON system maintains characteristics from Recommendations ITU-T G.982 and ITU-T G.983.x-series. This is to promote backward-compatibility with existing optical distribution networks (ODNs) that comply with those Recommendations.

G-PON systems are characterized, in general, by an optical line termination (OLT) system and an optical network unit (ONU) or optical network termination (ONT) with a passive ODN interconnecting them. There is, in general, a one-to-many relationship between the OLT and the ONU/ONTs, respectively.

2.2.1.1 Network architecture

The G-PON system is targeted to be a very widely deployed solution, with applications in many scenarios and providing many types of services. The scenarios include fibre-to-the-home, building, business, curb and cabinet (see Figure 2.-1). These scenarios differ most fundamentally in the physical location of the ONU, and therefore in the physical layout and characteristics of the ONU. The services include POTS, private lines, TDM circuit emulation, video broadcast, video on demand, file downloads, Internet access, symmetric data networking, and xDSL backhaul. These services tend to bridge over several of the scenarios, and so can be seen as really a menu of all the possibilities, from which each consumer can choose.

The reference configuration is shown in Fig. 2.2-1. Note that this configuration is quite similar to that of the B-PON system (see Figure 2.1-1), as was intended. However, there is a distinct addition, in that additional systems are envisioned to coexist alongside the G-PON system. This is achieved by using WDM components to combine the G-PON wavelengths with the other system wavelengths. When this was originally conceived, the system was mainly assumed to be for the video overlay (as introduced in ITU-T G.983.3). But, later, this was extended to include the next generation of PON. The network element shown in Figure 2.2-1 indicates at present other system equipment, such as video overlay, or future generations of PONs.



ONU	Optical network unit
ONT	Optical network terminal
ODN	Optical distribution network
OLT	Optical line termination
WDM	Wavelength division multiplex module (if WDM is not used, this function is not necessary.)
NE	Network element which uses a different wavelength from the OLT and the ONU
AF	Adaptation function (sometimes, it may be included in the ONU.)
SNI	Service node interface
UNI	User network interface
S	Point on the optical fibre just after the OLT (downstream)/ONU (upstream) optical connection point (i.e., optical connector or optical splice)
R	Point on the optical fibre just before the ONU (downstream)/OLT (upstream) optical connection point (i.e., optical connector or optical splice)
(a) Reference point	If AF is included in the ONU, this point is not necessary.
POINT A/B	If WDM is not used, these points are not necessary.

NOTE – Whether or not the AF is an operating object of the Q interface depends on the service.

Figure 2.2-1 – Reference configuration for G-PON

2.2.1.2 System requirements

The G-PON system has a set of capability requirements for the system as a whole. These include bit rate, reach, delay and split ratio. These requirements were developed in a process that attempted to balance the needs of operators and users against the practical construction of the technology. This section will review each of these with a short discussion of the considerations that led to the choice.

The bit rate of practical G-PON systems is 2.488 Gbit/s downstream, and 1.244 Gbit/s upstream. Note that initially there were seven data rate options, but over time, only two options remain in ITU-T G.984.1, and of these, only the asymmetric rate listed is used. These data rates were selected because the rapid growth of broadband applications made aggregate bandwidths of over 1 Gbit/s necessary (which was really the whole rationale for the G-PON development). In the upstream, the more conservative 1.244 Gbit/s speed was used to economize on the ONU transmitter. However, in the downstream the OLT transmitter is shared, and so the more aggressive 2.488 Gbit/s speed was seen as affordable. This trade-off has indeed proven to be the commercial successful one, as every deployment of G-PON has used this rate combination.

The reach of G-PON systems is somewhat more complex. Within a given optical budget the reach is analysed in three aspects: the physical reach, the logical reach and the differential reach. The physical reach is the maximum distance of fibre between the OLT and ONU, and is limited by effects like fibre dispersion, fibre loss and power split loss. The physical reach must be at least 20 km in most cases. There is an option for a 10 km system; however, this is not used much in practice because it does not offer compelling cost savings over the more capable 20 km version. Many systems can in fact go farther; however, they will not be able to serve as many ONUs at a longer distance. The logical reach is related to the maximum round-trip time delay between the OLT and ONU. This is related to the maximum fibre distance through the speed of light in the fibre. This has implications on the design of the TDMA control logic, and is set to be at least 60 km. The differential reach is the maximum difference in the distance of the ONUs from the OLT on a PON. Again, this has an impact on the TDMA control, and is set to be 20 km in the nominal system (the ITU-T G.984.7 expanded this to 40 km.)

The values of 20 km for physical reach and differential reach where chosen for the reason that current access networks have a topology such that over 90% of the subscribers are within 20 km of their serving central office. Therefore, in a nominal PON deployment where the OLT is being placed at the central office, 20 km reach and reach differential will allow it to connect the vast majority of customers. There is the possibility of reaching subscribers at the neighbouring central offices, and this is the origin of the 60 km logical reach. It is assumed (safely, it turns out) that the normal physical layers will not enable this long reach application, but it was desired that the logical design of the G-PON equipment should support it for possible further improvements of the physical reach in the future.

The practical splitting ratio of 1:64 was chosen, in that many PONs with a relatively short fibre length (5 km is a common value) can be practically constructed with a 1:64 split ratio. However, it was hoped that enhanced optics could enable larger splitting, and so the maximum split ratio was set at 1:128.

Signal transfer delay refers to the amount of time from when a user signal enters the G-PON system on one end to when it exits on the other. This is set to be 1.5 ms, which yields a 3 ms round-trip delay. This value is in keeping with the traditional access allocation of the total end-to-end delay across the telecom network. The primary motivation of this delay allocation is to enable voice services that exhibit good quality, without echo and without bothersome conversational delay.

2.2.1.3 Protection and related topics

There are two recommended protection schemes for G-PON (which was a down-selection from the types in B-PON) (see Section 1.2.5). Type B protection involves duplicating the OLT side of the PON, using a 2:N splitter to bridge the two ports onto a single PON. Type C protection duplicates the entire PON network (OLT, ODN and ONU). Type C is more expensive, but also more capable. In either case, the switching outage speed for exacting services like circuit emulation remains 50 ms. However, some mention is made of slower speeds, such as 120 ms for packetized voice.

NOTE – From the viewpoint of administration of the access network, the protection architecture of G-PON is considered to enhance the reliability of the access networks. However, protection shall be considered as an optional mechanism because its implementation depends on the economical realization of systems.

In the above two protection schemes, it is typical that the two OLT interfaces are located in the same piece of equipment. This makes their control and coordination very simple. However, to achieve even better service availability, it is desirable to locate the OLT ports in separate equipment, and better still, in separate central offices. This possibility of dual parenting resilience is still under discussion in ITU-T.

In a related topic, a new resilience scheme named "external access network backup" is described, wherein a completely different access network can be used to provide a failover capability for the PON. This scheme will likely be much slower in switching, and should properly be described as a means of service restoral, and not protection.

2.2.1.4 Typical equipment designs

The G-PON system can be adapted into many different types of equipment, on both the OLT and ONU ends of the network. The OLT can be a "pure" OLT, which only adapts a common SNI into the G-PON interface, or it can be a "grooming" OLT, which not only terminates the G-PON but also grooms the different traffic types towards different SNIs. The grooming case is shown in Figure 2.2-2.

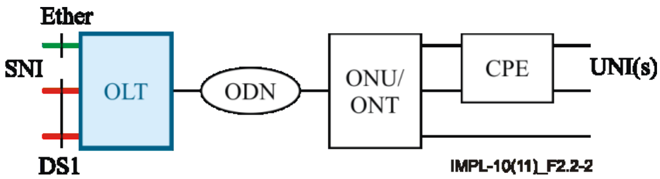


Figure 2.2-2 – Grooming OLT scenario

The ONU can take on many variations. For example, there are the "G-PON modem," "VDSL/POTS," "integrated," and "residential gateway" types of ONU. But certainly there are even more types of ONU that are possible. Figure 2.2-3 shows the "G-PON modem" style of ONU, where the ONT only terminates the G-PON protocol and hands the data flows to a customer premises equipment (CPE). In this solution the ONT is made as small and simple as possible: it resembles a modem that provides layer 1 and 2 interworking between the G-PON optical interface and the data link technology. The data link then carries all service flows to the CPE, which does the bulk of the service interworking function. However it requires auxiliary equipment to provide services other than just pure data.

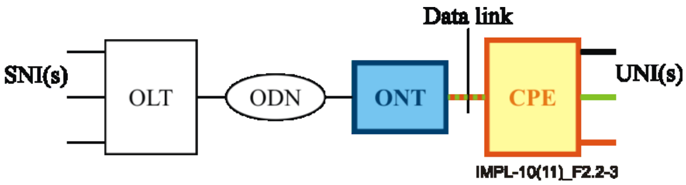
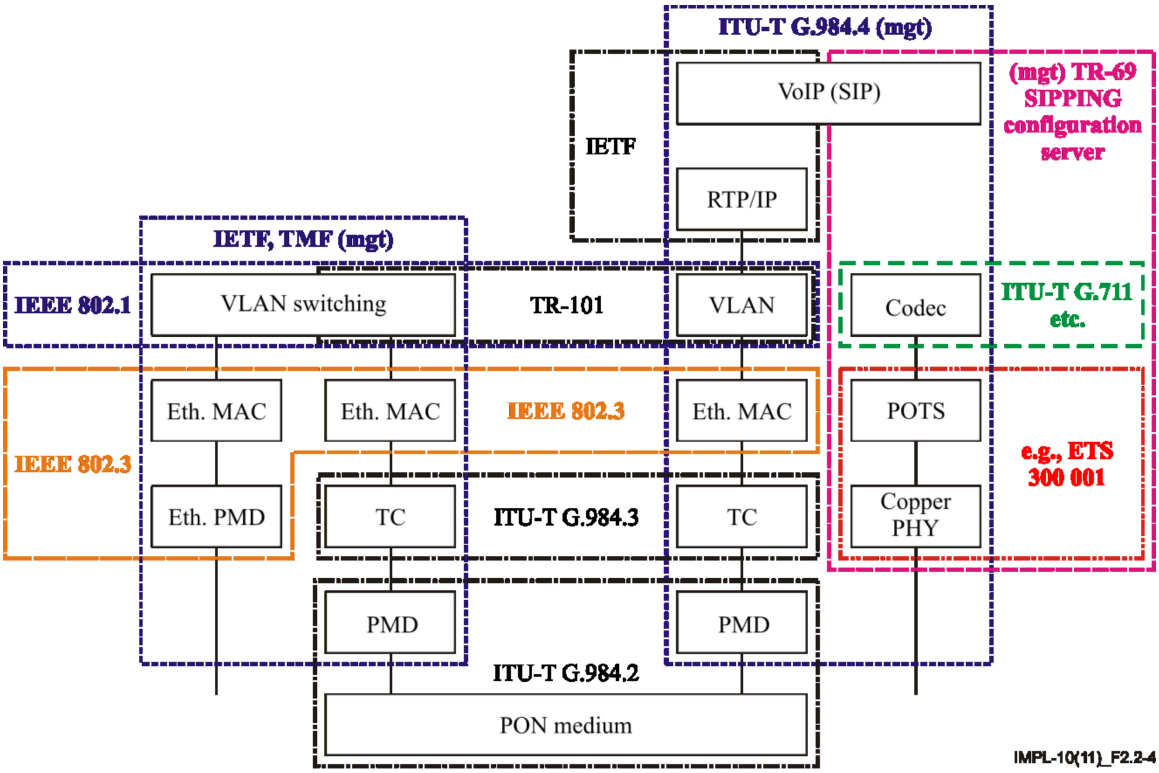


Figure 2.2-3 – GPON modem scenario

2.2.1.5 Typical service protocols

Once again, G-PON is a very general networking system, and virtually any service protocol could be enabled using it. However, as the system was developed and deployed, there was a desire to identify the most active and commonplace service implementations. This was done, and a set of service protocol stack diagrams was developed. Figure 2.2-4 shows an example of such a diagram, in this case for packet voice service. While the details of this particular one are not critical, the main aspects of such diagrams are that they specify the location of each function, the relevant standard describing each function, and the peering relationship between the functions. These diagrams help to greatly reduce the solution space for real G-PON systems, and make the implementation of G-PON systems simpler and more interoperable.



TR-101 = Broadband Forum Technical Report 101
TR-69 = Broadband Forum Technical Report 69
TMF = Telemanagement Forum
IETF = Internet Engineering Task Force
RTP = Real-Ttime Transport Protocol

Figure 2.2-4 – Packet voice service

2.2.2 PMD layer specifications

Editor: Frank J. Effenberger

(For further information see Recommendation ITU-T G.984.2.)

This section describes the physical layer specifications for G-PON. The nominal line rates of 1244.160 Mbit/s and 2488.320 Mbit/s in the downstream direction and 155.520 Mbit/s, 622.080 Mbit/s, 1244.160 Mbit/s and 2488.320 Mbit/s in the upstream direction are described; however, only the 2.488 Gbit/s downstream/1.244 Gbit/s upstream system has seen widespread use. In fact, the detailed budget for this rate combination has been refined in later amendments. The various aspects of physical layer performance are enumerated, and performance levels are given. Also, several aspects of optical performance monitoring are described.

As said above, the G-PON system represents an evolutionary development from the B-PON system. To the greatest extent possible, G-PON maintains the requirements of ITU-T G.983.1 (B-PON) to insure maximal continuity with existing systems and optical fibre infrastructure. The reference points and nomenclature for G-PON remain the same as in B-PON. For example, the optical interface at the ONU is the R/S interface, and the optical interface at the OLT is the S/R interface.

2.2.2.1 Physical medium dependent parameters

The physical layer parameters are given in Recommendation ITU-T G.984.2 in the form of a set of tables. The properties of the optical distribution network (ODN) are given in Table 2a of ITU-T G.984.1. As mentioned above, these parameters follow those given in the B-PON system, and of course meet the requirements given in the preceding section. For the transmitter and receiver, the key to finding the appropriate table is the listing given in Table 2.2-1. Parameters to be defined are categorized by downstream and upstream, and nominal bit rate as shown. By taking the appropriate combination, a link can be composed.

Table 2.2-1 – Relation between parameter categories and tables

Transmission direction	Nominal bit rate	Table within ITU-T G.984.1
Downstream	1244.16 Mbit/s	Table 2b (downstream, 1244 Mbit/s)
	2488.32 Mbit/s	Table 2c (downstream, 2488 Mbit/s)
Upstream	155.52 Mbit/s	Table 2d (upstream, 155 Mbit/s)
	622.08 Mbit/s	Table 2e (upstream, 622 Mbit/s)
	1244.16 Mbit/s	Table 2f-1 (upstream, 1244 Mbit/s) Table 2f-2 (upstream, 1244 Mbit/s)
	2488.32 Mbit/s	Table 2g-1 (upstream, 2488 Mbit/s) Table 2g-2 (upstream, 2488 Mbit/s)

While six different link budgets are tabulated, only two of them have really seen real development and deployment. Those are the 2.4 Gbit/s downstream (ITU-T G.984.1 Table 2c) and 1.2 Gbit/s upstream (ITU-T G.984.1 Tables 2f-1 and 2f-2). ITU-T G.984.1 Table 2f-1 describes a conventional link design, where the transmitter operates at a fixed average power level. At the time of its development, it was feared that the burst mode receiver would have difficulty with the large dynamic range that the PON would create when the ONUs are at short distance from the OLT. Therefore, a scheme termed “power levelling” was developed, wherein a nearby ONU would reduce its transmit power to protect the OLT receiver. The parameters for power levelling are described in Table 2.2-1 (ITU-T G.984.1 Table 2f-2). Over time, it has become clear that power levelling is not needed, and it has not seen any significant use.

It should also be noted that the optical budgets for the 2.4/1.2 Gbit/s system have been updated in an amendment to ITU-T G.984.2 in order to specify the "industry best practice" for a G-PON that meets the B+ optical loss budget that was specified for the B-PON system (Table 2.2-2). On top of this, a single-sided extended budget (i.e., class "C+", or 17 to 32 dB total ODN loss) has been specified (Table 2.2-3). These budgets (or ones similar to them) are the ones actually in use in field deployments today.

NOTE – The single-sided extended 2.488/1.244 Gbit/s G-PON is achieved by using a more capable OLT interface. This interface would have all the characteristics of the existing S/R interface, with the exception of certain OLT optical parameters, as listed in Table 2.2-2.

Table 2.2-2 – Optical power levels for the 2.4 Gbit/s downstream, 1.2 Gbit/s upstream system (Class B+)

Items	Unit	Single fibre
OLT:		**OLT**
Mean launched power MIN	dBm	+1.5
Mean launched power MAX	dBm	+5
Minimum sensitivity	dBm	–28
Minimum overload	dBm	–8
Downstream optical penalty	dB	0.5
ONU:		**ONU**
Mean launched power MIN	dBm	+0.5
Mean launched power MAX	dBm	+5
Minimum sensitivity	dBm	–27
Minimum overload	dBm	–8
Upstream optical penalty	dB	0.5

Table 2.2-3 – Optical power levels for the 2.4 Gbit/s downstream, 1.2 Gbit/s upstream single-sided reach extended system (Class C+)

Item4	Unit	Single fibre
Reach-extended OLT:		**OLT**
Mean launched power MIN	dBm	+3
Mean launched power MAX	dBm	+7
Downstream optical penalty	dB	1
Bit error ratio (pre-FEC) (Note 1)		10^{-4}
Minimum sensitivity (Note 1)	dBm	–32
Minimum overload	dBm	–12
Upstream wavelength range (ITU-T G.984.5)	Nm	1290-1330

ONU:	–	**ONU**
Mean launched power MIN	dBm	+0.5
Mean launched power MAX	dBm	+5
Upstream optical penalty	dB	0.5
Upstream wavelength range (ITU-T G.984.5)	nm	1290-1330
Bit error ratio (pre-FEC) (Note 2)	–	10^{-4}
Minimum sensitivity (Note 2)	dBm	–30
Minimum overload (Note 3)	dBm	–8
NOTE 1 – The OLT sensitivity assumes the use of the optional Reed Solomon (R-S) (255,239) FEC capability of the G-PON TC layer, as well as intrinsic detector technology improvements, e.g., semiconductor optical amplifier (SOA) pre-amplification. NOTE 2 – The ONU sensitivity assumes the use of the optional R-S (255,239) FEC capability of the G-PON TC layer with the current class B+ ONU detector technology. NOTE 3 – The ONU overload is set at –8 dBm to be common with the class B+ value, even though in this application –10 dBm is sufficient.		

2.2.2.2 Interactions with the TC layer

For the most part, the physical layer's task is to relay bit streams from the TC layer of the transmitter to that of the receiver without change. However, there are a few exceptions to this in the G-PON system. These include the use of forward error correction (FEC), power levelling and burst mode performance.

The first interaction is with FEC. While FEC is implemented at the TC layer, it impacts the physical layer. The essential fact is that the physical layer can be operated at a lower bit error rate than otherwise required. The status of the FEC function is that it is optional, and so a G-PON system not otherwise specified should be able to deliver the optical performance specified in Table 2 of ITU-T G.984.2 without using FEC. In the initial phase of development, it was thought that a good use of FEC would be to permit the use of multi-longitudinal mode lasers at 20 km and at 1.244 Gbit/s. Such lasers will exhibit a very large mode-partition noise penalty, but the introduction of FEC can neutralize this penalty. As time went on, however, single mode lasers have proven to be cost effective, and so using FEC for this purpose is not necessary. On the contrary, the introduction of the C+ loss budget places pressure on the loss budget (because C+ has a 4 dB larger loss than B+). This increase in budget is now a popular way to take advantage of the gain one can achieve using FEC.

The second interaction is power levelling. As mentioned above, there was some concern that the normal output power of the ONU might overload the OLT receiver when the ONU is at close range. Even worse, this overload might even permanently damage the receiver. The power levelling feature was introduced to handle this problem. The details of the action of power levelling are developed, foreseeing the ONU with the capability of transmitting at normal power, 3 dB lower power, and 6 dB lower power. It was estimated that three levels spaced 3 dB apart was the practical limit for cost-effective ONU transmitters. The details of the control protocol are described in ITU-T G.984.2, including how the ONU should first activate on a PON, and how it should respond to OLT requests during operation. With all of that stated, it has turned out that power levelling is not needed. The OLT receivers are indeed quite capable of handling the ONU at maximum power and minimum link loss. Therefore, this optional feature has not seen widespread implementation.

The third interaction is the burst mode timing. The fundamental function that makes a TDMA PON special is the use of burst mode optical transmission. In the B-PON system, the upstream ran at 155 Mb/s, which was low enough to make many receiver methods possible, and quite aggressive burst mode timing possible (i.e., B-PON specifies the gap between valid data receptions only 24 bits long). In the G-PON system, the data rate is raised to 1.244 Gbit/s, which starts to be a more challenging speed range. Therefore, consideration of proper burst mode timing parameters was required. This is a trade-off problem. A very short burst overhead timing will be efficient, but it will make the optical transceivers more expensive. A long burst overhead can allow easier and cheaper optics, but it will be inefficient. In G-PON, the design choice was made to target fairly aggressive burst timing parameters. The recommended values are given in Table 2.2-4. Current systems comply with these parameters; however, early implementations exhibited some issues with the OLT preamble time. For this reason, additional flexibility was added to the system, with a new extended overhead PLOAM message being defined to inform the ONUs that additional preamble time is required.

Table 2.2-4 – Recommended allocation of burst mode overhead time for OLT functions

Upstream data rate (Mbit/s)	Tx enable (bits)	Tx disable (bits)	Total time (bits)	Guard time (bits)	Preamble time (bits)	Delimiter time (bits)
155.52	2	2	32	6	10	16
622.08	8	8	64	16	28	20
1244.16	16	16	96	32	44	20
2488.32	32	32	192	64	108	20
Notes	Maximum	Maximum	Mandatory	Minimum	Suggested	Suggested

2.2.3 G-PON transmission convergence layer specification

Editor: Denis A. Khotimsky

(For further information see Recommendation ITU-T G.984.3.)

This section describes the transmission convergence layer of Gigabit-capable passive optical network systems. Its scope includes the description of the G-PON transmission convergence (GTC), the adaptation sublayer and of the GTC framing sublayer. The content of this section is mainly based on Recommendation ITU-T G.984.3.

NOTE – The ITU-T G.984.3 was originally approved in 2004 providing support for both the asynchronous transfer mode (ATM) encapsulation method and system-specific G-PON encapsulation method (GEM). The Recommendation was comprehensively revised in 2008. While the revision kept the major features intact, it integrated a set of maintenance amendments, deprecated the ATM encapsulation method, eliminated certain options that had not been used in industry practice, introduced a reference model for the dynamic bandwidth assignment (DBA), and generally streamlined the presentation. The subsequently approved amendments of February 2009 and November 2009 specified the ONU registration method and Time-of-day distribution mechanism.

2.2.3.1 G-PON system overview

The Gigabit-capable passive optical network (G-PON) system uses time-division multiplexing in the downstream direction and time-division multiple access in the upstream direction. It operates over a power-splitting ODN, providing two nominal rate options: an asymmetric rate option of 2.48832 Gbit/s downstream/1.24416 Gbit/s upstream, and a symmetric rate option of 2.48832 Gbit/s downstream/2.48832 Gbit/s upstream. In practice, the industry opted for the asymmetric rate option only.

The G-PON system is synchronous in that in the downstream direction it transmits a continuous stream of fixed-length 125 µs GTC frames with well-defined structure. The notion of a GTC frame is retained in the upstream direction as well, but in this case the frames do not have a well-defined structure, but rather provide a convenient sequence of timing reference points.

While multiple ONUs are using essentially the same medium to communicate with the OLT, the OLT tightly controls the timing of the upstream transmissions by individual ONUs in order to avoid overlaps and interference between them (see Figures 2-1 and 2-2).

The G-PON system can transport multiple traffic types using the G-PON encapsulation method (GEM). Whereas the corresponding mappings are defined for Ethernet, Internet protocol (IP), multiProtocol label switching (MPLS), synchronous digital hierarchy (SDH), and time division multiplexing (TDM) data, the primary transported protocol in practice is Ethernet.

Coexistence between G-PON and the earlier generation of the TDM/TDMA PON system, B-PON, is not provided.

2.2.3.2 G-PON transmission convergence layer, sublayers and functions

ITU-T G.984.3 identifies two sublayers of the G-PON transmission convergence (GTC) protocol stack: the adaptation sublayer and the framing sublayer. The layered structure of the GTC protocol stack is shown in Figure 2.2-5. Note that, like most other layered models, this model may contain abstractions, generalizations, and undocumented exceptions. There is a distinction between the user data plane and the control/management plane, but because of uniform framing and uniform GEM for data and management flows, this division remains largely academic.

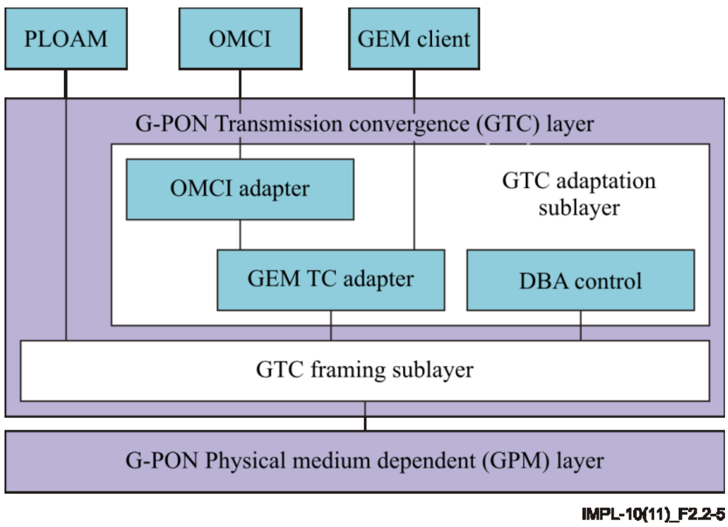


Figure 2.2-5 – GTC protocol stack sub-layering

The GTC layering structure is applicable to both the OLT and ONU sides of the communication link.

The GTC adaptation sublayer (or more accurately, service adaptation sublayer) is primarily concerned with conversion between the upper layer protocol service data units (SDUs), indicated in the figure as GEM client, and the GTC payload (output of the GTC adaptation sublayer). The key functions of the GTC service adaptation sublayer are SDU encapsulation, fragmentation, multiplexing and delineation in the course of transmission over PON. Its central concept is a G-PON encapsulation method (GEM) frame. A GEM frame contains an upper layer protocol SDU, an OMCI packet, or a fragment of an SDU or OMCI packet, and associates it with a logical port identified by the GEM Port-ID.

The GTC framing sublayer exchanges GTC payloads with the GTC framing adaptation sublayer and is primarily concerned with construction, parsing and processing of the overhead fields that support necessary PON management functions. The key functions of the GTC framing sublayer fall into two groups. One group includes functions that are related to logical management: upstream multiparty medium access control, dynamic bandwidth assignment (DBA) control and PLOAM messaging channel support. The functions in the other group are related to improving the detection, reception and delineation properties of the physical signal transmitted over an optical link: downstream and upstream synchronization, forward error correction (FEC) and scrambling. While it would be possible to isolate these groups into two separate sublayers (as it has been done later in XG-PON), Recommendation ITU-T G.987.3 considers them on the same level of the protocol stack.

2.2.3.3 GTC framing sublayer

2.2.3.3.1 Downstream framing

The structural unit of the downstream traffic flow in G-PON is a 125 µs GTC frame. The GTC frames are transmitted continuously by the OLT towards the ONUs. The format of a GTC frame depends on whether or not FEC is enabled in the downstream direction. The structure of a downstream GTC frame, before FEC is applied, is shown in Figure 2.2-6.

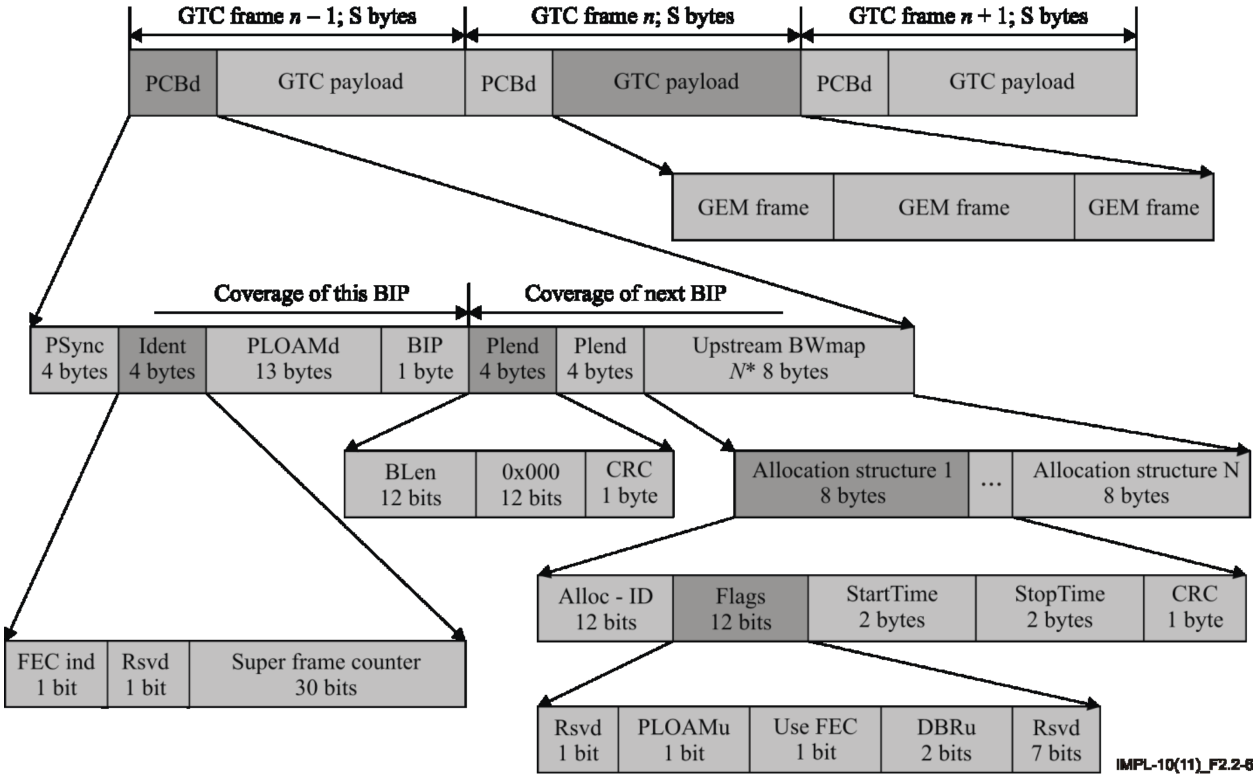


Figure 2.2-6 – Downstream GTC frame

A pre-FEC GTC frame has a fixed size of *S*, where the value of *S* is exactly 38 880 bytes, if FEC is not enabled, and exactly 36 432 bytes, if FEC is enabled. Each downstream GTC frame contains a header known as downstream physical control block (PCBd) and GTC payload. The GTC payload comprises a sequence of GEM frames. The format of GEM frames, which are used to encapsulate upper layer protocol SDUs and OMCI traffic in both the downstream and upstream directions, is reviewed in Section 2.2.3.4.

The PCBd block contains six fixed length-fields and a variable length bandwidth map. The fields and their functions are as follows:

- PSync (4 bytes) is a fixed pattern that is used by the ONUs to synchronize to the downstream frame flow.
- Ident (4 bytes) carries attributes of the GTC frame itself and contains three subfields:
  - FEC Ind (1 bit) confirms whether FEC is applied in the downstream direction; while the indication is per-frame, changing the FEC encoding status is not meant to be done on a per-frame basis, and may cause a loss of data.
  - Rsvd (1 bit) is a reserved field.
  - Superframe counter (30 bits) increments with every GTC frame and provides GTC frame identification to the ONUs.
- PLOAMd (13 bytes) is the downstream physical layer OAM messaging channel.
- BIP (1 byte) is a bit-interleaved parity (BIP) byte for the preceding (*S*-1) bytes of the downstream flow; the scope of BIP crosses the frame boundary as shown in Figure 2.2.6.
- Plend (4 bytes) controls the length of the variable section of the frame header. As knowing the size of the variable header is critical for correct parsing of the frame, this field is protected by the cyclic redundancy code (CRC) and transmitted twice for extra robustness. It contains the following subfields:
  - BLen (12 bits) contains the length of the bandwidth map expressed as a number of the allocation structures.
  - Alen (12 all-zero bits) is a reserved field that in the earlier version of the standard carried the length of the presently deprecated ATM partition.
  - CRC (8 bits) is a cyclic redundancy check code on the Plend structure.
- BWmap (N * 8 bytes) is variable length sequence of allocation structures for upstream transmissions, whose length N is specified by the BLen field above. An allocation structure is 8-byte long and contains the following fields:
  - Alloc-ID (12 bits) identifies the recipient of the upstream bandwidth allocation.
  - Flags (12 bits) controls the format of the corresponding upstream transmission; out of 12 available bits, only four are presently defined to provide three indication fields (bits 0..6 and 11 are reserved):
  - PLOAMu (bit 10) instructs ONU to send an upstream PLOAM message; ONU must comply with both positive and negative indication, but may use an empty (No_Message type) PLOAM, when no functional PLOAM message is awaiting transmission.
  - Use FEC (bit 9) instructs ONU to apply FEC to the upstream transmission; for a given ONU, the value must be the same for all allocations within a burst, but may occasionally change from one burst to another; the ONU must comply with negative

indication, but may ignore positive indication (if it is unable to support FEC encoding), signalling this fact in the overhead of the upstream burst.

– Send dynamic bandwidth report upstream (DBRu) (bit 8 and 7) instructs ONU to send a dynamic bandwidth assignment (DBA) buffer status report per individual allocation using the appropriate format mode; ONU must comply including an appropriately formatted field into upstream transmission.
– StartTime (2 bytes) points to a byte position within the upstream GTC frame where the allocation transmission must begin; for the first allocation of a burst, the burst preamble, the burst delimiter and the burst header are transmitted immediately prior to the StartTime byte position.
– StopTime (2 bytes) points to a byte position within the upstream GTC frame where the allocation transmission must end.
– CRC (1 byte) is a cyclic redundancy check code on the allocation structure.

2.2.3.3.2 Downstream FEC

OLT applies forward error correction on the downstream transmission at its discretion, usually with the goal to effectively increase the link optical budget while sacrificing approximately 7% of the effective downstream data rate. FEC uses Reed-Solomon (R-S) (255, 239) block code.

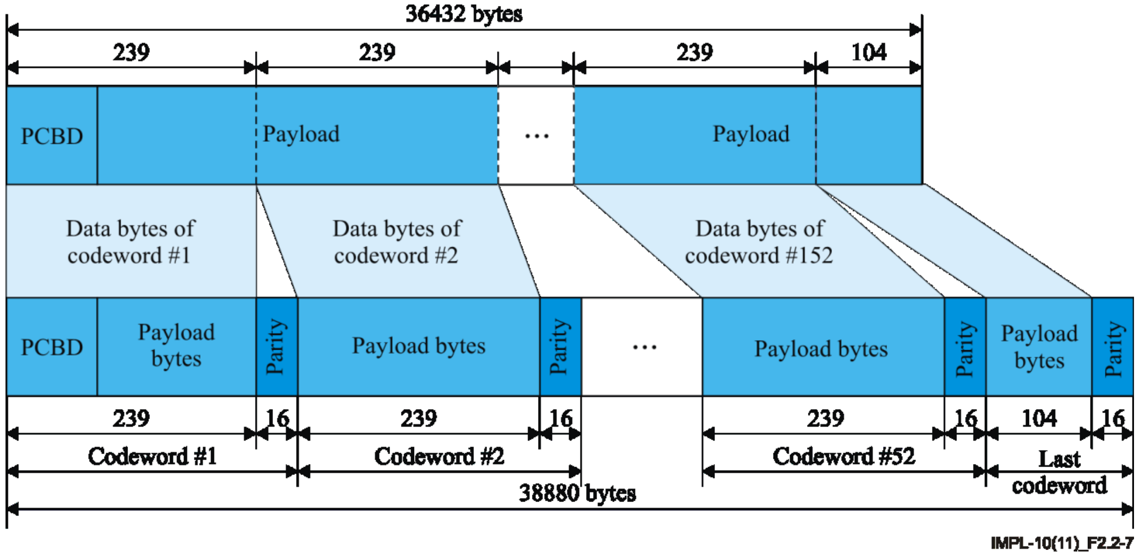


Figure 2.2-7 – Downstream FEC calculation

When FEC is enabled, each pre-FEC GTC frame of the size S = 36 432 bytes is partitioned into data blocks of 239 bytes each (Figure 2.2-7). There are 152 full-size data block and the last short data block of 104 bytes. The last short block is prepended with 135 zero bytes. Sixteen parity bytes are computed for each data block and appended to the data block forming a 256-byte code word. Following the removal of the 135 bytes of padding from the last code word, a post-FEC GTC frame of 38 880 bytes is obtained, which is used for downstream transmission.

2.2.3.3.3 Downstream scrambling

Downstream scrambling is a mandatory operation that is applied to the bit stream to improve the pattern of zeros and ones and thus to mitigate the adverse effects of the long strings of identical digits on the optical link transmission.

Immediately prior to passing to the PMD layer, the 38 880-byte downstream GTC frame is scrambled using a well-known pattern generated by the polynomial x^7+x^6+1. The scrambling pattern is added modulo 2 to the data starting at the first bit following the PSync field of the PCBd.

2.2.3.3.4 Upstream framing

The structural unit of the upstream traffic flow in G-PON is a GTC burst, a single uninterrupted upstream transmission by an ONU. A burst may contain multiple allocations pertaining to different traffic sources or queues within an ONU. The time instants when an ONU starts and finishes transmission of each allocation and, therefore, a GTC burst as a whole are specified by the OLT. The structure of an upstream GTC burst, before FEC is applied, is shown in Figure 2.2-8.

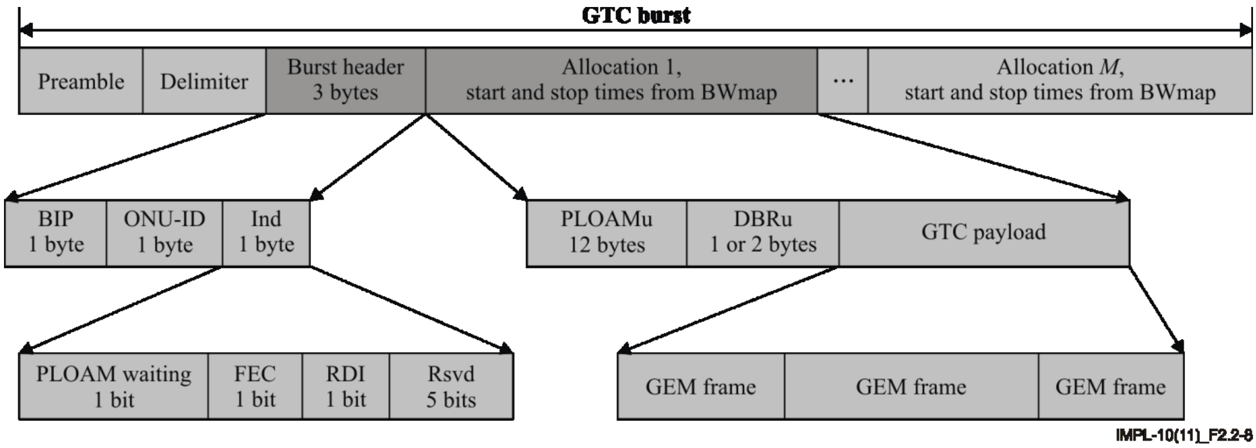


Figure 2.2-8 – Upstream GTC burst

The GTC burst comprises the preamble and delimiter, the burst header and a series of allocation intervals, the number of which is inferred from the BWmap. The post-FEC size of the GTC burst is inferred from the BWmap by summing up the lengths of contiguous allocations forming the burst and adding the 3 bytes of the burst header length and well-known size of the preamble and delimiter. The fields and their functions are as follows.

- Preamble (the length and structure determined by the OLT) is a well-defined bit pattern that allows the OLT receiver to adjust to the 0 and 1 levels in the optical signal and to recover the clock.
- Delimiter (16 to 24 bits) is a well-defined bit pattern that allows the OLT receiver to delineate the start of the burst header.
- Burst header (3 bytes) comprises identification and control data that pertain to the ONU as a whole; it contains three fields:
  - BIP (1 byte) is a bit-interleaved parity byte whose scope covers the preceding burst of the same ONU.
  - ONU-ID (1 byte) is a unique identifier of the ONU on the given PON port.
  - Ind (1 byte) provides signalling information to OLT; out of 8 available bits, only 3 are presently defined (bits 0..4 are reserved):
    - PLOAMu waiting (bit 7) indicates to the OLT that an upstream PLOAM message is pending transmission.
    - FEC status (1 bit) indicates to the OLT whether or not FEC has been applied to the upstream burst.
    - RDI status (1 bit) provides remote defect indication to the OLT.

- Allocation interval is an upstream transmission associated with a particular traffic-bearing entity within the ONU; its position within the upstream GTC frame, size and format are specified by the corresponding allocation structure of the BWmap; the allocation interval may contain:
  - PLOAMu (13 byte) is the upstream physical layer OAM message which is included into the allocation in response to PLOAMu flag of the BWmap allocation structure.
  - DBRu (1 or 2 bytes) the dynamic bandwidth assignment buffer occupancy report which is included into the allocation in response to the Send DBRu indication of BWmap allocation structure.
  - GTC Payload comprises a sequence of G-PON Encapsulation Mode (GEM) frames. The format of GEM frames, which are used to encapsulate upper layer protocol SDUs and OMCI traffic in both the downstream and upstream directions, is reviewed in Section 2.2.3.4.

2.2.3.3.5 Upstream FEC

OLT requests forward error correction to be applied to the upstream transmission on its discretion, usually with the goal to effectively increase the link optical budget while sacrificing at least 7% of the effective upstream data rate. FEC uses Reed-Solomon (R-S) (255, 239) block code.

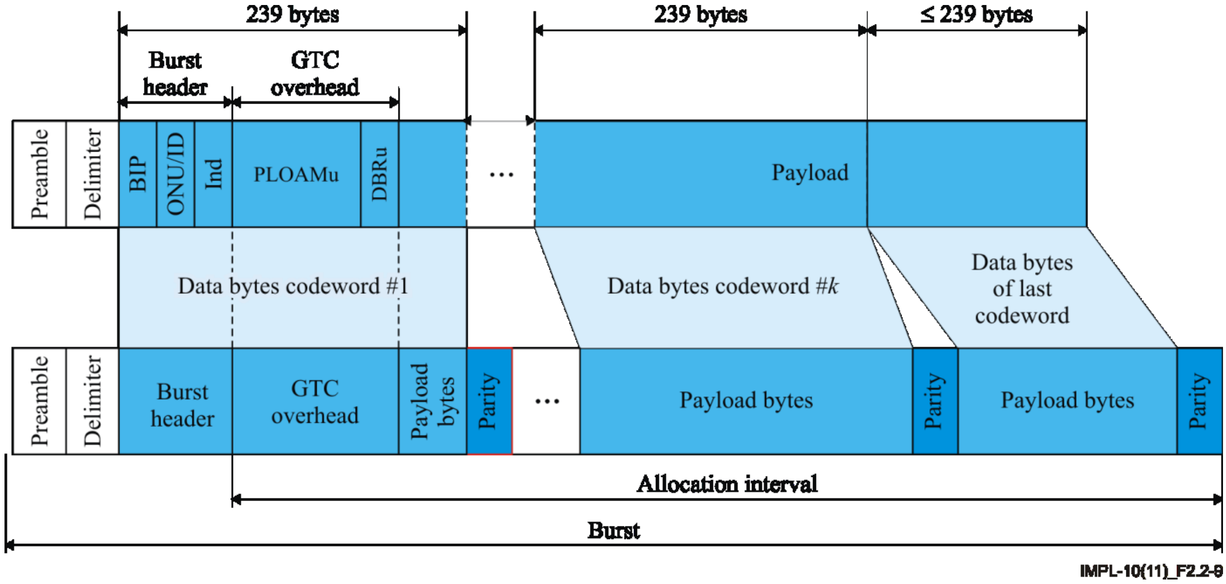


Figure 2.2-9 – Downstream FEC calculation

When FEC is enabled in the upstream, the ONU computes the number of code words and the overall size of the pre-FEC data from the GTC burst size inferred earlier from the BWmap (less the size of preamble and delimiter), as shown in Figure2.2-9. For each 239-byte data block and, possibly, the last short data block with prepended zero padding, sixteen parity bytes are computed and appended to the data block forming a 256-byte code word. Following the removal of the padding, if any, from the last code word a post-FEC GTC burst is obtained.

If the OLT enables upstream FEC for an ONU, it must ensure that the boundaries of the contiguous allocations within a burst do not fall on the FEC parity bytes (more precisely, the StartTime pointer should not point to a FEC parity byte), as doing the opposite may confuse the ONU and lead to unpredictable effects.

Note that in ITU-T G.987.3 this limitation is naturally avoided, as a burst is specified with a single StartTime in the BWmap.

2.2.3.3.6 Upstream scrambling

Upstream scrambling is a mandatory operation that is applied to the bit stream to improve the pattern of zeros and ones and thus to mitigate the adverse effects of the long strings of identical digits on the optical link transmission.

Immediately prior to passing to the PMD layer, the upstream GTC frame is scrambled using a well-known pattern generated by the polynomial x^7+x^6+1. The scrambling pattern is added modulo 2 to the data, starting at the first bit of the BIP filed of the burst header.

2.2.3.4 GTC adaptation sublayer

2.2.3.4.1 Construction of the GTC payload

The process of conversion between the upper layer protocol SDUs and the GTC payloads is nearly the same for the upstream and downstream direction. The available size of the GTC payload is provided by the GTC framing sublayer.

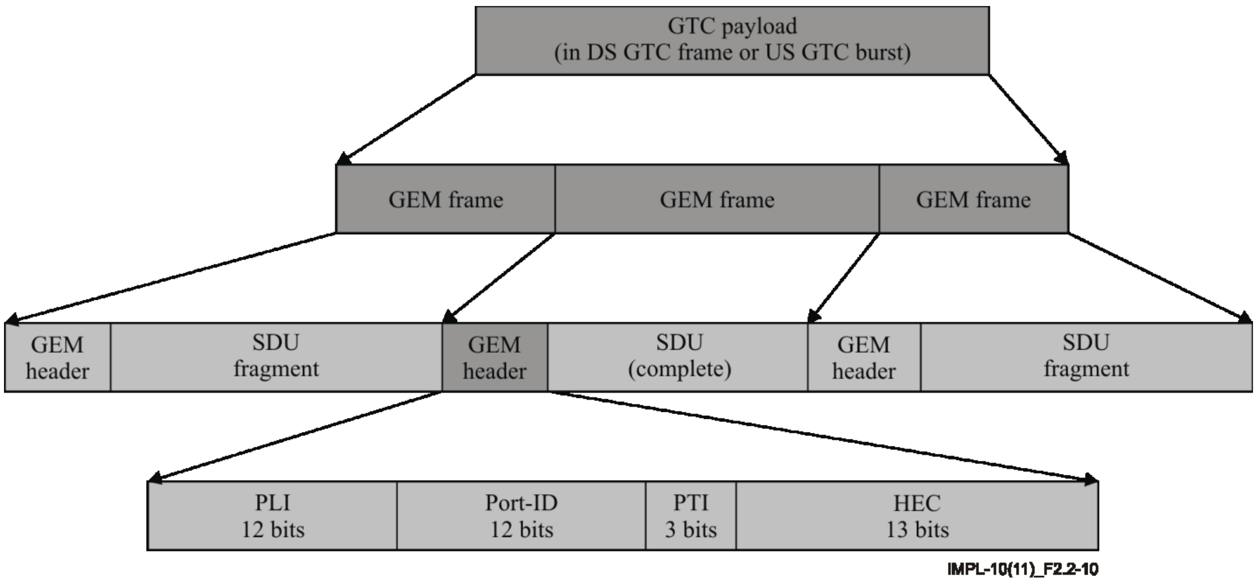


Figure 2.2-10 – GTC payload construction

The GTC payload comprises a sequence of GEM frames, encapsulating upper layer protocol SDUs and OMCI packets or fragments thereof. A GEM frame has the following format (Figure 2.2-10):

GEM header (5 bytes) is a protected structure that supports SDU multiplexing, fragmentation and delineation; it contains four fields:

– PLI (12 bits) provides GEM Payload Length Indication.

– Port-ID (12 bits) provides a traffic flow IDentifier for multiplexing and demultiplexing of up to 4096 flows.

NOTE – Traffic flow is a sequence of data packets, frames or other similar structural data units that follow the same route or cross the same interface and share some common characteristic, such as source, destination, class of service, etc.

– PTI (3 bits) is a Payload Type Indicator that had been inherited from ATM, but in practice the only supported function of the PTI is to distinguish between the last (or only) fragment of an SDU and an intermediate fragment of an SDU.

– HEC (13 bits) field is a combination of Bose-Chaudhuri-Hocquengham (BCH) (39, 12, 2) error-correcting code and a single parity bit.

The presence of PLI in the GEM header allows the receiver to delineate a continuous stream of GEM frames by walking from one GEM header to another. HEC validation confirms that the next GEM frame has been found correctly. Recommendation ITU-T G.984.3 provides for a possibility to restore GEM frame synchronization within the same GTC payload, once frame delineation is lost.

The SDU fragmentation is allowed in two situations: when the available GTC payload is insufficient to accommodate the entire SDU, and when a time-sensitive SDU arrives for transmission behind a lower priority SDU. In the latter case, the time-sensitive SDU may pre-empt the lower priority SDU that has already commenced transmission.

2.2.3.4.2 GEM payload encryption

Data encryption is supported in the downstream direction only, where traffic flow is naturally accessible to all ONUs on the PON. According to the adopted threat model, the upstream direction is assumed inherently secure.

Only the GEM frame/fragment payload is encrypted. The GEM header is not encrypted. Encryption applies to the specific GEM Port-ID identified via the PLOAM channel.

The encryption system employs the 128-bit Advanced Encryption Standard algorithm (AES-128) operating in the counter (CTR) mode. In this mode the AES-128 engine operates on a well-defined and reproducible stream of unique data blocks (a sequence of counting values presents an example of such a stream, hence the name), rather than on the plain text data block themselves. The encrypted counter stream blocks are added modulo 2 to the plain text data blocks.

The reproducible counter stream is derived from the superframe counter identifying the downstream GTC frames, and the intra-frame counter that is reset to zero at the first byte of PCBd and is incremented every 4 bytes. The encryption keys are generated by each respective ONU and are conveyed to the OLT, in the clear, using the PLOAM channel. As an additional security measure, the OMCI specification (Recommendation ITU-T G.988) contains provisions to implement a symmetric-key-based three step authentication procedure that allows the OLT and the specific ONU to establish a shared secret, the master session key (MSK). In a system supporting this feature, an ONU can transmit the newly generated traffic encryption key with the MSK.

2.2.3.4.3 Upstream multiple access control

A key function of the GTC layer is the medium access control in the upstream direction. Each of the GTC frames that form a continuous flow in the downstream direction contains an overhead field, known as downstream physical control block (PCBd), which carries an upstream bandwidth map (BWmap). A BWmap is a collection of pointers indicating the time at which each ONU may begin and end an upstream transmission associated with a particular traffic-bearing entity identified by Alloc-ID. Whereas each ONU may lie on a different fibre distance from the OLT and, therefore, may have a different round-trip time, the OLT constructs the BWmap in such a way that the upstream bursts from different ONUs arrive at the OLT without overlap. The BWmap pointers are given in the units of bytes and refer a particular location within the upstream GTC frame, whereas each ONU is able to precisely identify the start of an upstream GTC frame with reference to the corresponding received downstream GTC frame. Note, however, that because of the varying fibre distance, each ONU has a generally unique view on the start of the downstream and upstream GTC frames. The concept of G-PON medium access control is illustrated in Figure 2.2-11.

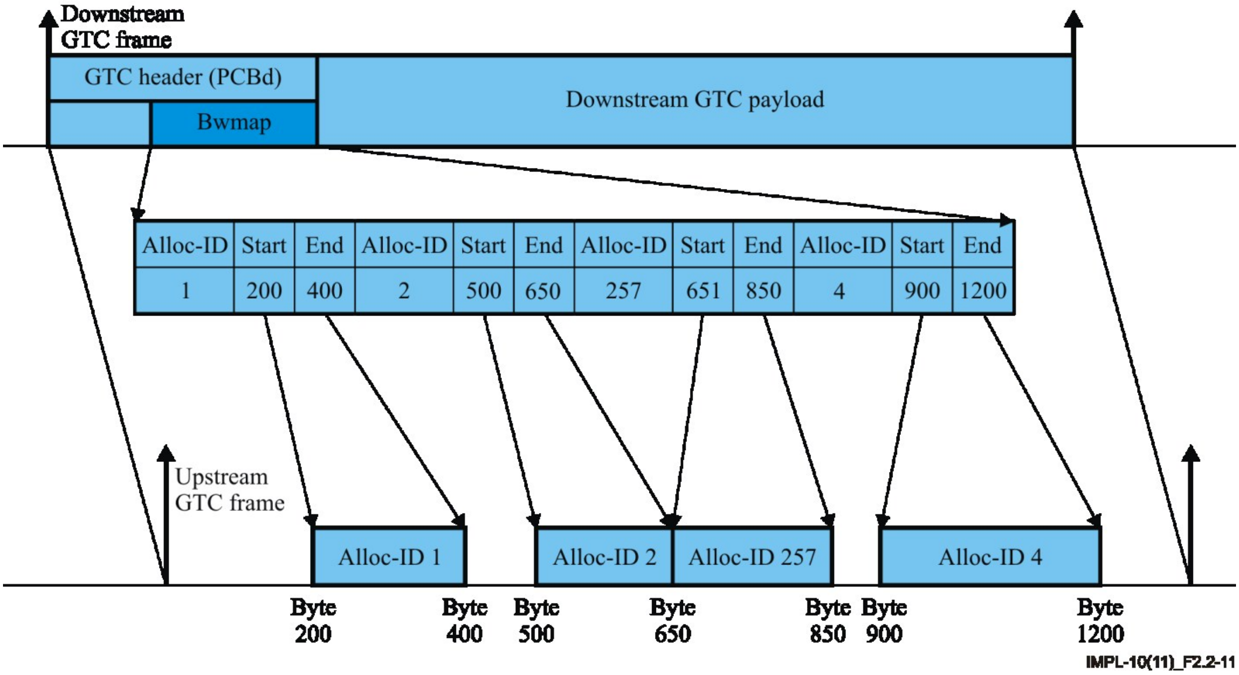


Figure 2.2-11 – GTC medium access control

When constructing a BWmap, the OLT must adhere to several rules.

The allocations to the same ONU within a single burst must be exactly contiguous: the StartTime of the subsequent allocation structure points to the next byte after the StopTime of the preceding allocation structure.

The allocation structures belonging to adjacent bursts (to different ONUs) must be sufficiently spaced to accommodate the guard time, the preamble and delimiter as well as the burst header of the subsequent GTC burst.

If the upstream FEC is enabled, the OLT must ensure that the StartTime of an allocation does not point to the parity bytes within the GTC burst payload.

Finally, a somewhat artificial rule prohibits an allocation from crossing the GTC frame boundary.

NOTE – Recognizing that the upstream GTC frame boundaries are just the timing reference points that are not associated with any format feature or repeated structure, in ITU-T G.987 XG-PON this rule was eliminated.

2.2.3.5 PLOAM messaging channel

A physical layer OAM (PLOAM) message field is present in each downstream GTC frame and, on OLT request, can be present in an upstream GTC burst. The PLOAM messaging channel supports such functionality as ONU activation, ONU configuration and OMCI channel setup, encryption configuration, data encryption key management and alarm signalling. The PLOAM message format, which is common for the upstream and downstream direction, is shown in Figure 2.1-12.

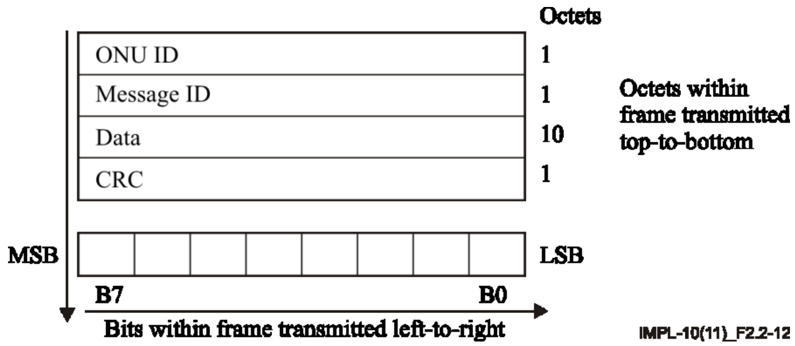


Figure 2.1-12 – PLOAM message format

The format is structured as follows:

ONU-ID (1 byte) is a unique identifier of the ONU (sender in the upstream, receiver in downstream) on the given PON port. The special ONU-ID code points allow for addressing all connected ONUs in the downstream and identifying a newly active ONU that has not yet been assigned an ONU-ID in the upstream.

Message type (1 byte) specifies the functionality of the PLOAM message and defines the inner format of the message data field. Eighteen PLOAM message types are defined in the downstream and nine in the upstream.

Message data (10 bytes) is the body of the PLOAM message; its format is dependent on the message type and may be entirely or partially padded.

CRC (1 byte) is a cyclic redundancy check code on the PLOAM message.

2.2.3.6 Dynamic bandwidth assignment

Dynamic bandwidth assignment (DBA) in Gigabit-capable passive optical networks (G-PONs) is the process by which the optical line terminal (OLT) reallocates the upstream transmission opportunities to the traffic-bearing entities within optical network units (ONUs) based on the dynamic indication of their activity status and their configured traffic contracts. The activity status indication can be either explicit through buffer status reporting, or implicit through transmission of idle GEM frames in place of granted upstream transmission opportunities.

In comparison with static bandwidth assignment, the DBA mechanism improves the G-PON upstream bandwidth utilization by reacting adaptively to the ONUs bursty traffic patterns. The practical benefits of DBA are twofold. First, the network operators can add more subscribers to the PON due to more efficient bandwidth use. Second, the subscribers can enjoy enhanced services, such as those requiring variable rate with the peaks extending beyond the levels that can reasonably be allocated in a static fashion.

Dynamic bandwidth assignment process, as a standard feature in the context of passive optical networks, was first introduced by Recommendation ITU-T G.983.4 (2001), which was an additional specification for the broadband PON (B-PON) family of standards. For Gigabit PON (G-PON), the DBA process was defined within Recommendation ITU-T G.984.3 (2004), which is the main G-PON transmission convergence layer specification. The ITU-T G.984.3 (2004) specification defined two DBA methods: status reporting and traffic monitoring, provided options for three DBA signalling mechanisms and three status reporting format modes. The revised Recommendation ITU-T G.984.3 (2008) undertook major overhaul of the standard through reduction of the option space. The only signalling mechanism, piggyback reporting as well as two format modes, remained in the standard. The revised ITU-T G.984.3 (2008) also introduced a formal model for dynamic bandwidth assignment. This is a fluid reference model that for the given traffic load allows for obtaining the ideal bandwidth assignment under specific isolation and fairness criteria. It is by no means a DBA algorithm, but rather a target that can be approximated by a practical DBA algorithm.

The central concept of DBA is a transmission container, or T-CONT. A T-CONT is a managed entity within the ONU that accommodates one or more physical queues and aggregates these queues into a single logical buffer. At the transmission convergence protocol layer, each T-CONT is represented by the corresponding allocation identifier (Alloc-ID). In this section the two terms are interchangeable. An ONU may contain multiple T-CONTs, but a T-CONT may not span multiple ONUs.

A T-CONT with its associated logical buffer represents the highest granularity traffic flow unit to which an upstream transmission opportunity granted by the OLT is applied. Accordingly, under the explicit buffer occupancy reporting method, a T-CONT is also representing the most granular traffic flow unit for which the traffic load demand needs to be estimated by the OLT. The traffic demand (or offered load) is estimated through the logical buffer occupancy. The ONU provides the indication of the buffer occupancy either explicitly through buffer status reporting (status reporting DBA method), or implicitly through transmission of idle slots in place of granted upstream transmission opportunities (traffic monitoring DBA method).

The DBA task at the OLT can be viewed as twofold. First, the OLT performs bandwidth assignment for each T-CONT, which is a relatively slow process that uses the traffic demand estimates obtained through status reporting or traffic monitoring. Second, the OLT performs bandwidth allocation by computing the bandwidth map (BWmap) for each upstream frame and broadcasting it on the PON. The BWmap is a scalar array of allocation structures, where each allocation structure is addressed to a specific T-CONT and specifies the exact timing of the T-CONT's upstream transmission. This is a fast process that is performed on frame-by-frame basis and employs the slowly changing assigned bandwidth values.

Recommendation ITU-T G.984.3 retains two DBA format modes, mode 0 (single byte) and mode 1 (two byte). However, the utility of mode 1 buffer occupancy reporting depends on the fairness model.

2.2.4 Enhanced wavelength bands

Editor: Frank J. Effenberger

(For further information see Recommendation ITU-T G.984.5.)

The physical layer for G-PON was originally designed to achieve the lowest cost system solution. As time progressed, it was observed that for a negligible cost increment some additional future-proofing capabilities could be added. This section describes those enhancements.

The major new features that are described are:

Wavelength ranges reserved for additional service signals to be overlaid via wavelength division multiplexing (WDM) in future passive optical networks (PON) for maximizing the value of optical distribution networks (ODNs).;

X/S (interference signal(s)/optical power of the basic band signal) tolerance of the ONUs, to minimize the effect of interference signals;

Example parameters of a discrete WDM filter that combines and isolates the G-PON up/down signals and enhancement bands at the OLT side;

Examples of wavelength allocation for next generation-access (NGA) services and video distribution services.

2.2.4.1 Wavelength ranges to be reserved

The physical media-dependent (PMD) layer specification for G-PON in the absence of an enhancement band is defined in ITU-T G.984.2. PMD layer specifications for G-PON in the presence of enhancement bands are defined by the combination of ITU-T G.984.2 and ITU-T G.984.5. Whenever a parameter specified in ITU-T G.984.2 is not explicitly mentioned in ITU-T G.984.5, its value given in ITU-T G.984.2 remains valid. Whenever a parameter is specified in both ITU-T G.984.2 and ITU-T G.984.5, the specification in ITU-T G.984.5 takes precedence.

The wavelength ranges are diagrammed in Fig.2.2-13. There are three variable elements to consider. The first is on the upstream wavelength. There are three options that are defined. The originally defined G-PON upstream band (1260 nm to 1360 nm) is named the “regular” band. A somewhat narrower 1290 nm to 1330 nm spectrum is named the “reduced” band. It was observed that all practical G-PON ONUs were based on distributed feedback (DFB) lasers and all of these ONUs had a spectrum that fit within the “reduced” band. It is safe to assume, therefore, that all deployed G-PONs comply with the reduced band specification. An even more aggressive 1300 nm to 1320 nm “narrow” band is defined. This is also achievable at a modest cost increment.

The next variable element has to do with the spectrum in the 1400 nm range. If the ODN is constructed with low water content fibre, then the band of usable wavelengths stretches from 1400 nm to 1450 nm. If older fibre that contains appreciable water content is deployed (with an attenuation peak around 1390 nm), then the mid-band would be 1415 nm to 1450 nm. Note that in either case, these bands may exhibit excessive loss due to the fact that the passive components are typically not specified in these bands.

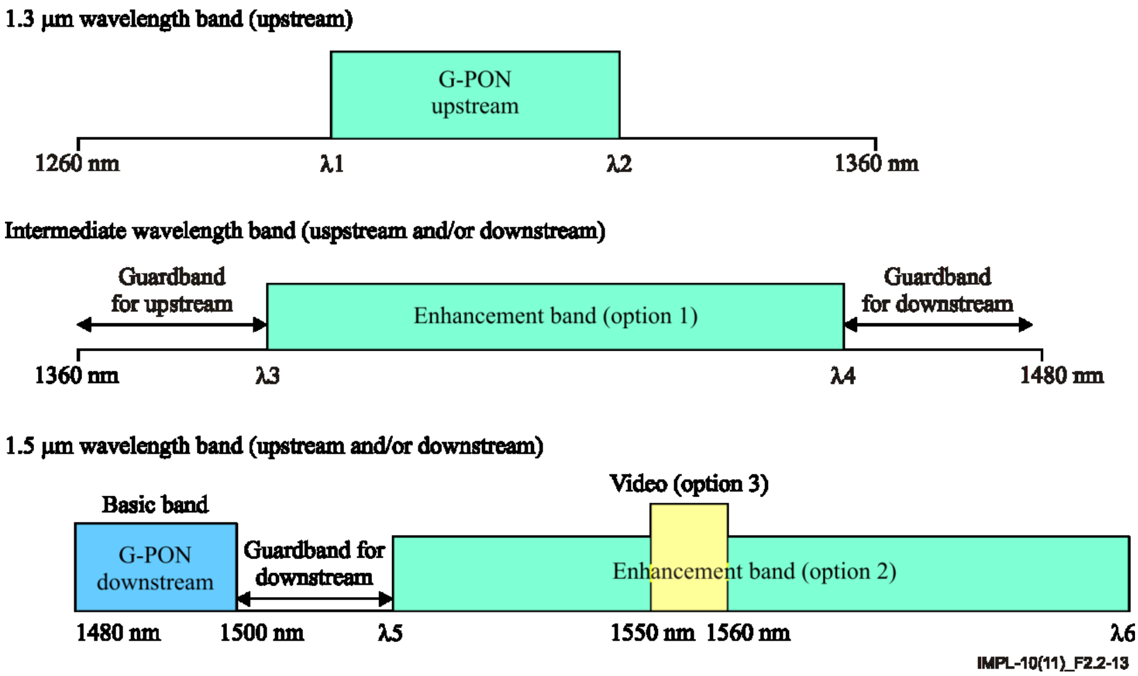


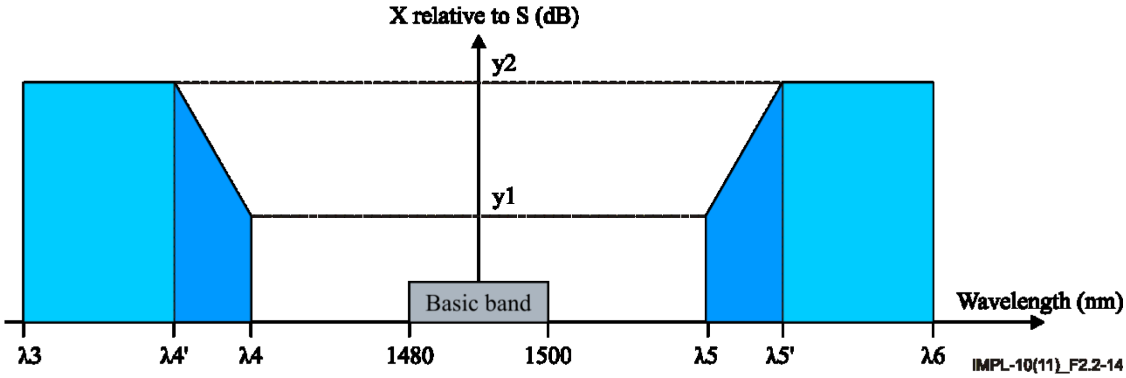
Figure 2.2-13 – Wavelength allocation

The last variable element concerns the spectrum in the 1550 nm range. The lower end of this range is 1530 nm (as will be described next, this is a “soft edge”). The upper end may vary depending on deployment of the ODN and related equipment. In the most conservative case, 1580 nm would be the longest wavelength to be used by enhanced PON equipment, as wavelength above that may exhibit excessive fibre bending loss, or loss due to optical time domain reflectometer (OTDR) filters. In the most optimistic case, wavelengths up to 1625 nm may be used by enhanced PON systems.

An application of this wavelength allocation is given in Section 2.2.4.4.

2.2.4.2 X/S tolerance of the ONUs

The minimum optical sensitivity of a G-PON ONU must be met in the presence of the interference signals caused by next generation-access (NGA) and/or video signals in the enhancement band. To minimize the effect of interference signals, G-PON ONUs need to isolate interference signals using an appropriate wavelength blocking filter (WBF) for blocking interference signals to Rx and a WDM filter. There is no specification of the isolation characteristics of the WBF and WDM filters themselves, but only the specification of the X/S tolerance of the G-PON ONU. Here S is the optical power of the basic band signal and X is that of the interference signal(s), The X/S tolerance of the G-PON equipment is diagrammed in Figure 2.2-14. The X/S tolerance requires that the ONU can achieve its specified sensitivity in the face of an interfering signal that is X/S dB greater than the G-PON downstream signal. This tolerance depends on the difference between the interfering wavelength and the basic G-PON band. For wavelengths away 39 nm or more from the basic band, an X/S of 22 dB is specified. For wavelengths 30 nm away from the basic band edges, an X/S of 7dB is specified. The X/S is linearly interpolated between these points. This soft band edge takes into account the usual shape of wavelength filters that are used to implement an ONU blocking filter.



Wavelength (nm)	λ3	λ4'	λ4	λ5	λ5'	λ6
	1415/1400 *(informative)*	1441 *(informative)*	1450 *(informative)*	1530	1539	1580 to 1625
X relative to S (dB)	y2	y2	y1	y1	y2	y2
	22 *(informative)*	22 *(informative)*	7 *(informative)*	7	22	22

Figure 2.2-14 – X/S tolerance mask of ONU

2.2.4.3 Example parameters of a discrete WDM filter

Once the enhancement spectrum has been reserved, and the ONUs are constructed with blocking filters to protect themselves from the enhancement signals, the next step is to use WDM filters at the OLT end to multiplex the G-PON OLT equipment to the enhancement equipment. There are many such filter designs, commonly referred to as “WDM1”.

An example with all the possible signals is shown in Figure 2.2-15. This filter interfaces with the PON feeder fibre on the common side, and with four disparate systems: the G-PON OLT, the video broadcast transmitter, the next generation-access (NGA) equipment, and an OTDR test set. The detailed objectives for insertion loss and isolation for such filters are given in Amendment 1 of ITU-T G.984.5.

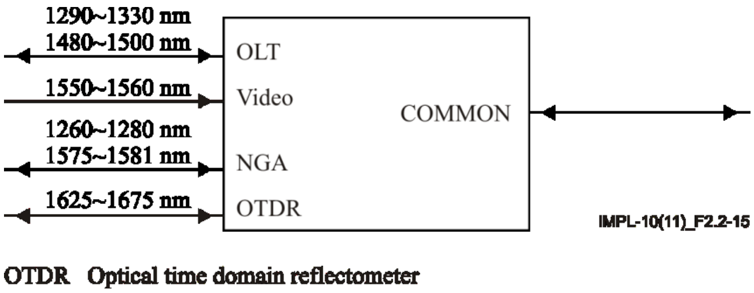


Figure 2.2-15 – Reference diagram of a WDM1r with video and OTDR support

NOTE – In Amendment 1 to ITU-T G.984.5 there are some examples of filters termed "WDM1r" to signify that they are a revised specification reflecting the newer wavelength plan for NGA systems.

2.2.4.4 Examples of wavelength allocation for NGA services and video distribution services

Here, the interplay of the video overlay enhancement and the NGA enhancement is described. Considering the possible network scenarios that allow the coexistence of G-PON, NGA and video services, it is assumed that additional guard bands are needed at both sides of the video band (1550-1560 nm) to avoid interference which could cause the degradation of performances of the video receiver (Figure 2.2-16).

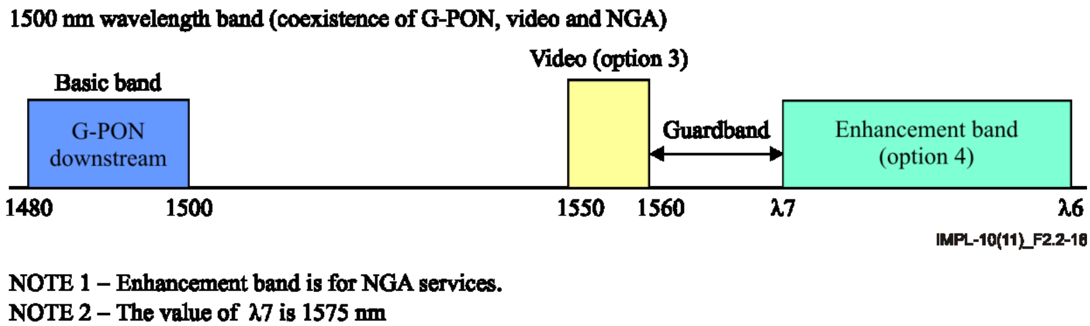


Figure 2.2-16 – Wavelength allocation

2.2.5 Extended reach capabilities

Editor: Frank J. Effenberger

(For further information see Recommendation ITU-T G.984.6.)

The reach of the G-PON systems is typically limited by the physical layer, most significantly by the loss budget limitations of cost-effective optics. Increasing the optical capability, which includes both increased overall fibre length and increased overall splitting ratio, is referred to as "reach extension". The primary concerns addressed for extending the reach of a G-PON are the increase of the loss budget and the management of optical impairments.

2.2.5.1 Optical extension schemes and architectures

A reach extension can be obtained using an active extension node placed in the middle of the optical network (mid-span extension), as shown in Figure 2.2-17. A mid-span extender device is inserted between the ODN (compliant with existing PON-related Recommendations) and an optical trunk line (OTL), which is connected to the OLT. This architecture extends the reach of the PON by the length of the OTL, and may also increase the split ratio of the PON. However, it does require electrical power for the mid-span extender. Single-sided extension has been described in ITU-T G.984.2 Amendment 2, as part of the physical layer specifications (extended budget optics).

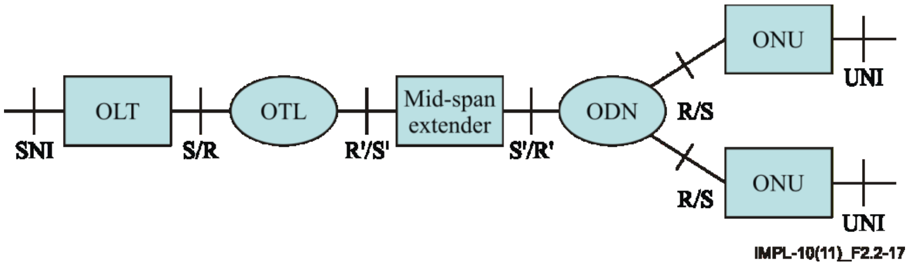


Figure 2.2-17 – Mid-span reach extension

A key requirement of the systems considered here is that they must remain compatible with existing ONUs / ONTs. Furthermore, the approaches should maintain compatibility with existing OLTs to the maximum extent possible. It is recognized that some modification of the OLT equipment may be necessary, but this should be minimized.

Two basic techniques are considered for the mid-span extenders: optical amplification, and opto-electronic regeneration. Both of them can be viewed as providing reach extension at the physical layer. Various architectures may be built from these techniques. Figure 2.2-18 shows two such architectures: the pure optical amplification style of RE (fig. a) and the pure optical/electrical/optical (OEO) style of RE (fig. b). Moreover various hybrid styles are possible, as well; for example, using optical amplification in the downstream and regeneration in the upstream. The key interfaces and functional blocks in each of these architectures are identified and specified in ITU-T G.984.6.

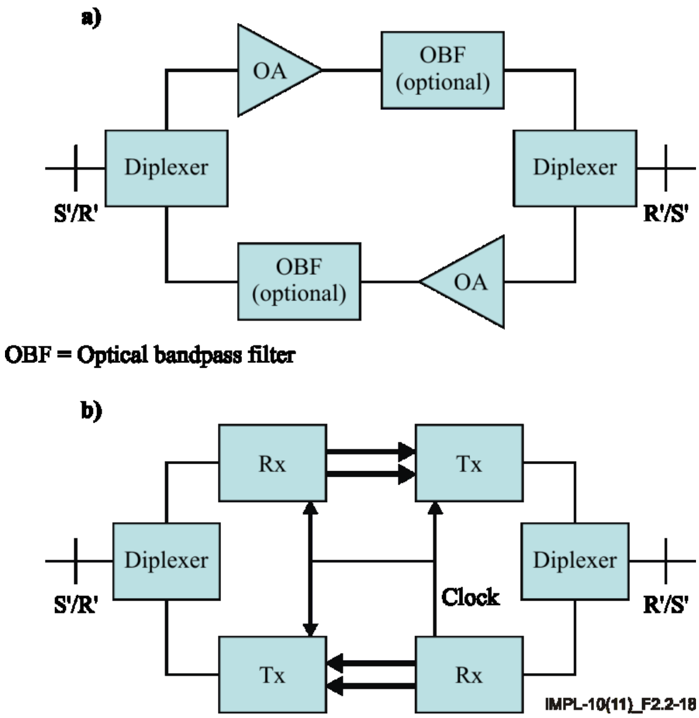


Figure 2.2-18 – The two basic extender architectures: optical amplifier and repeater

One aspect of extended reach PONs is that the OTL exhibits a relatively low utilization of the long distance fibre facilities. Typical inter-office fibres have traditionally supported thousands of customers' traffic; however, in the architecture above, they support less than a hundred. For this reason, the multiplexing techniques for the OTL were incorporated into the reach extender specification. The basic architecture is shown in Figure 2.2-19a and Figure 2.2-19b. In the former, the multiple PON signals are multiplexed using wavelengths. This requires a wavelength conversion (WC) function on either side of the OTL: at the input, to convert the ordinary PON wavelengths to the multiplex wavelength plan; and, at the output, to route and possibly to revert the multiplex wavelength plan back to the ordinary PON wavelengths. In the latter, the PON signals are converted from their bursty (burst mode, BM) native format to a continuous (continuous mode, CM) signal format. This format can then be carried over the optical transport network as any other continuous mode signal can be. Of course, at the egress from the OTN link, the continuous format signal must be reverted to its original format. (For more details see ITU-T G.984.6 Amendment 1.)

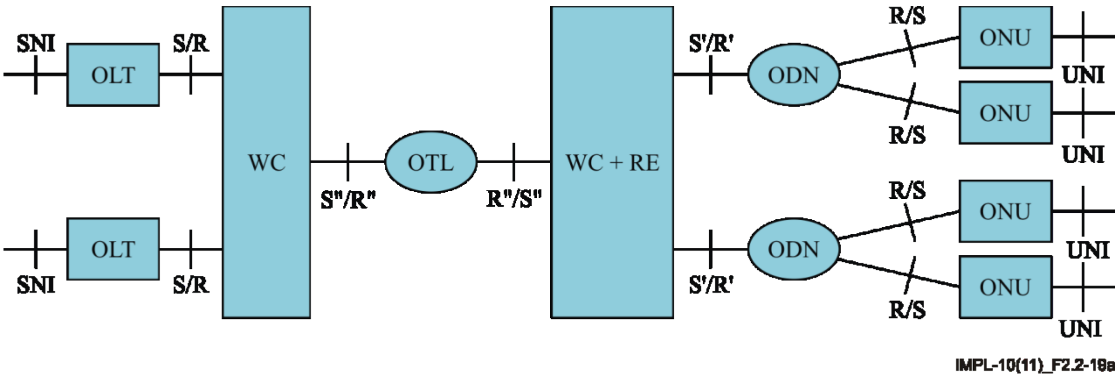


Figure 2.2-19a – Wavelength conversion (WC) reach extender (RE) architecture

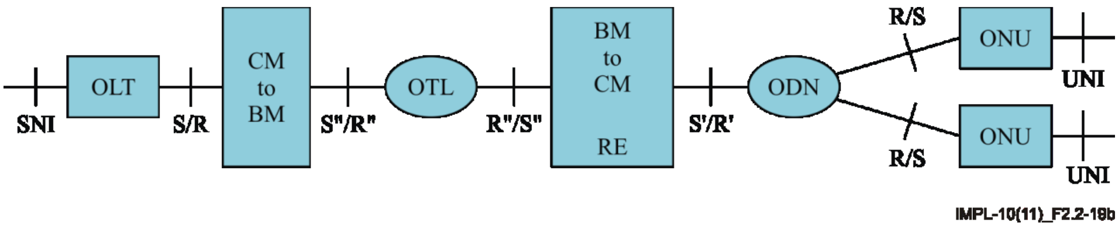


Figure 2.2-19b – Burst mode-to-continuous mode conversion reach extender architecture

One of the key drawbacks of the mid-span reach extender is the requirement for electrical power at the mid-span location. One architecture that can avoid this is the Raman-pumped RE, shown in Figure 2.2-20. The Raman RE device is inserted between the OLT and the optical trunk line (OTL), which is optical fibre. This approach extends the reach of the PON by increasing the allowable length of the OTL, and may also increase the split ratio of the PON. Note the Raman-RE device can be co-located with the OLT at central office and therefore it keeps the ODN passive (no electrical power required in R'/S' to R/S section). The notable aspect of this type of extender is that the optical power launched into the fibre is quite high (over 20 dB), and so special handling procedures and eye safety measures must be employed.

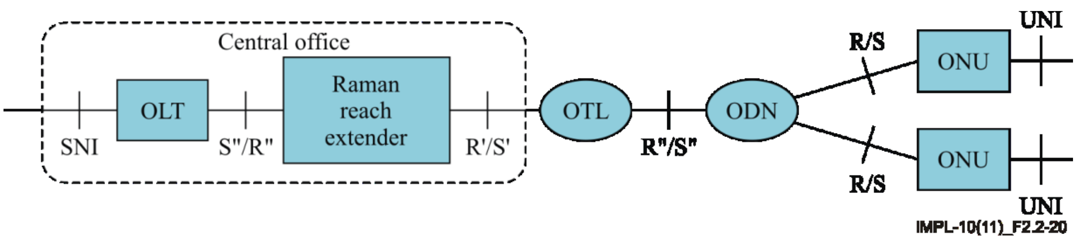


Figure 2.2-20 – Raman G-PON reach extension

2.2.5.2 Optical specifications for mid-span extenders

The detailed specifications of the optical links on the ODN and OTL links are derived directly from the appropriate specifications in the B-PON (see Section 2.1). The one item that is completely new is the specification of the loss of the OTL. However the design objective of this was to emulate the loss budget of the ODN as closely as possible. The loss numbers are given in Table 2.2-5. In comparison, the loss range for the standard class B+ ODN is 14 to 28 dB. The loss range for the OTL differs from this in two ways. First, the maximum loss is reduced by 0.5 dB. This intentionally makes the OTL link slightly “easier” and thereby adds more headroom for accumulated jitter penalties that will occur in the extended systems. Second, the maximum loss for the 1490 nm link is reduced to 23 dB. This recognizes that there is a loss differential between the 1490 nm and 1310 nm wavelengths in the fibre.

Table 2.2-5 – Physical medium dependant layer parameters of OTL

Items	Unit	Specification
Fibre type	–	ITU-T G.652
Attenuation range for 1290-1330 nm range	dB	14-27.5
Attenuation range for 1480-1500 nm range applicable for OEO type of reach extenders	dB	11-23
Attenuation range for C-band (1535 nm – 1565 nm) applicable for WC type of extenders	dB	14 – 27.5
Maximum attenuation for L-band (1564 nm – 1625 nm) applicable for WC type of extenders	dB	14 – 27.5
Maximum optical path penalty	dB	1
Maximum fibre distance between S/R and R'/S' points	km	60 minus the distance used in the ODN
Bidirectional transmission	–	1-fibre WDM
Maintenance wavelength	nm	To be defined

2.2.5.3 General requirements on G-PON reach extenders

While there are a range of technologies and architectures for reach extenders, several functions are generically applicable to all of them. This subsection discusses the major generic features of PON reach extenders.

Compatibility

Any reach extender should be compatible with existing G-PON 2.4/1.2 Gbit/s class B+ rated ONT equipment and class B+ ODN. The reason for this is that the ODN and ONU are the two most costly elements in the PON system, and are very difficult to change once they are deployed. Therefore, the reach extension technique should be seen as an add-on to the existing system that does not disturb the choice of passive optical components, construction techniques, or ONU optics.

In some cases, the OLT specifications will need to be modified due to the intrinsic behaviour of the reach extender. The most salient examples are the increased OLT tolerance for poor extinction ratio caused by OA-type REs, and the increased upstream overhead requirement for OEO-type REs.

These tend to be rather small changes to the OLT equipment and do not affect hardware in most cases.

Management

The RE function is an active device in a remote location, and as such it requires remote management. The preferred means to affect this is to embed an ONU into the RE. This ONU then creates a management link to the OLT using the OMCI (as usual), and then the OMCI MIB can fully represent the RE to the OLT. The OLT then acts as a proxy for the RE to the higher-layer management systems in the network. An implicit feature of this scheme is that the OLT is automatically aware of all subtending REs, and so the OLT can properly modify its own characteristics and functions to suit them. For example, if the RE loses power, then the OLT would know this via the embedded management link, and therefore filter the loss alarms of all the subtending ONUs, in order to avoid redundant alarms and notification overflow.

Power

All RE types require electrical power, typically in a remote location. It is expected that this power has some means of backup, since primary electrical power is prone to outage. Typically, this backup employs batteries, and these have issue with limited capacity and lifetime degradation. To minimize these problems, the power consumption of the RE function should be minimized.

Protection

The RE function (and its corresponding OTL) is a shared function, and as such the failure group size approaches an unacceptably large value. To address this, protection of part or all of the RE and OTL can be implemented. Because the RE has active electronic functions, it can go beyond a classical type-B protection scheme (see Figure 2.1-12). These forms of protection are discussed to some degree in Amendment 1 to ITU-T G.984.6.

2.2.6 Long-reach G-PON specification

Editors: Denis A. Khotimsky and James Zhang

(For further information see Recommendation ITU-T G.984.7.)

This section discusses the G-PON physical media-dependent requirements and transmission convergence layer requirements that allow extending the maximum differential fibre distance of a G-PON system to 40 km versus the conventional 20 km (see Section 2.2.2). The differential distance of 40 km ranging from 0 to 40 km, 20 to 60 km, or elsewhere in-between allows significant flexibility in PON deployment and offers many benefits including the ability to serve sparsely populated areas in an efficient manner.

2.2.6.1 G-PON long-reach overview

Figure 2.2-21 shows the construction of a quiet window for the serial number (SN) acquisition in a G-PON system, where all ONUs are within the 20 km fibre reach.

The quiet window is a time interval during which the OLT suppresses all bandwidth allocations to in-service ONUs in order to avoid collisions between their upstream transmissions and the transmissions from ONUs whose burst arrival time is uncertain. The OLT opens a quiet window to allow new ONUs to join the PON and to perform ranging of specific ONUs.

The quiet window in the case where all ONU are within the 20 km must accommodate the 200 μs variation of the round-trip propagation delay (0 to 200 μs), the 2 μs variation of the ONU processing time (34 to 36 μs), and the 48 μs ONU random delay (0 to 48 μs) (see clause 10.4.2 of ITU-T G.984.3). Therefore, the minimum size of the quiet window is 250 μs (200+2+48 μs).

For the sake of specificity, it is assumed that the OLT does not start the quiet window construction until the transmission of the serial number request grant. (See clause 10.4.5 of ITU-T G.984.3 for the discussion of the alternatives.) In this case, the OLT employs the pre-assigned delay, which is not less than the combined variation of round-trip propagation delay and ONU processing time (202 µs). The minimum offset of the quiet window at the OLT (i.e., the time to earliest arrival of the serial number response after transmission of a serial number request grant) can be determined as 236 µs, a sum of the pre-assigned delay and the minimum ONU response time.

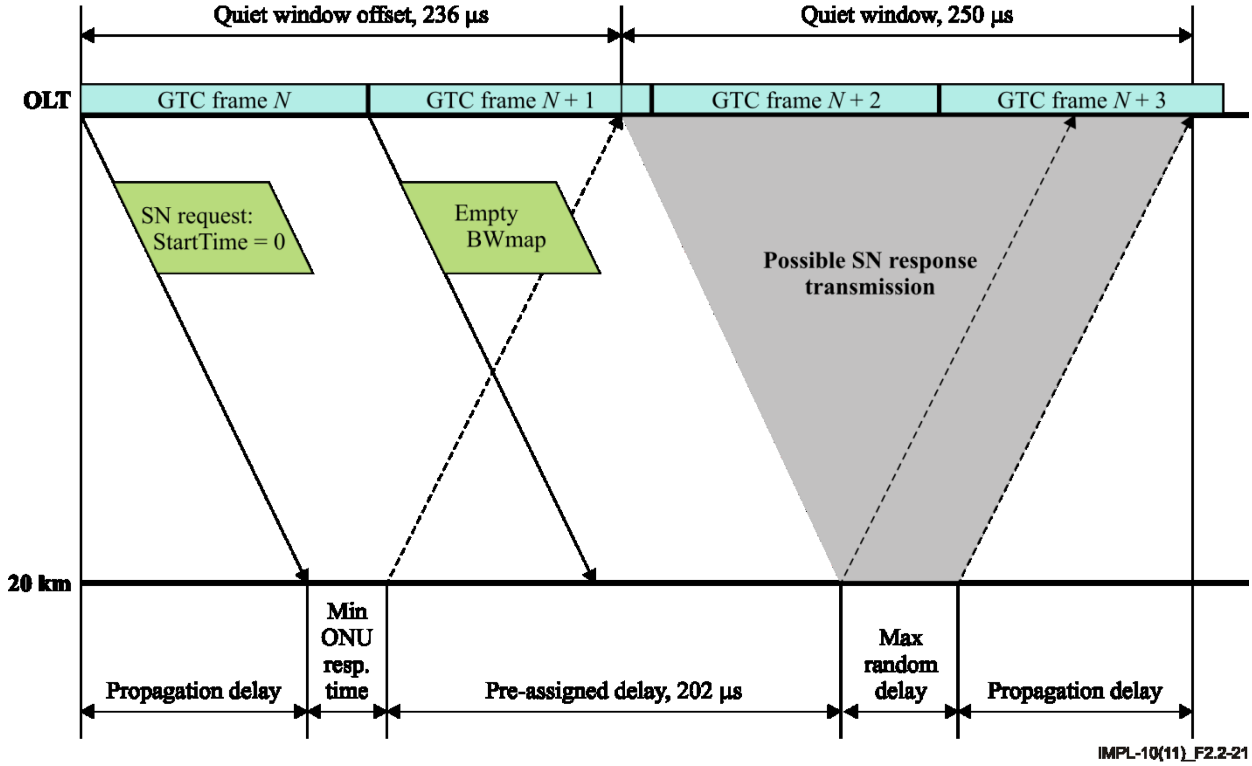


Figure 2.2-21 – Construction of G-PON quiet window with the 0 to 20 km distance range

Figure 2.2-22 shows the quiet window construction for serial number acquisition in a G-PON system where the fibre distances of all ONUs vary between 20 km and 40 km. The maximum differential fibre distance is the same as in the example above, i.e., 20 km. Since ONU's design and protocol parameters depend on fibre distance only, through the maximum differential fibre distance, they too remain the same. The minimum quiet window size in this case is also 250 µs. On the other hand, the round-trip propagation delay now varies from 200 to 400 µs, and the minimum round-trip propagation contributes to the quiet window offset, which becomes 436 µs.

In a G-PON system with extended differential reach (an EDR G-PON system), an ONU farthest away from the OLT could have a 40 km longer fibre distance than the closest ONU. Therefore, the range of the round-trip propagation delay variation between any two ONUs is 0 to 400 µs, while for a conventional G-PON system this range is 0 to 200 µs. Consequently, the size of the quiet window that the OLT has to open for serial number acquisition in such a system, with other parameters being invariant, must be at least 450 µs.

Figure 2.2-23 shows a possible approach to the quiet window construction for an extended differential reach (EDR) G-PON, under the assumption that the pre-assigned delay equals the combined variation of round-trip propagation delay and ONU processing time, i.e., 402 µs. The offset of the quiet window in this case can be determined as 436 µs.

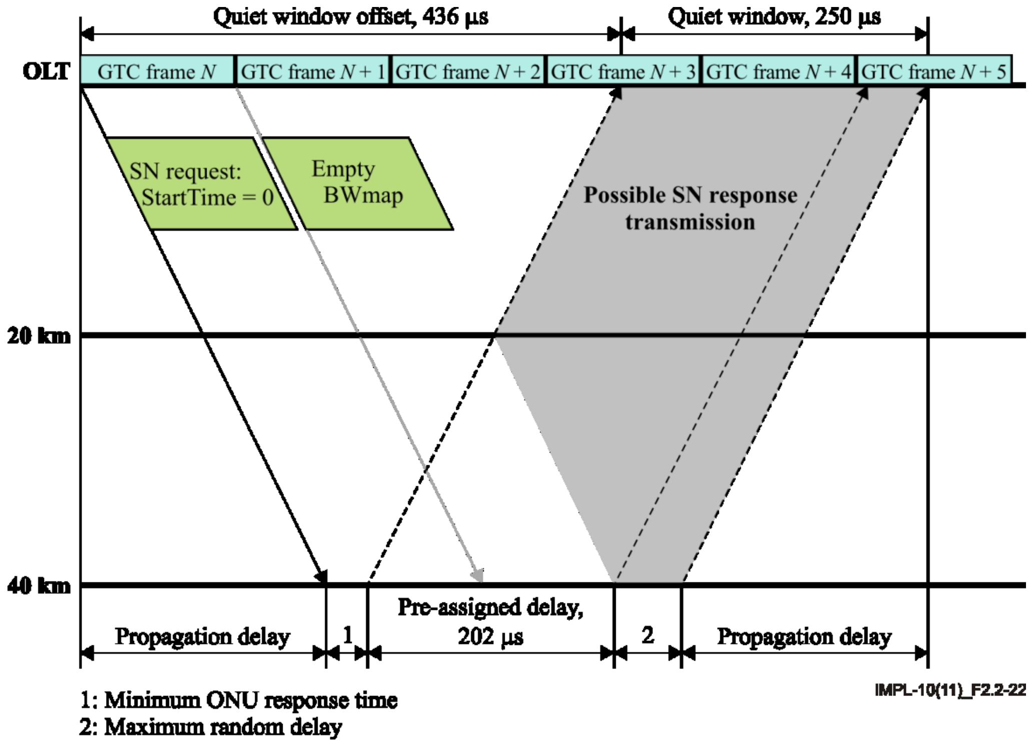


Figure 2.2-22 – Construction of G-PON quiet window with the standard differential distance and 20 km to 40 km distance range

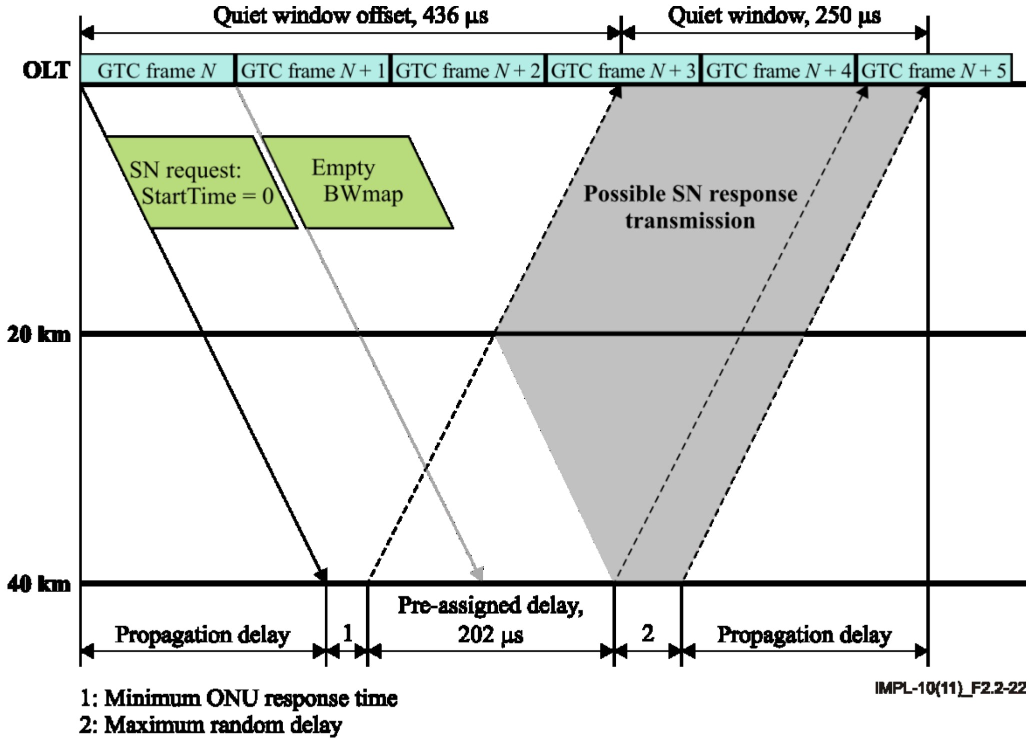


Figure 2.2-23 – Construction of G-PON quiet window with proposed extended differential distance (0 to 40 km)

2.2.6.2 Physical layer requirements

Spectral width

For a G-PON system operating at 2488 Mbit/s downstream rate and 1244 Mbit/s upstream rate and able to serve ONUs deployed 0-20 km, the OLT laser 20 dB spectral width was originally specified as 1 nm (ITU-T G.984.2).

In order to serve ONUs deployed 0-40 km, 20-60 km or at distances in between with a 40 km differential distance from the OLT, the OLT laser 20 dB spectral width needs to be less than or equal to 0.6 nm.

Attenuation range

An EDR G-PON system shall employ the optical components and maintain the optical power levels consistent with one of the standard attenuation range classes: Class B+, Class C, and Class C+. It shall support the maximum fibre distance and the maximum differential fibre distance as specified in Table 2.2-6.

Table 2.2-6 – Physical medium dependant layer parameters of ODN

Attenuation class	Attenuation range, dB	Max physical reach, km	Max differential fibre distance, km
Class B+	13-28	40	40
Class C	15-30	40	40
Class C+	17-32	60	40

ODN topology

The ODN shall be based on ITU-T G.652 fibre and shall possess the topology, including the location and degree of the power splitter and possible use of passive optical attenuators, to ensure that the minimum loss requirement is met for each ONU.

An ODN accommodating the differential fibre reach approaching 40 km may employ an unbalanced cascade of splitters, where the shortest fibre branches experience the highest degree of split. An example of a Class B+ ODN supporting 13-28 dB attenuation range with maximum physical reach of 40 km and differential fibre reach of 40 km is shown in Figure 2.2-24. In this example, the ONUs with shorter fibre distance experience the higher degree of split than the remote ONUs. Specifically, assuming, in the first approximation, 3.5 dB attenuation per binary split and 0.4 dB per kilometre of fibre, it can be obtained for the group of near ONUs the total attenuation of 17.5 dB and for the group of remote ONUs the total attenuation of 26.5 dB, both values being within the allowed window for the class.

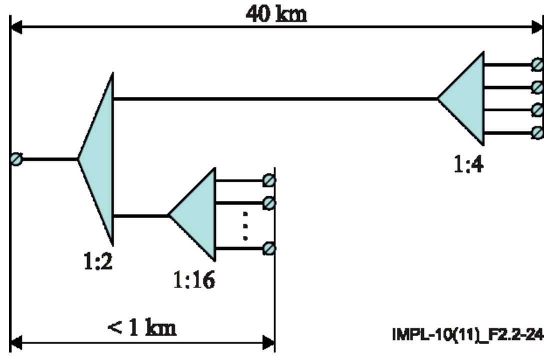


Figure 2.2-24 – Example of Class B+ ODN supporting the differential fibre reach of 40 km

2.2.6.3 Transmission convergence layer requirements

OLT side

At the serial number acquisition and ranging phases of the activation process, the OLT shall be able to create a quiet window appropriate for a 40 km differential fibre distance between the farthest and closest ONUs.

ONU side

An ONU in an EDR G-PON system has to provide enough buffering for the upstream traffic arriving at the ONU within the quiet window, which is approximately twice as large as in a conventional G-PON system. And, an ONU in an EDR G-PON system shall support larger storage to accommodate twice as many BWmaps as a conventional G-PON system.

2.2.7 ITU-T G.984.4 OMCI

Editor: Dave Hood

When G-PON evolved from its roots in Recommendation ITU-T G.983.1 B-PON, the management messages and the information model migrated from ITU-T G.983.2 to the new Recommendation ITU-T G.984.4. Over the years, ITU-T G.984.4 was extended to include many new features, for example reach extension, and to expand the scope of many existing features, such as DSL and voice over Internet protocol (VoIP) provisioning.

It was an open question whether the same approach should be taken in the development of the ITU-T G.987.x series of Recommendations dealing with XG-PON. Because ITU-T G.984 and G.987 systems are expected to coexist for many years, the creation of a distinct XG-PON OMCI Recommendation would have implied parallel maintenance of two Recommendations for the indefinite future. In addition, other technologies such as ITU-T G.986 (Ethernet point-to-point) also chose to use OMCI for management.

Accordingly, it was agreed to create a single new Recommendation, ITU-T G.988, which would encompass all aspects of OMCI for all of the technologies that used it. Several features of ITU-T G.984.4 were not migrated into ITU-T G.988, because market experience had indicated that there was little interest in them. These features include 802.11 wireless and router features, both of which are important, but neither of which has a constituency advocating OMCI management. In addition, most of the final remnants of ATM were left behind in ITU-T G.984.4.

ITU-T G.984.4 is no longer being maintained. The primary reference for OMCI is now ITU-T G.988, with ITU-T G.984.4 valid for features that are not included in ITU-T G.988.

NOTE – Section 2.5 gives an overview of the content of ITU-T G.988.

2.2.8 Means and impact of G-PON power-saving

Editor: Denis A. Khotimsky

(For further information see Supplement 45 to the ITU-T G-series Recommendations.)

This section presents a spectrum of ONU power-saving techniques that were discussed in the G-PON context. Only a few of these techniques has since become a normative part of the G-PON standard. However, a larger subset of them, as a result of further study and discussion, is incorporated into the XG-PON transmission convergence (TC) layer specification. This section is primarily based on ITU-T G. Supplement 45 published in 2009 which summarizes the requirement gathering effort as well as the results of the studies available at that time.

2.2.8.1 G-PON ONU power-saving objectives and requirements

On one hand, the requirements focus on conserving power in regular (mains powered) operations and minimizing the carbon dioxide emissions generated by information and communications technologies (ICTs). On the other hand, the effort is driven by the emergency services support under the a.c. mains power failure and is targeted at the prolongation of the battery operation time. The key difference between the two objectives and the two associated requirements profiles is the degree of compromise on the scope and quality of service that is considered acceptable. There are also varying approaches to the degree of freedom delegated to the end user in asserting his or her preferences with regard to G-PON functionality under power outage.

ICT power conservation and reducing its carbon footprint have been embraced by the industry and the society in general as necessary goals. The European Union is leading the cause with the *Code of Conduct on Energy Consumption of Broadband Communication Equipment* (referred herein as BBCoC), a document issued by the European Commission that sets out the basic principles and goals to be followed by all parties involved in broadband equipment in respect of energy-efficiency. In particular, the BBCoC specifies the target power consumption values for G-PON ONUs in the On (full power) state and low power state in the specific time-frame. All service providers, network operators, equipment and component manufacturers are invited to sign this document on a voluntary basis. For example, for the G-PON-based home gateway core functions in the time-frame of Jan 1 – Dec 31, 2011, Version 3 of BBCoC specifies the target power consumption of 4.0 W in the low power-state and 7.7 W in the on-state, making additional allowances for specific user-facing interfaces and optional functions. Version 4 of the BBCoC is in preparation.

The specific requirements associated with the second objective of power-saving are subject to local regulations that normally establish the duration of time an access provider should maintain the basic services to the customers after a power failure that may vary from 4 to 24 hours in different jurisdictions. This regulatory norm has roots in the traditional telephone service that maintains the line power to the customer phone. It has been observed that in many cases the existing regulations tend to suit the conventional copper plant (which provides power from the central office), and are yet to address the specifics of fibre access.

2.2.8.2 Classification of power-saving techniques

The current and prospective ONU power-saving techniques can be characterized by the behaviour of the ONU receiver and transmitter while the ONU is in a low power mode. The following three categories have been identified (Figure 2.2-25).

- ONU power shedding is characterized by powering off or reducing power to non-essential functions and services while maintaining a fully operational optical link.
- ONU dozing is associated with additional powering off of the ONU transmitter for substantial periods of time on the condition that the receiver remains continuously on.

- ONU sleeping means that both ONU transmitter and ONU receiver are turned off for substantial periods of time. The latter category is further subdivided into ONU deep sleep, whereby the transmitter and receiver remain off for the entire duration of the power save state sojourn, and the ONU fast sleep, where the power save state sojourn consists of a sequence of sleep cycles, each composed of a sleep period and an active period.

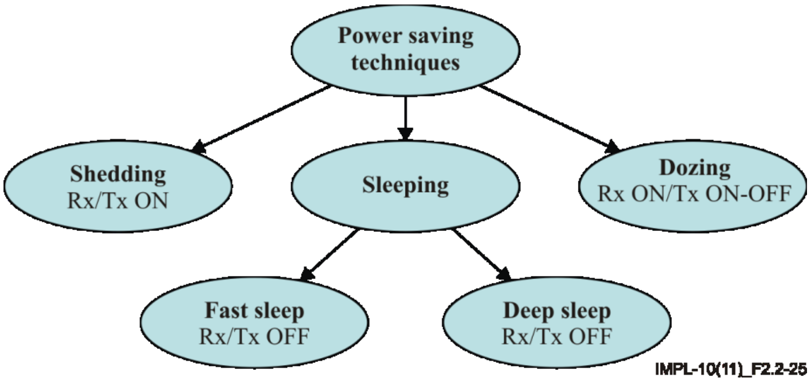


Figure 2.2-25 – Classification of the power-saving techniques

Each power-saving technique can be further characterized by the depth of impact on the system's TC layer.

It has been observed that a description of each current and prospective power-saving technique necessarily contains the elements of the power save mode maintenance mechanism (OLT's support of a particular power save mode) and the elements of the power save mode signalling mechanism (establishing transitions to and from a particular power save mode). These two mechanisms are largely independent from each other and can be discussed and selected separately.

2.2.8.3 Power-saving maintenance

Power shedding

The existing G-PON standard allows the ONU to perform controlled power shedding, that is, to switch off specific services when the ONU operates under battery power. The feature is configured via the ONU management and control interface (OMCI) and does not require real-time signalling between the OLT and ONU. A set of shedding classes is identified, one shedding class for each interface type. For each shedding class, a statically specified time interval determines the time between the moment of a.c. power failure and the moment the support of the respective interface type is turned off in an effort to save battery power. As presently specified, the feature addresses the a.c. power failure scenario only.

Fast sleep

An ONU in the fast (also called "cyclic") sleep mode alternates between sleep periods, when the optical transceiver is completely powered off along with all the non-essential functions and only the timing and activity detection functions remain active, and active periods when the optical transceiver as well as the necessary supporting functions are powered on. An active period and the subsequent sleep period constitute a sleep cycle. The transitions from active periods to sleep periods and from sleep periods to active periods (wake-ups) are synchronized by all the ONUs in the fast sleep mode and may require the physical layer operations, administration and maintenance (PLOAM) channel support.

Deep sleep

The ONU in a deep sleep has its optical transceiver completely powered off along with most other functions and services. The timing and activity detection functions may optionally remain active. The OLT may continue sending the downstream traffic (or, optionally, discard it) and provide upstream allocations, but considers the absence of the upstream traffic as normal. In order to support timely recovery of the ONU waking up on a local stimulus, the OLT allocates regularly targeted (i.e., narrow) ranging windows to the sleeping ONUs.

Dozing

The idea of the dozing mode lays in continuous powering of the ONU receiver, allowing uninterrupted monitoring of the downstream traffic and nearly instantaneous wake-up in case of need as indicated by the OLT. A dozing ONU wakes up when it receives upstream traffic from a designated local interface or when so requested by the OLT. Compared with the sleep modes, dozing may achieve fast wake-up and minimize service impact at the expense of a lesser degree of power-saving than the low power mode.

2.2.8.4 Power-saving signalling

Regardless of how the power-saving behaviour is maintained, the events of entering and leaving the power-saving mode of operation must be signalled between the OLT and ONU. The power-saving mode signalling shall ensure timeliness of communication so that the corresponding OLT and ONU state machines can adequately represent each other's behaviour, and that any race conditions are effectively resolved. The following text contains a review of the available signalling methods.

OMCI channel signalling

The OMCI channel is necessarily involved in the provisioning and configuration of the power-saving behaviour and may also support the real-time "handshake". The ONU and OLT may support multiple optional power-saving techniques. The specific technique or techniques that are activated in a particular PON deployment depend on the technical capabilities of the equipment and the operational requirements. The capability versus requirements negotiation takes place at initial ONU configuration via the OMCI management channel supporting appropriate extensions.

In principle, the OMCI channel can also be used to provide a handshake indicating transitions from low power to full power modes. Such usage (assuming software implementation) can be available in G-PON as well as in the future generations of PON systems. Nevertheless, the inherent latency of the OMCI channel makes it least preferable for real-time signalling.

PLOAM channel signalling

PLOAM-based signalling can apply to any power-saving maintenance mechanism and may involve either defining new PLOAM message types or new parameters and semantics of the existing PLOAM message types.

Since at the time of the ONU power-saving discussion, the G-PON TC layer specification had been stable for a while and had served as a basis for numerous hardware implementations, it was problematic to introduce new PLOAM channel amendments. However, the PLOAM signalling method for power-saving is perfectly feasible in the XG-PON context.

Embedded field signalling

The power-saving signalling method with least latency involves the use of the embedded fields of the G-PON transmission convergence (protocol layer) (GTC) framing overhead. In the G-PON context, the use of this method would have been even more intrusive for the existing hardware implementations than the use of the PLOAM channel signalling. However, in the XG-PON context, the embedded signalling represents a promising approach.

2.2.8.5 Study conclusions

The study of the ONU power-saving techniques in the G-PON context leads to the conclusions that are summarized below.

Considering the objectives for power-saving, the primary target is to reduce the size and cost of backup batteries, and therefore power-saving modes that operate during main power failure are of primary interest. The secondary goal is to reduce the average power consumption at all times. An adverse impact on service quality and availability must be evaluated and kept in mind; in particular, lifeline telephony services should always be available.

The approaches to ONU power-saving are prioritized as follows.

- First priority is a continuous improvement of equipment design and reduction of power consumption, including optimization of the electronic circuitry to consume power only when necessary.
- Second priority is the implementation of the local power-saving techniques, such as power shedding, that do not rely on the OLT-ONU protocol features and have a minimal service impact.
- Third priority is the implementation of the power-saving techniques, represented by dozing, that do involve interaction between OLT and ONU, but are associated with limited additional complexity and service impact.
- Finally, the last priority includes the aggressive power-saving techniques (ONU sleeping) that can achieve the maximum power reduction at the cost of increased complexity, negative system impact, and connectivity loss.

To date, the power-saving in G-PON relies on the approaches of the top two priorities. Within the framework of XG-PON standardization, another round of power-saving studies were performed that led to a specification of power-saving mechanisms involving PLOAM-based and embedded signalling, and the combination of dozing and sleeping maintenance techniques (see Section 2.3.4 and Recommendation ITU-T G.987.3).

2.3 XG-PON

Editor: Gastone Bonaventura

Maturity of G-PON implementation and ever increasing G-PON deployments showed a necessity for ITU to soon provide an upgrading path with full re-use of the legacy ODN to overcome situations where the G-PON bandwidth becomes a bottleneck. So it was necessary to move to the XG (i.e.: 10 Gigabit)-PON era.

Moving through the ITU-T Recommendations of the ITU-T G.987.x series, three terms are used:

- XG-PON which is a generic term that covers both XG-PON1 and XG-PON2;
- XG-PON1 that features 10 Gbit/s downstream and 2.5 Gbit/s upstream;
- XG-PON2 so far investigated, but put on hold till the market requires it, that features symmetrical line rates of 10 Gbit/ downstream and 10 Gbit/s upstream.

The present version of the Technical paper only addresses XG-PON1. XG-PON2 will be addressed in a further version, when the technology becomes more mature. For this reason in this Section 2.3 XG-PON will stand for XG-PON1.

Inheritance of G-PON mechanisms that proved efficient was a strong basis that enabled to speed up the specification process. Revisions were limited to clean up some limitations caused by compatibility with past technologies and add flexibility enhancing features.

In order to smooth the XG-PON early deployment experience a scheme enabling progressive deployment for high bandwidth demanding network termination has been preferred. Also experience of some operators migrating between PON generations (from B-PON to G-PON) stressed the interest for an overlay capability either through WDM filters (see ITU-T G.984.5) or via TDMA compatibility.

2.3.1 Passive optical access: concepts, definitions, and conventions

Editor: Denis A. Khotimsky

(For further information see Recommendation ITU-T G.987.)

This section deals with the common concepts, definitions, and terminological conventions pertaining to passive optical network systems. Its content is mainly based on the Recommendation ITU-T G.987. Whereas this Recommendation formally belongs to the XG-PON series of specifications and does contain over 200 acronyms and 60 definitions, many of which are specific to XG-PON, it also provides a general terminological discussion – in part, explicative, in part, stipulative – that has a much wider scope of applicability. It is the latter part of ITU-T G.987 that interests here.

2.3.1.1 Definition system

Although passive optical network (PON) systems have been conceptually known for a quarter of a century and widely deployed for at least a decade, there has been surprisingly little agreement with respect to what PON actually is. In early 2009, when the work on the ITU-T G.987 series began, there were at least dozen distinct definitions characterizing PON as an architecture, a system, a network, a technology, a cost-effective means to use the fibre infrastructure, etc. All the referenced entities shared a common attribute of containing, using or relying upon a fibre infrastructure with no active (electronic) components between the central office interface and the user equipment interface. The existing definitions at times contradicted each other and, almost invariably, the deployment practices. For example, it was easy for an unscrupulous commentator to pick a suitable definition in order to make fun of an allegedly oxymoronic nature of G-PON with an active reach extension, a concept that had been standardized a year earlier. Moreover, within ITU-T's own documents, a formal definition of PON was lacking, and some of the PON-related concepts were defined using circular definitions.

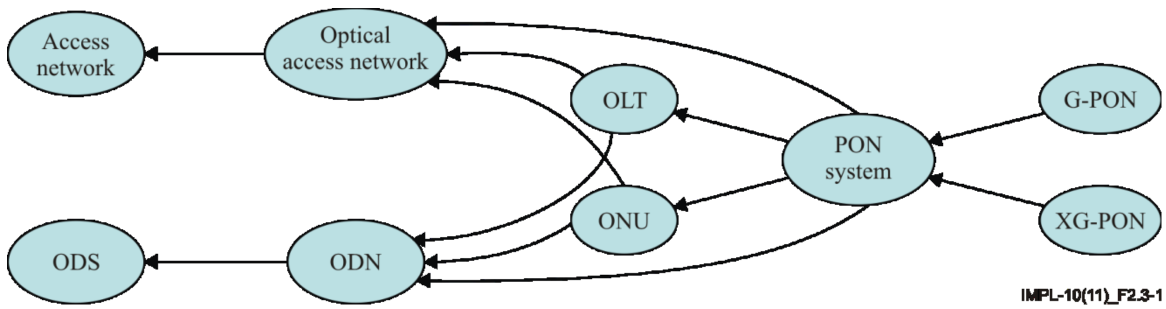


Figure 2.3-1 – Directed graph of the ITU-T G.987 definition system

A complete, consistent and extendable definition system of the modern PON-related concepts rests on the foundation composed of the two parts (see Figure 2.3-1 for formal graph of the G.987 definition system, where each directed arc corresponds to the relation "is defined via"):

- the concept of an optical access network (OAN), which is defined as a part of the access network (AN) whose network elements are interconnected by optical communication channels. (The precise definition of an access network is provided by ITU-T G.902.); and
- a thoroughly defined concept of an optical distribution network (ODN). An ODN is point-to-multipoint optical fibre infrastructure (not necessarily entirely passive), which can be either simple or composite. A simple ODN, or an optical distribution segment (ODS), is an entirely passive single-rooted point-to-multipoint tree of optical fibres with splitters, combiners, filters and possibly other passive optical components. A composite ODN consists of two or more passive segments interconnected by active devices, each of the segments being either an optical trunk line segment or an optical distribution segment.

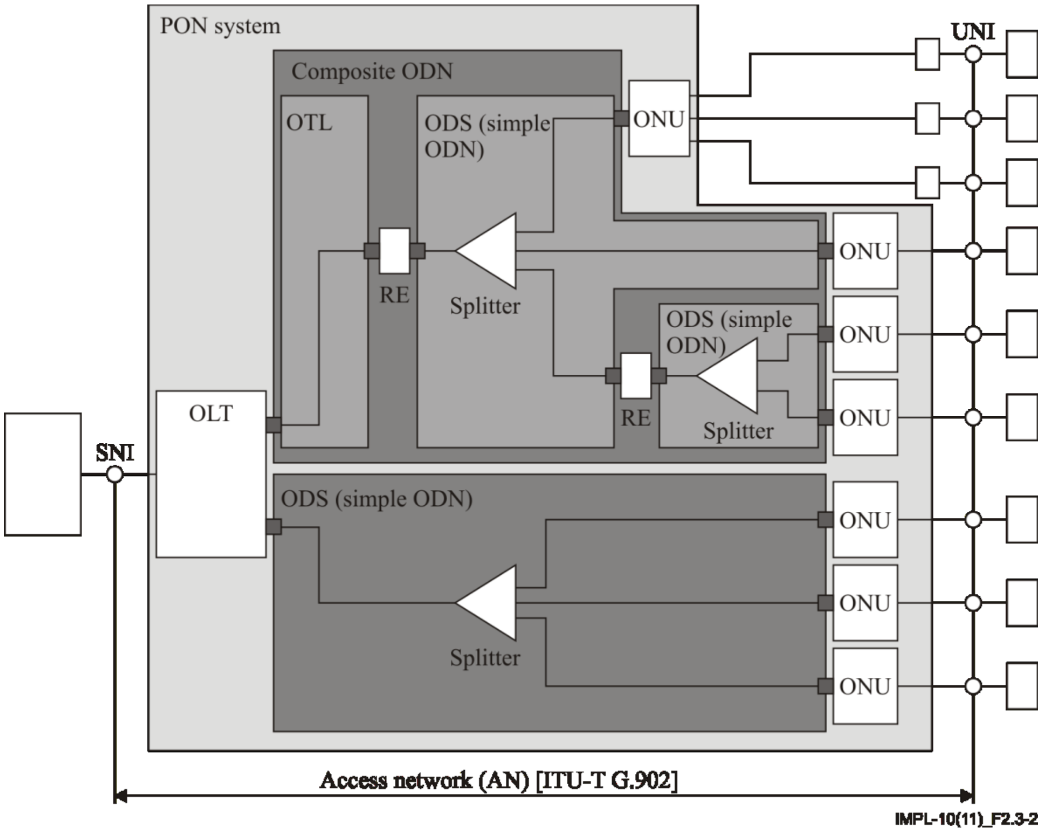


Figure 2.3-2 – ITU-T G.987 reference access network architecture

An OLT and an ONU are defined as network elements in an ODN-based optical access network that, respectively, terminate the root of the ODN (providing service network interface of the OAN) and a leaf of the ODN (providing the user network interface of the OAN). A passive optical network (PON) system is a combination of network elements in an ODN-based OAN that includes an OLT and multiple ONUs. While a PON system is designed to operate over a simple (entirely passive ODN), it may also operate over a composite ODN containing active elements – reach extenders. Various specific PON systems can be identified based on the type of passive devices used for optical distribution, the nominal line rates and the implemented protocol suite.

The ITU-T G.987 reference network architecture of passive optical access is shown in Figure 2.3-2.

2.3.1.2 Power and loss budget parameters

The design of a PON-based optical access network involves establishing a balance between the optical power parameters of the transceivers and the loss parameters of the ODN.

An optical transmitter is characterized by the range of variation of the mean optical launch power, i.e., minimum mean Tx launch power and maximum mean Tx launch power. “Mean” refers to the averaging over a given digital sequence, whereas qualifiers “minimum” and “maximum” refer to variation within a sample and over time. The minimum mean launch power provides the power level that the transmitter should guarantee at all times, and the maximum mean launch power provides the power level that the transmitter should never exceed. When applied to burst mode transmission, the term pertains to the time interval during which the transmitter is fully active, and excludes possible starting and ending transient behaviour.

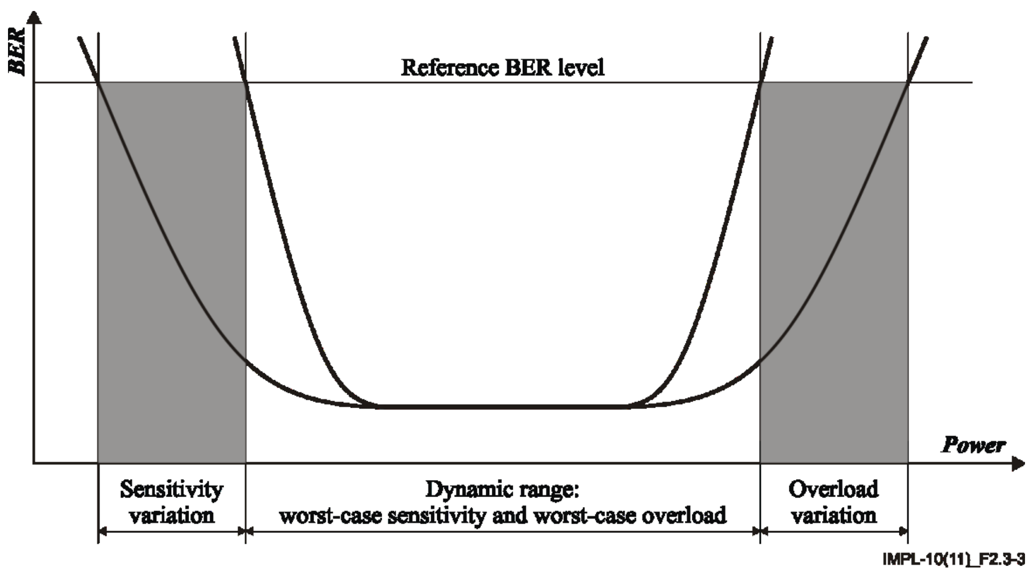


Figure 2.3-3 – Rx output BER as a function of mean received optical power and dynamic range

An optical receiver (Rx) is characterized by its dynamic range, i.e., Rx sensitivity and Rx overload. Receiver sensitivity and overload are defined, respectively, as the minimum and maximum average received optical power at which the BER at the receiver output remains at or below the specified level. Here qualifiers “minimum” and “maximum” refer to the mean received optical power. In recognition of possible variation of the Rx parameters within a sample and under various operating conditions, the dynamic range is formally defined as an interval between the worst case (or maximum) sensitivity and the worst-case (or minimum) overload. Here qualifiers “minimum” and “maximum” refer to the range of operating conditions. A receiver can successfully process an optical signal if the optical power of the signal incident upon receiver is within the receiver’s dynamic range (Figure 2.3-3).

For a standards-based PON system the Tx launch power range and Rx dynamic range belong to the corresponding physical medium dependent (PMD) layer specification.

A point-to-multipoint ODN is characterized by the optical attenuation along each path between its root and any of the leaves. The attenuation is an ODN design parameter that is dependent upon the fibre distance, the number and type of optical devices along the path, the number of connectors and splices, parameters of the wavelength plan, etc. The minimum and maximum ODN attenuation belong to the PMD specification.

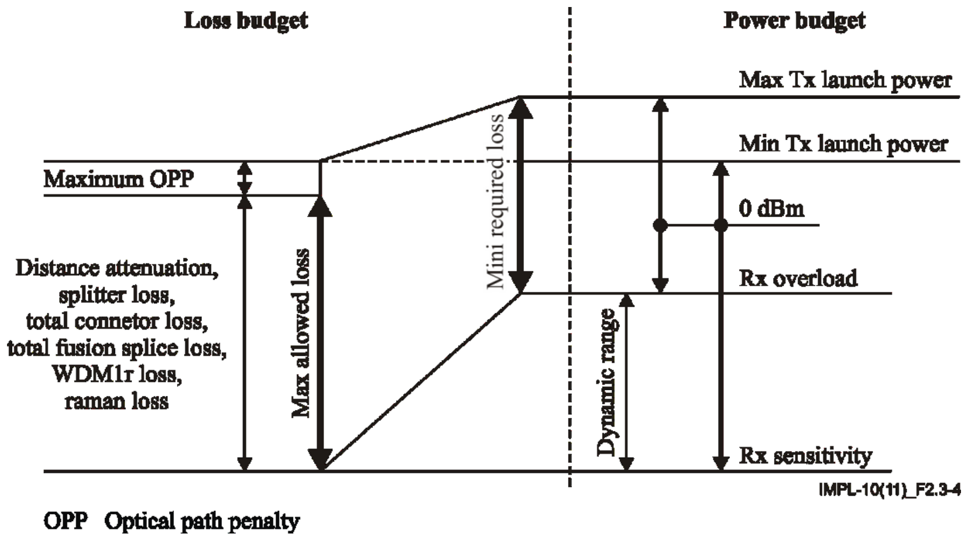


Figure 2.3-4 – Relationship between the power and loss budget parameters

To ensure that the mean power of the received optical signal is within the Rx dynamic range, the following two balance conditions between the standards-specified parameters should be met (Figure 2.3-4).

1. The ratio between the max Tx launch power and the worst-case Rx overload should be *at most* as large as the minimum ODN attenuation.
2. The ratio between the min Tx launch power and the worst-case Rx sensitivity should be *at least* as large as the maximum ODN attenuation less specified optical path penalty.

2.3.1.3 Terminological clarifications

2.3.1.3.1 Fibre reach and fibre distance

An ONU is characterized by its fibre distance. For each pair of ONUs on the same OLT PON interface, the differential fibre distance is the difference between the two individual fibre distances. Each specific PMD layer parameter set contains a provision to support a specific maximum fibre distance. The XG-PON TC layer specification contains a provision to support specific ranges of maximum fibre distance and maximum differential fibre distance. These ranges can be configurable for a given system. One can expect that for each XG-PON deployment, the configured TC layer maximum fibre distance will match the maximum fibre distance supported by the selected PMD layer parameter set (Figure 2.3-5).

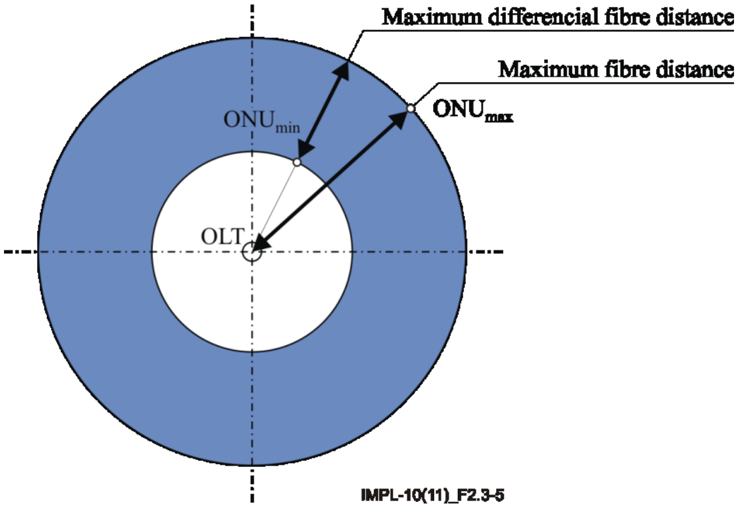


Figure 2.3-5 – Fibre distance concepts

The physical reach system parameter of the earlier PON system specifications corresponds to the maximum fibre distance supported by the system PMD layer. The logical reach system parameter of the earlier PON system specifications corresponds to the maximum fibre distance supported by the system TC layer.

2.3.1.3.2 Use of the terms ONU and ONT

The network element interfacing the end-user access facilities and the ODN is referred to as an ONU, irrespective of the number and type of user interfaces or the depth of fibre deployment. Historically, the term ONT has been used either interchangeably with ONU or with the particular semantics of "an ONU that is used for FTTH and includes the user port function" (ITU-T G.983.1), or "a single-subscriber ONU" (ITU-T G.984 series). The latter approach in defining ONT is at present currently used in ITU-T.

Alternative interpretations may apply and, therefore, the reader is advised to clarify the exact meaning of the term in each specific context. In particular, in some external contexts, the term ONT may be used generically to refer to any device terminating a leaf of the ODN.

2.3.1.3.3 Use of the terms T-CONT and Alloc-ID

A transmission container (T-CONT) is an OMCI managed entity representing a group of logical connections that appear as a single entity for the purpose of upstream bandwidth assignment in a PON system.

For a given ONU, the number of supported T-CONTs is fixed. The ONU autonomously creates all the supported T-CONT instances during ONU activation or upon OMCI management information base (MIB) reset. The OLT uses the ONU management and control channel (OMCC) to discover the number of T-CONT instances supported by a given ONU and to manage those instances.

The Allocation identifier is a number that the OLT assigns to an ONU to identify a traffic-bearing entity that is a recipient of upstream bandwidth allocations within that ONU. Such a traffic-bearing entity is usually represented by a T-CONT but may also be represented by an internal non-managed structure.

Each ONU is assigned at least its default Alloc-ID and may be explicitly assigned additional Alloc-IDs per the OLT's discretion.

To activate a T-CONT instance for carrying the upstream user traffic, the OLT has to establish a mapping between the T-CONT instance and an Alloc-ID, which has been previously assigned to the given ONU via the PLOAM messaging channel. Mapping of T-CONTs to Alloc-IDs is performed via the OMCC. The OMCC itself is mapped, in the upstream direction, to the default Alloc-ID. This mapping is fixed; it cannot be managed via the OMCI MIB and it should survive OMCI MIB reset.

While in many cases the mapping between T-CONTs and Alloc-IDs is one-to-one, strictly speaking, it is the Alloc-ID, not a T-CONT, which is visible at the TC layer of the system.

2.3.1.3.4 Use of the terms bandwidth assignment and bandwidth allocation

It is important to disambiguate between these two terms in a technical context, as they appear nearly undistinguishable in common use. The term "bandwidth assignment" refers to the distribution of the upstream PON capacity between the ONUs' traffic-bearing entities based on the provisioned services and using certain isolation and fairness criteria. The term "bandwidth allocation", on the other hand, denotes the process of granting individual transmission opportunities to the ONUs' traffic-bearing entities on the timescale of a single PHY frame. Bandwidth allocation employs the results of bandwidth assignment as one of its inputs, the other inputs being provided by the system requirements for various overhead types.

2.3.2 XG-PON: general requirements

Editor: Fabrice Bougart

(For further information see Recommendation ITU-T G.987.1.)

The general requirements of 10 Gigabit-capable passive optical network (XG-PON) systems are based on those of the previous ITU-T PON generations. This section of the Technical paper intends to guide and motivate the development of physical layer and the transmission convergence layer specifications, including system and operational requirements with principal deployment configurations identified by operators. Examples of services, service node interfaces (SNIs) and user network interfaces (UNIs) for business, residential and mobile backhaul applications over various architectures are given.

As much as possible, the characteristics specified for the B-PONs (see Section 2.1) and for the G-PONs (see Section 2.2) have been maintained. This is to promote backward compatibility with existing optical distribution networks (ODNs) that comply with those plants. Furthermore, this section provides a mechanism that enables seamless subscriber migration from Gigabit PON (Generic term to represent both G-PON and GE-PON) to XG-PON using the wavelength division multiplexing (WDM) defined in Section 2.2.

NOTE – GE-PON stands for Gigabit Ethernet passive optical network.

2.3.2.1 Architecture of the XG-PON networks

2.3.2.1.1 Reference configuration

The XG-PON basic reference configuration reuses the generic PON configuration shown in Section 2.1, which also indicates the reference points to be considered (Figure 2.3-6).

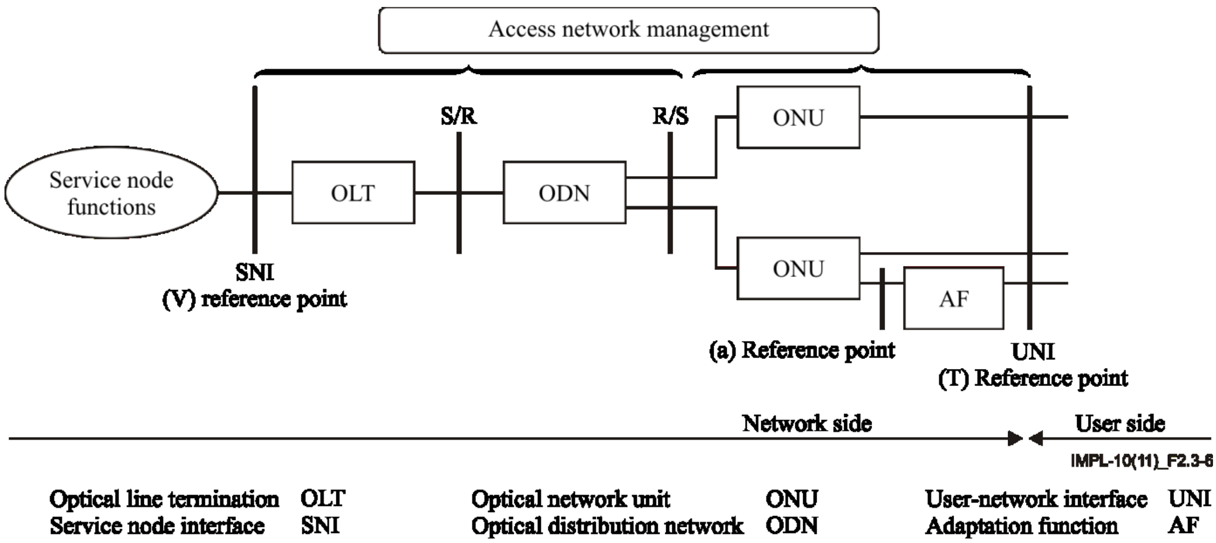


Figure 2.3-6 – High-level reference configuration of XG-PON

A XG-PON system consists of optical line termination (OLT), optical network unit (ONU) and ODN. The ODN offers one or more optical paths between one OLT and one or more ONUs. Each optical path is defined between reference points S and R in a specific wavelength window. The two directions for optical transmission in the ODN are identified as follows:

- downstream direction for signals travelling from the OLT to the ONU(s);
- upstream direction for signals travelling from the ONU(s) to the OLT.

The fibre cable has a passive optical network (PON) configuration with a passive optical splitter. One fibre is passively split between multiple ONUs who share the capacity of one fibre. Because of the passive splitting, special actions are required with respect to privacy and security. Moreover, in the upstream direction a TDMA protocol is required. (For further information see Recommendation ITU-T G.983.1.)

2.3.2.1.2 Network architectures

Figure 2.3-7 gives a reference architecture showing that an XG-PON ODN can consist of a single passive optical distribution segment (ODS), or a group of passive ODSs interconnected with reach extenders (REs).

Since from the G-PON era, REs have been introduced, which allows the full benefit of transmission capability, namely the highest possible split ratio and the maximal distance. An extension to passive plant definition introducing the notion of composite ODN has been introduced in XG-PON, which inherited the notion of passive plant sections (see Section 2.2.5 of this Technical paper and ITU-T G.984.6).

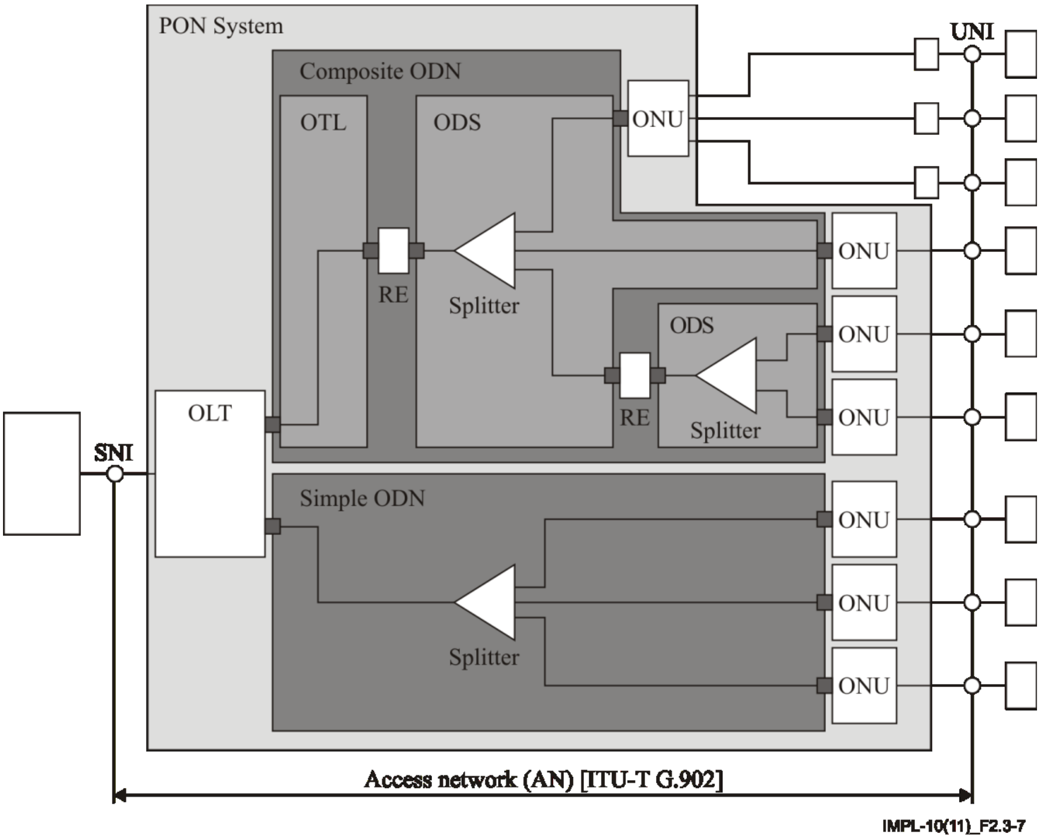
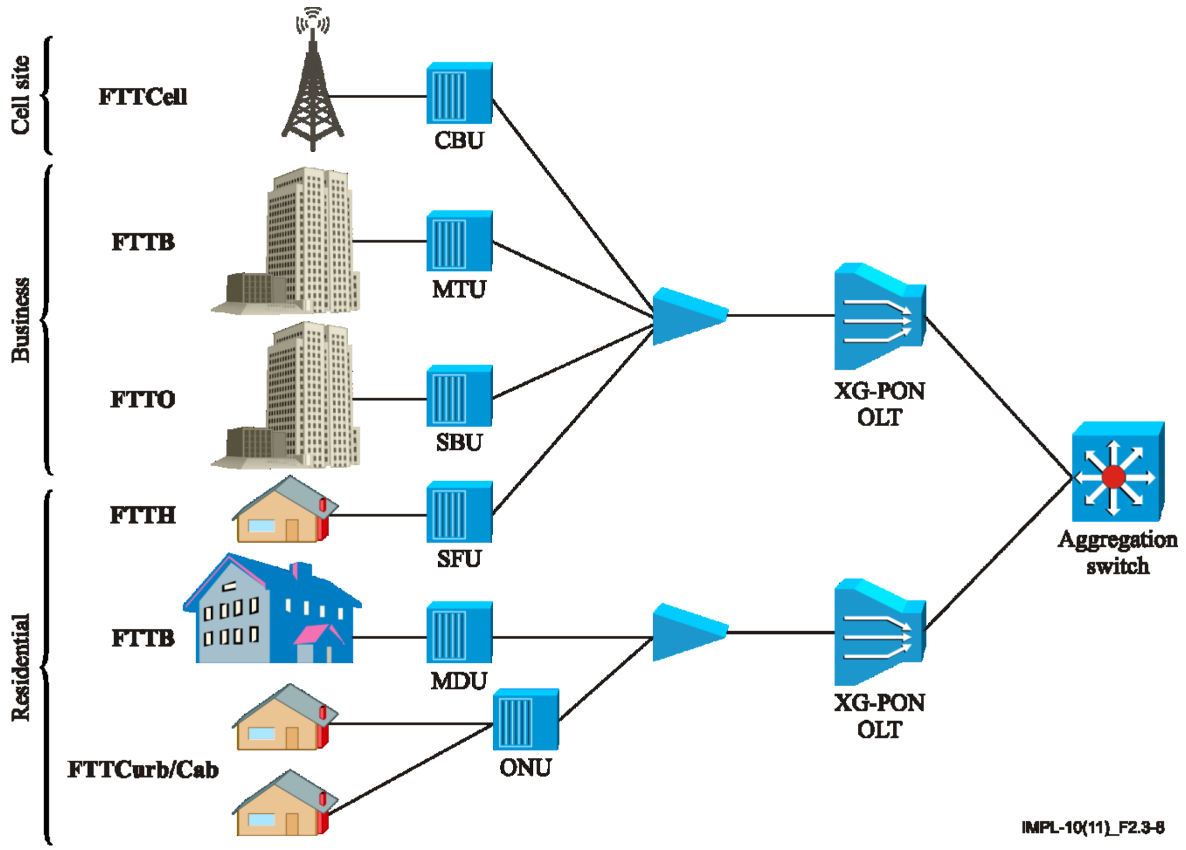


Figure 2.3-7 – Reference plant access network architecture

There are two types of network architecture:

- purely passive (FTTH/FTTO/FTTCell) architectures;
- active architectures in which the multi dwelling units (MDUs) and the ONUs are shared between several users/applications (FTTB/FTTCurb/FTTCab). In this case the MDU/ONU can be subject to indoor and outdoor conditions.

Different names are given to the ONUs depending on their application, as shown in Figure 2.3-8, which also gives an example of a combination of PON architectures sharing a single PON interface.



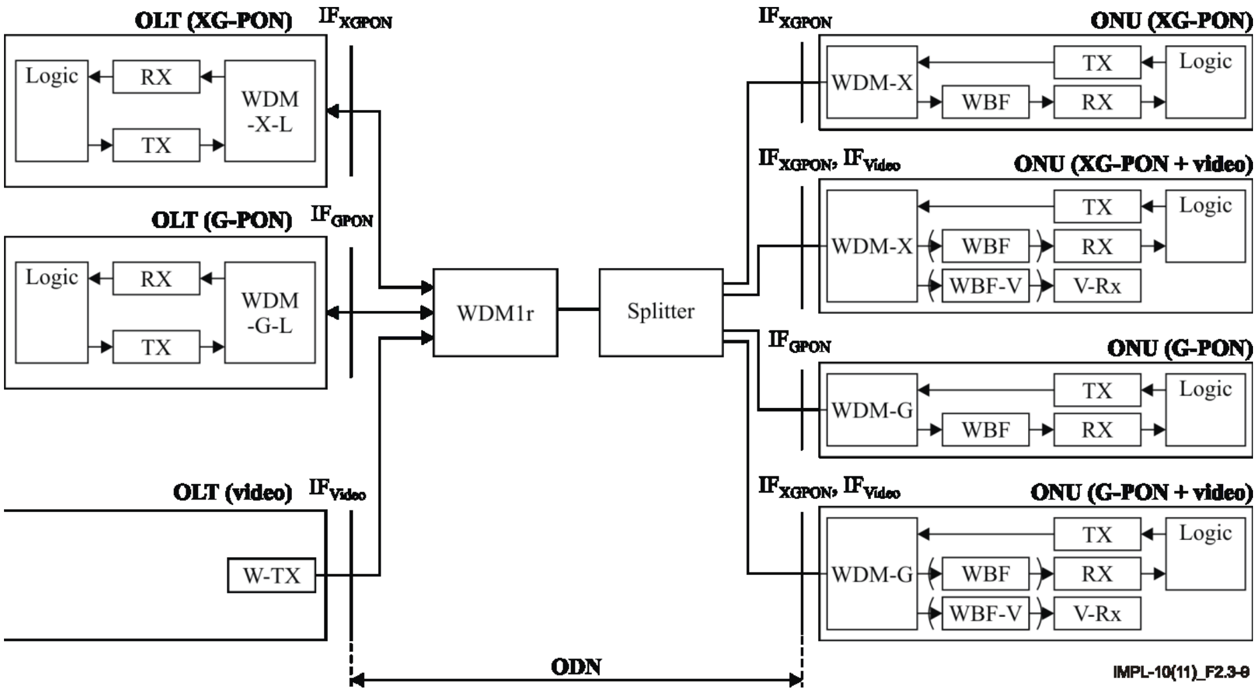
CBU Cell-site backhauling unit
MTU Multi-tenant unit
SBU Small business unit
SFU Single family unit
MDU Multi-dwelling unit
ONU Optical network unit
OLT Optical line terminal

Figure 2.3-8 – Collection of XG-PON scenarios

2.3.2.1.3 ODN architectures

In the ODN architecture the option of overlaying broadcast RF video services through a dedicated wavelength at 1550 nm and of coexistence with G-PON systems on the same fibre is considered. These options require both an injection point at the central office side and a related filtering within the ONUs. Two scenarios for injection can be envisioned at the central office either through a wavelength filter or via the ports of an N * M achromatic power splitter.

Both options are shown in Figure 2.3-9, one with a power splitter on the left side and the other with a wavelength filter on the right side of the ODN.



Tx	Optical Transmitter;
Rx	Optical Receiver;
V-Tx	Video Transmitter;
V-Rx	Video Receiver;
WBF	Wavelength Blocking Filter for blocking interference signals to Rx;
WBF-V	Wavelength blocking filter for blocking interference signals to V-Rx;
WDM-X	WDM filter in XG-PON ONU to combine/isolate the wavelengths of XG-PON upstream and downstream;
WDM-X'	WDM filter in XG-PON ONU to combine/isolate the wavelengths of XG-PON upstream and downstream and isolate the video signal(s);
WDM-G	WDM filter in G-PON ONU to combine/isolate the wavelengths of G-PON upstream and downstream;
WDM-G'	WDM filter in G-PON ONU to combine/isolate the wavelengths of G-PON upstream and downstream and isolate the video signal(s);
WDM-X-L	WDM filter in XG-PON OLT to combine/isolate the wavelengths of XG-PON upstream and downstream;
WDM-G-L	WDM filter in G-PON OLT to combine/isolate the wavelengths of G-PON upstream and downstream of one or more channels;
WDM1r	WDM filter that may be located in the central office to combine/isolate the wavelengths of XG-PON and G-PON signals and which occasionally combines the video signals.

Figure 2.3-9 – Reference optical configuration for XG-PON coexistence with G-PON through WDM1r

2.3.2.1.4 Operating wavelength for G-PON and XG-PON

The wavelength range of the XG-PON downstream signal on a single-fibre system is from 1575-1580 nm and the range of upstream signal for XG-PON is from 1260-1280 nm. This subsection redefines the reserved wavelength range and specifies the tolerance for interference signals of XG-PON ONUs to enable the coexistence of XG-PON and additional services such as G-PON and video services.

Figure 2.3-10 and Table 2.3-1 show the wavelength allocation plan including the wavelength bands reserved for additional services. The wavelength range of the XG-PON downstream signal is referred to as the "basic band". Reserved bands are referred to as the "enhancement band". Applications for the enhancement band may include G-PON and/or video services. The wavelength range for video services remains the same range as indicated in Section 2.2.4 of this Technical paper and in ITU-T G.983.3).

A guard band separates the XG-PON upstream and downstream from the enhancement band. The interference between signals in these two bands causes signal degradation of each band, so it must be reduced to a negligible level. Wavelength blocking filters (WBFs) are used to obtain the required isolation outside the guard band. The wavelength values specified in Table 2.3-1 consider guard bands that can be achieved with commercially available low-cost WBFs.

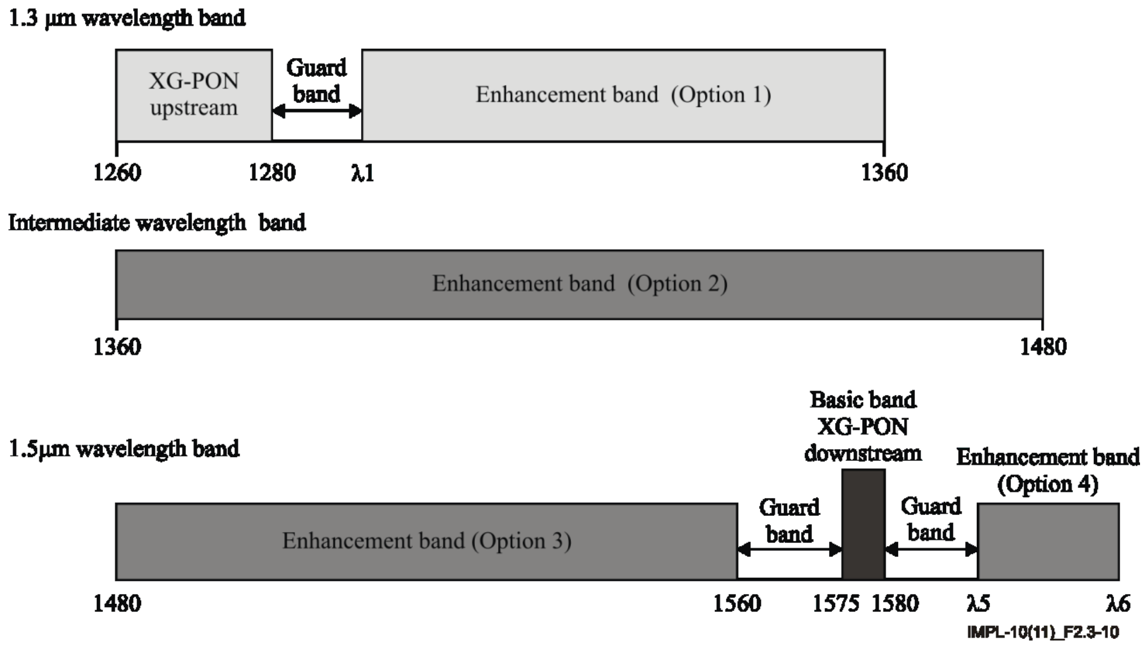


Figure 2.3-10 – Wavelength allocation diagram

Table 2.3-1 – Parameters for wavelength allocation in Figure 2.3-10

Items	Notation	Unit	Nominal value	Application examples
XG-PON upstream				For use in XG-PON1 upstream.
Lower limit	–	nm	1260	
Upper limit	–	nm	1280	
Enhancement band (option 1)				For use in G-PON upstream (reduced option: 1290-1330 nm).
Lower limit	λ1	nm	1290	
Upper limit	–	nm	1330	
Enhancement band (option 2)				For future use. (Note 1)
Lower limit	–	nm	1360 *(informative)*	
Upper limit	–	nm	1480 *(informative)*	
Enhancement band (option 3)				For use in G-PON downstream (1480-1500 nm) and/or video distribution
Lower limit	–	nm	1480	

Table 2.3-1 – Parameters for wavelength allocation in Figure 2.3-10

Items	Notation	Unit	Nominal value	Application examples
Upper limit	–	nm	1560	service (1550-1560 nm).
XG-PON downstream (basic band)				For use in XG-PON downstream.
Lower limit	–	nm	1575	
Upper limit	–	nm	1580	
Enhancement band (option 4)				For future use. (Note 2)
Lower limit	λ5	nm	TBD	
Upper limit	λ6	nm	TBD to 1625	
NOTE 1 – The values are informative. The loss in this band is not guaranteed in optical branching components for PON (i.e., power splitters) specified in ITU-T G.671 nor in optical fibres specified as ITU-T G.652 Categories A and B (non-low-water-peak fibres). NOTE 2 – The upper-limit value is determined as an operator choice from to be determined (TBD) to 1625 nm, considering the following factors: - bending loss of optical fibre that increases at longer wavelengths; - loss of a filter that separates/combines a monitoring signal and user signal(s) (if an optical monitoring system is used).				

2.3.2.1.5 Layered structure of XG-PON optical network

XG-PON transmission is based on a layered structure, similar to the one used on previous PON generations. This layered structure will be used for definition of the PMD (for further information see Section 2.3.3 and ITU-T G.987.2) and TC layer (for further information see Section 2.3.4 and ITU-T G.987.3), as shown in Table 2.3-2.

For the meaning of the specific terms used in Table 2.3-2, see Sections 2.3.1, 2.3.4 and ITU-T G.987 and ITU-T G.987.3.

2.3.2.2 Migration scenarios

Gigabit PONs such as G-PON (ITU-T G.984.x series) and 1G-EPON (IEEE 802.3, 2008) have been standardized and are now being deployed worldwide. With the ever increasing bandwidth demand from consumer and business applications, the most general requirement for a next generation-PON (NG-PON) is to provide higher bandwidth than Gigabit PON. In addition, given the major investments spent (time and money) on deploying Gigabit PON mainly in the fibre infrastructure, NG-PON must be able to protect the investment of the legacy Gigabit PONs by ensuring seamless and smooth migration capability for subscribers from Gigabit PON to NG-PON. Coexistence between XG-PON and G-PON, shown in the previous section, is enabled through the wavelength bandplan enhancements, which also provides optional overlay capability of broadcast TV on a separate wavelength.

NOTE – In the context of ITU-T standards development activity, next generation-PON (NG-PON) is a generic term referencing the PON system evolution beyond G-PON. The concept of NG-PON currently includes NG-PON1, where the ODN is maintained from B-PON and G-PON, and NG-PON2, where a redefinition of the ODN is allowed from that defined in B-PON and G-PON.

Table 2.3-2 – XG-PON layered structure

<table>
<tr><th colspan="3">Path layer</th><th></th></tr>
<tr><td rowspan="3">Transmission medium layer

(Note)</td><td rowspan="2">XGTC layer</td><td>Adaptation</td><td>XGEM encapsulation</td></tr>
<tr><td>PON transmission</td><td>DBA
XGEM port bandwidth allocation
QoS handling & T-CONT management
Privacy and security
Frame alignment
Ranging
Burst synchronization
Bit/byte synchronization</td></tr>
<tr><td colspan="2">Physical medium layer</td><td>E/O adaptation
Wavelength division multiplexing
Fibre connection</td></tr>
<tr><td colspan="4">NOTE – The transmission medium layer must provide the related OAM functions.
XGTC XG-PON transmission convergence (protocol layer)
XGEM XG-PON encapsulation method
DBA Dynamic bandwidth assignment
QoS Quality of service
T-CONT Transmission container
E/O Electrical/Optical
OAM Operation, administration and maintenance</td></tr>
</table>

2.3.2.2.1 Migration to XG-PON

There are several migration scenarios to meet different service providers' needs. These reflect recognition that differing service introduction strategies might affect requirements for the NG-PON specifications. Two likely migration scenarios are described below.

PON brown field migration scenario

PON brown field scenario refers to a deployment scenario where a PON system has already been deployed and network operators decide to leverage this existing fibre infrastructure to offer higher bandwidth carrier services, using XG-PON. Some subscribers on an existing Gigabit PON system might require an upgrade to such higher speed tier service and the network operator may therefore choose to move over these subscribers to the XG-PON system, while other subscribers remain on the Gigabit PONs. At a certain point, some network operators may eventually perform a 'forced migration' from Gigabit PON to XG-PON when the number of Gigabit PON subscribers becomes low. It is likely that both Gigabit PONs and XG-PONs will continue to coexist for a relatively long time in this scenario. In a similar, but slightly different migration scenario, a network operator might want to replace an existing Gigabit PON with an XG-PON completely. In this case, it would still make sense to run both Gigabit PON and XG-PON at the same time and update customers one at a time. However, the upgrade window is much shorter.

General requirements for this scenario are as follows:

- coexistence between Gigabit PON and XG-PON on the same fibre must be supported for the case that the fibre resource is not necessarily abundant;
- service interruption for the non-upgrade subscribers should be minimized;
- XG-PON must support/emulate all G-PON legacy services in the case of full migration.

PON green field migration scenario

Renovating the access network to FTTx infrastructure is the biggest investment of service providers and may take a long time. When XG-PON technology becomes mature, service providers might be interested in using XG-PON to replace copper-based infrastructure or to deploy in a brand new development area for the benefit of higher bandwidth and/or a higher splitting ratio. An area where Gigabit PON had not been deployed before is referred to as "PON green field". This scenario may help service providers achieve better economics while supporting the same or better bandwidth offer per user as Gigabit PON. In this scenario, the requirement of coexistence with Gigabit PONs is not necessary.

2.3.2.2.2 Migration from legacy PON to XG-PON

To assure this smooth migration capability, overlay through WDM technology in compliancy to optical wavelength allocation described in Section 2.2.4 must be implemented in all ONUs. It will, of course, remain the discretion of the operator whether to use this capability or rather run a full PON active devices replacement from day one of an upgrade process.

To get simultaneous G-PON and XG-PON working in the transition period, a WDM1r combiner/splitter is installed in the network, as illustrated in Figure 2.3-11.

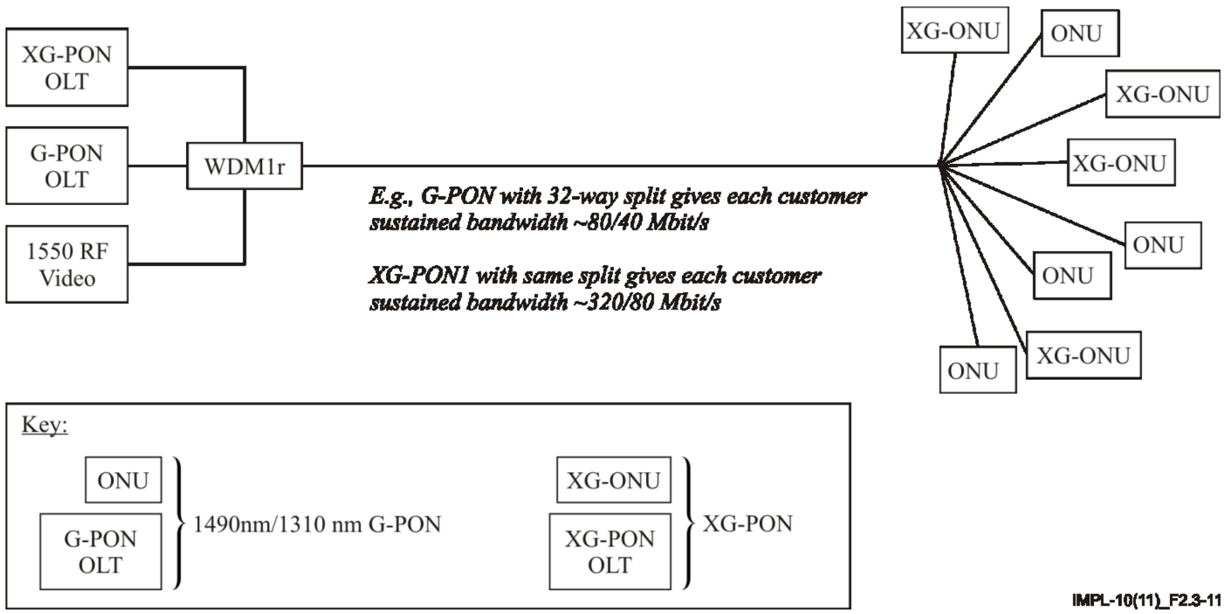


Figure 2.3-11 – Example of coexistence of G-PON and XG-PON with video overlay option

Any coexistence combination of XG-PON may be used. Specifically, XG-PON can coexist with RF video overlay only.

2.3.2.2.3 Reach extender options

In order to get the full benefit of the XG-PON maximal split and maximum distance, the use of RE is seen as a major necessary step for network consolidation with reduction of OLT point of presence. Reach extenders will be further defined in Section 2.3.5 in two configurations whether legacy G-PON has already been reach extended or not, according to the two architectures shown in Figure 2.3-12.

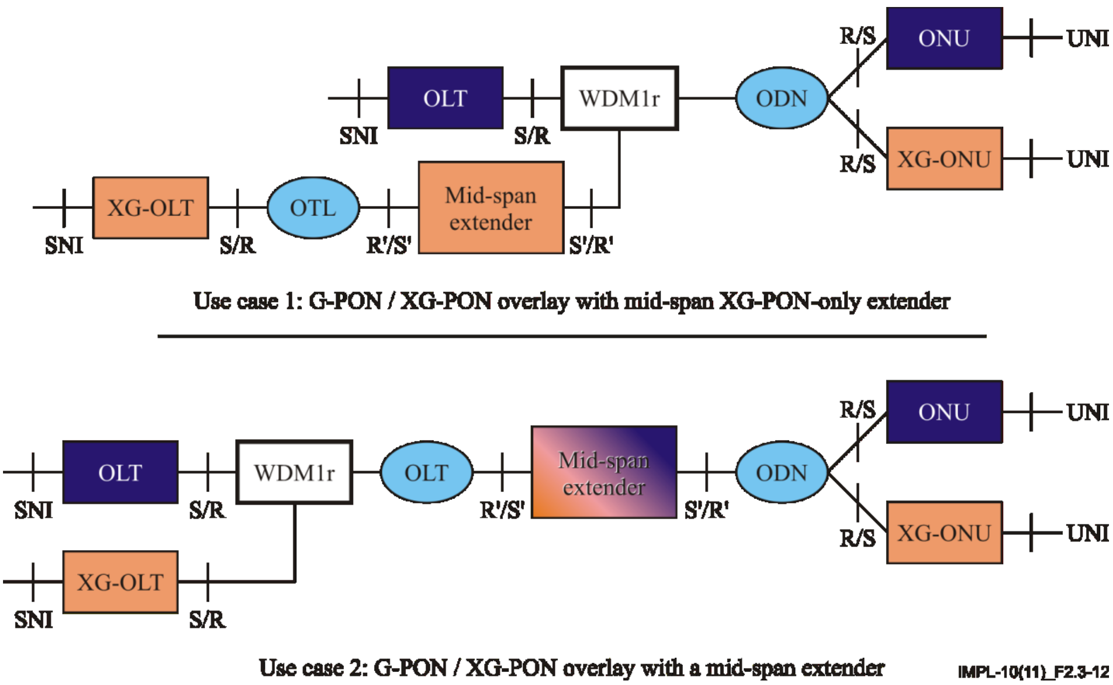


Figure 2.3-12 – Deployment of reach extenders

2.3.2.3 Service and interface requirements

Since XG-PON aims at supporting the full range of architecture for a comprehensive list of existing services, special care has been taken to ensure:

- a low delay/latency capability of 1.5 ms with an 8 kHz reference for POTS and for mobile backhauling applications requiring additional frequency/phase and time synchronization with basic performances described in Appendix II of ITU-T G.987.1. Those features based on ITU-T G.8261 will be enhanced according to future long-term evolution (LTE) requirements under definition in ITU-R;
- capability of delivering IP multicast and unicast services with the following QoS enablers:
  - XG-PON must provide at least four classes of services to map UNI flows;
  - XG-PON must also support drop precedence within at least two traffic classes;
  - XG-PON ONUs must support rate controlled services (e.g., committed information rate/peak information rate, CIR/PIR) with policing and shaping function in addition to the priority based traffic management;
  - XG-PON must support any mix of residential, business and mobile backhaul traffic within the same PON;
  - XG-PON must support N:1 VLAN, 1:1 VLAN and access to VLAN for business Ethernet service (VBES) on the same PON.
- capability of accommodating business applications that require the transfer Ethernet jumbo frames up to 9000 bytes.

Some examples of UNI interfaces and of the related services required for X-PON are shown in Table 2.3-3.

Table 2.3-3 – Examples of UNI and services

UNI (Note 1)	Physical interface (Note 2)	Service (Note 3)
1000/100/10BASE-T (IEEE 802.3)	–	Ethernet
ITU-T Q.552		POTS
ITU-T G.703	PDH	DS3, E1, E3
ATIS 0900102 and ATIS 0600107	PDH	T1, DS3
NOTE 1 – There are many other services accommodated in XG-PON, but those services do not have specified UNIs. NOTE 2 – Each item in the "physical interface" column is illustrated by the corresponding entry in the "UNI" column. NOTE 3 – The column labelled "service" shows which services can be supported by the physical interface.		

Some examples of SNI interfaces and of the related services required for X-PON are shown in Table 2.3-4.

Table 2.3-4 – Examples of SNI and services

SNI (Note 1)	Physical interface (Note 2)	Service (Note 3)
1000BASE-T (IEEE 802.3)	–	Ethernet
10 GigE (IEEE 802.3)	–	Ethernet
40 GigE (IEEE 802.3)	–	Ethernet
100 GigE (IEEE 802.3)	–	Ethernet
ITU-T G.965	V5.2	POTS
ITU-T G.703	PDH, STM-1e	DS3, E1, E3, STM-1, DS1 (Note 4)
ITU-T G.957	STM-1,4,16	E1, E3, DS1, DS3, GFP, E4, STM-n (Note 4)
ATIS 0600107	PDH	DS1, DS3 (Note 4)
NOTE 1 – There are many other services accommodated in XG-PON, but those services do not have specified SNIs. NOTE 2 – Each item in the "physical interface" column is illustrated by the corresponding entry in the "SNI" column. NOTE 3 – The column labelled "service" shows which services can be supported by the physical interface. NOTE 4 – These acronyms refer to PDH and SDH hierarchical bit rates (see ITU-T manual *Optical Transport Networks from TDM to Packet*, Chapter 2).		

2.3.2.4 Physical layer requirements

Since the above requirements aim at coexistence on a legacy PON fibre plant with a XG-PON, physical layer transmission inherited the following features.

- Single fibre transmission between ONU and overlay enabling filter (as WDM1r).
- Transmission characteristics are based on the fibre described in ITU-T G.652. Other fibre types may be compatible with this Recommendation, e.g., ITU-T G.657 used, for example, for in-building cabling, drop section.
- Basic transmission line rates for XG-PON at present are 10 Gbit/s downstream and 2.5 Gbit/s upstream, not precluding that in the future when burst mode technology matures, a TDMA compatible solution named XG-PON2 could be defined featuring a 10 Gbit/s upstream capability. The retained optical budget options, all featuring an overlay capability to G-PON on at least a class B+ plant, have been designed with inclusion of the WDM1r device excess loss and anticipating improvement in transceivers technology to enable future compatibility with class C+ (see Table 2.3-5). The detailed specifications for nominal classes and the extended class will be addressed in Section 2.3.3.
- Split ratio and splitting structure must be at least compatible with G-PON legacy, featuring at least with nominal 32 or 64 ways split with a capability at logical level to extend it with enhanced optics to 1:256. The split ratio can be implemented in either a single or multi-stages scheme.
- A minimal fibre distance of 20 km must be nominally provided, with a TC layer extension capability of up to 60 km length (available with adapted optics), where a differential range of 40 km is required.

Table 2.3-5 – Classes for optical path loss

	Nominal 1	Nominal 2	Extended 1	Extended 2
Class B+ compatible	14-29 dB	16-31 dB	---	---
Class C+ compatible	---	---	18-33 dB	20-35 dB

2.3.2.5 System level requirements

2.3.2.5.1 Power-saving and energy efficiency

Power-saving in telecommunication network systems has become an increasingly important concern in the interest of reducing operators' operating expenditure (OPEX) and reducing the network contribution to greenhouse gas emissions. The primary objective of the power-saving function in access networks is to continue to provide the lifeline service(s) such as a voice service as long as possible through the use of a backup battery when electricity service goes out. For example, some operators require a minimum sustainability for a lifeline interface to operate for 4 to 8 hours after mains outage. Therefore, the XG-PON TC layer shall support better energy efficiency than the ITU-T G.984 G-PON TC layer whenever compatible with the service requirements, based on the mechanisms derived from Supplement 45 to the ITU-T G-series Recommendations.

The secondary goal is to reduce power consumption at all times. It is also an important requirement that service quality and user experience should not be sacrificed. Full service mode, dozing mode and sleep mode are the options that can offer various levels of power-saving during the normal mode of operation. In addition, when the mains outage happens, power shedding should be activated for the power-saving capability, realizing that detailed values may vary for XG-PON.

Section 2.2.8 and Supplement 45 to the ITU-T G-series Recommendations compare the efficiency of each power-saving technique as well as the level of service impact. Power-saving modes enabling partial and synchronized low energy modes have been defined when the ONU has no data to transmit so as to enable a minimal power consumption (for further information see Section 2.2.8). These include:

- power shedding: shutting down inactive UNI interfaces;
- dozing: shutting down upstream transmission of the ONU when it has no data to transmit;
- cyclic sleep: shutting down the whole ONU transceiver with periodical synchronous wake-up to check connectivity and maintain an efficient monitoring link with a short resume time.

2.3.2.5.2 Authentication/identification/encryption

Like G-PON, XG-PON is a shared-medium based system in which all the ONUs on the same PON receive full data. Accordingly, countermeasures must be taken to avoid impersonation/spoofing and snooping. Enhanced authentication/identification and encryption mechanisms have been added so that the most stringent conditions for operators wanting to enter a full optical access era can be fulfilled over a shared infrastructure.

2.3.2.5.3 Dynamic bandwidth assignment

The XG-PON OLT shall support DBA for the efficient sharing of upstream bandwidth among the connected ONUs and the traffic-bearing entities within the individual ONUs based on the dynamic indication of their activity. This functionality is described in Section 2.2.3.

2.3.2.5.4 Eye safety

Given the higher launched optical power that can be injected on the fibre in the XG-PON era, both at the OLT and the RE level, all necessary mechanisms must be provided to insure that no eye damage can be caused to the end users unaware of the risks, especially if fibre is terminated inside the home. The XG-PON elements need to conform to the following specific classes defined in IEC 60825-2, respectively:

- Class 1M for OLT
- Class 1 for ONU
- Class 1M for RE.

2.3.2.6 Operational requirements

2.3.2.6.1 OMCI managed ONU

It is highly desirable from the network operation perspective to manage an XG-PON system, i.e., an OLT together with its ONUs, as a single entity, with ONUs being managed via OLTs, wherever possible. Therefore, XG-PON should support full PON real-time management through ONU management and control functions, where concepts and approaches implemented for G-PON (e.g., OMCI) should be reused as much as possible. XG-PON shall optionally support the collaborative ONU management partition between XG-PON OMCI and remote configuration mechanisms. Although basic remote management of the ONU will be executed via the OMCI, some network operators require shared ONUs and that the ONU includes a residential gateway capability such that a dual management scheme might be possible.

2.3.2.6.2 PON supervision

While minimize capital expenditure in the initial stage of FTTH deployment is of paramount importance, today it is becoming more important to reduce operational expenditure as well as to optimize the balance between capital expenditure and operational expenditure according to the full deployment of FTTH. The goal of PON supervision is to reduce the operational expenditure of the PON systems, without significantly increasing the capital expenditure by including as much test and diagnostic capability as possible without compromising the available bandwidth for services. Test and diagnostics must be non-service affecting. Current G-PON's capability of basic testing and diagnostics, which operates at the PON and data layers, with reporting back of alarms and events, should be taken as a basis for XG-PON. The ability to reliably differentiate between optical and electrical faults and establish if the faults are in the ODN or in the electronics is a key operator requirement. PON supervision enablers have been included for XG-PON with enhanced optical modules monitoring capabilities (see ITU-T G.984.2 Amendment 2, Appendix IV).

2.3.2.7 Resilience and protection on ODN

Service resilience over previous generations of PONs has not been a strong requirement from operators. XG-PON is required to support a diverse range of high value services (e.g., Internet protocol television, IPTV) for residential and also business applications with increasing levels of system integration at the head-ends. Failures in the shared portions of the PON will impact multiple customers and services. Consequently, the capability to offer improved service availability figures in XG-PON systems will become increasingly important. Individual operators need to determine the best resilience architecture for their specific market and geography. As such, XG-PON should include a range of cost-effective resilience options with both duplex and dual-parented duplex system configurations, as well as the extensions described in Section 2.1.5 of this Technical paper and in ITU-T G.984.1. These resilience schemes should be options available on XG-PON scenarios whether they use mid-span reach extenders or not. Different types of service and specific offerings will require different recovery speeds. These may range from a few tens of milliseconds – for critical and important services such as protected leased lines – up to the order of minutes for residential applications. Note that support for resilience options should not increase the cost of such systems, if deployed without resilience options. The protection architecture of XG-PON should be considered as one of the means to enhance the reliability of the access networks. However, protection shall be considered as an optional mechanism because its implementation depends on the realization of economical systems. It is also likely to use other methods, such as using alternative access technologies, e.g., Mobile's 4G standard (also known as LTE), for backup with better economics. Further information on protection switching can be found in ITU-T G.808.1. When mid-span REs are used, their adaptation is still under study.

2.3.2.8 Examples of practical XG-PON system architecture

XG-PON aims at being compatible with many architectures, so it is not possible to describe all of them.

The XG-PON system basic architecture in Figure 2.3-13 is the most common one representing a FTTH with Ethernet-based SNI and UNI, i.e., a generic XG-PON system.

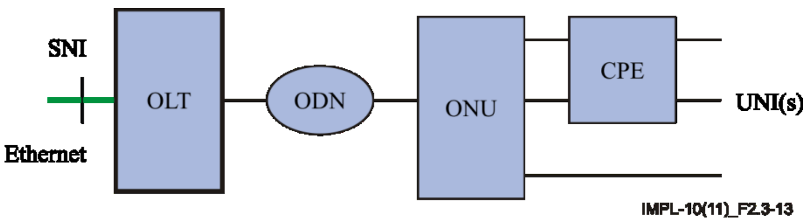


Figure 2.3-13 – XG-PON basic architecture

Figure 2.3-14 describes the case of an UNI (IEEE 802.1 and IEEE 802.3) directly offered by the ONU.

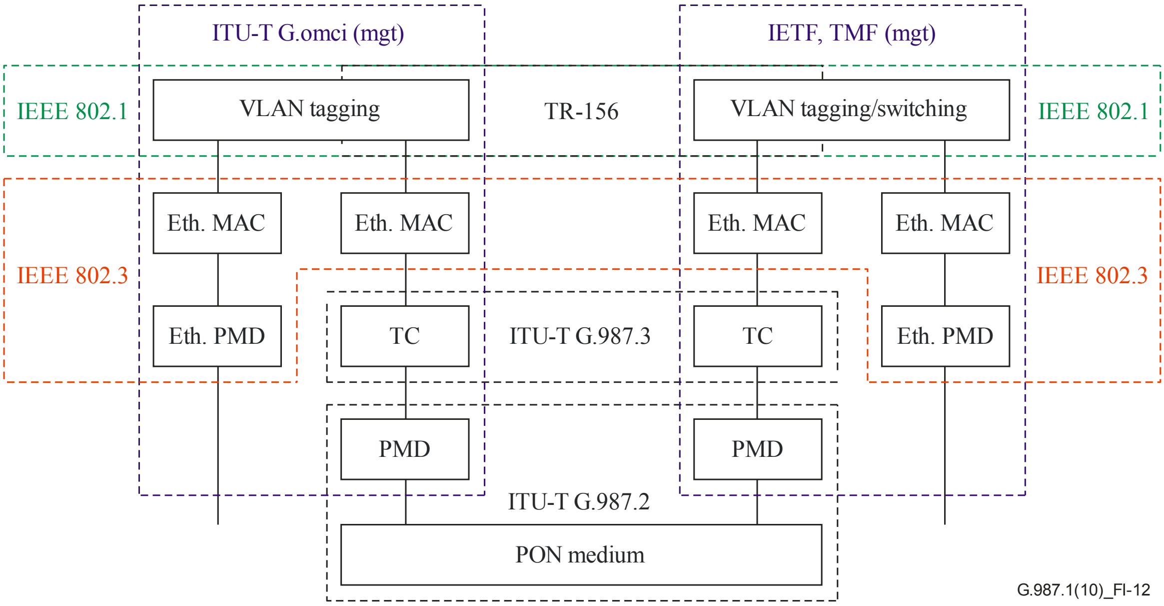


Figure 2.3-14 – Ethernet data service

Many more examples of architectures and related protocol stacks can be found in Appendix I to ITU-T G.987.1.

2.3.3 XG-PON physical media-dependent layer

Editors: Richard Goodson and Joe Smith

(For further information see Recommendation ITU-T G.987.2.)

A 10 Gigabit-capable passive optical network (XG-PON) is a PON system supporting nominal transmission rates of 10 Gbit/s downstream/2.5 Gbit/s upstream, and implementing the suite of protocols specified in the ITU-T G.987 series.

This section describes the requirements for the XG-PON physical media-dependent (PMD) layer. XG-PON is designed to operate over same ODN as its predecessor G-PON (see Section 2.2), but at four times (9.95328 Gbit/s) the downstream rate and twice (2.48832 Gbit/s) the upstream rate.

2.3.3.1 Classes for optical path loss

XG-PON has two basic optical path loss classes, normal and extended. The normal class is implemented using typical optical components as currently found in the industry whereas the extended class enhances the capabilities of currently deployed optical links, primarily by encompassing the use of optical amplifiers to increase link budgets. In total there are four optical path loss classes: N1, N2, E1 and E2 corresponding to optical path losses (in dB) shown in Table 2.3-6. The higher path loss classes can be used to increase the number of splits in the PON or to increase the reach of the PON.

Table 2.3-6 – Classes for optical path loss

	Nominal 1 class (N1 class)	Nominal 2 class (N2 class)	Extended 1 class (E1 class)	Extended 2 class (E2 class)
Minimum loss	14 dB	16 dB	18 dB	20 dB
Maximum loss	29 dB	31 dB	33 dB	35 dB

2.3.3.2 Categories for fibre differential distance

The differential fibre distance is the absolute difference between the fibre distances of two particular ONUs connected to the same OLT PON interface.

Two categories of differential fibre distance for XG-PON are shown in Table 2.3-7.

Table 2.3-7 – Categories for fibre differential distance

	DD20	DD40
Maximum differential distance	20 km	40 km

The amount of fibre dispersion that must be tolerated varies with the differential distance category. For example, the 20 km category (DD20) has a dispersion range of 0-400 ps/nm in the downstream direction, whereas the 40 km category (DD40) has a range of 0-800 ps/nm.

2.3.3.3 Physical media-dependent layer requirements for the XG-PON

All the parameters which characterize the optical interface parameters of the 10 Gbit/s downstream direction and of the 2.5 Gbit/s upstream direction are described and specified in ITU-T G.987.2. The main issues are dealt with below.

A key parameter in the determination of the transmit power and the receiver sensitivities for the various optical path loss classes was the type of optical receiver anticipated. Specifically, both PIN (”P” type “I” intrinsic “N” type photo diode) and avalanche photo diode (APD) optical receivers were anticipated. PIN receivers are assumed to have a sensitivity of -21.5 dB when forward error correction (FEC) is used, whereas APD receivers are assumed to have a sensitivity of -28 dB when FEC is used. Classes N1 and E1 are designed for APD receivers. Classes N2 and E2 are divided into two classes: N2a and E2a designed for APD receivers, N2b and E2b designed for PIN receivers. Note that FEC is required for downstream, while its use upstream is optional.

Figure 2.3-15 shows the transmit power, receive sensitivity and path loss for the various optical path loss classes.

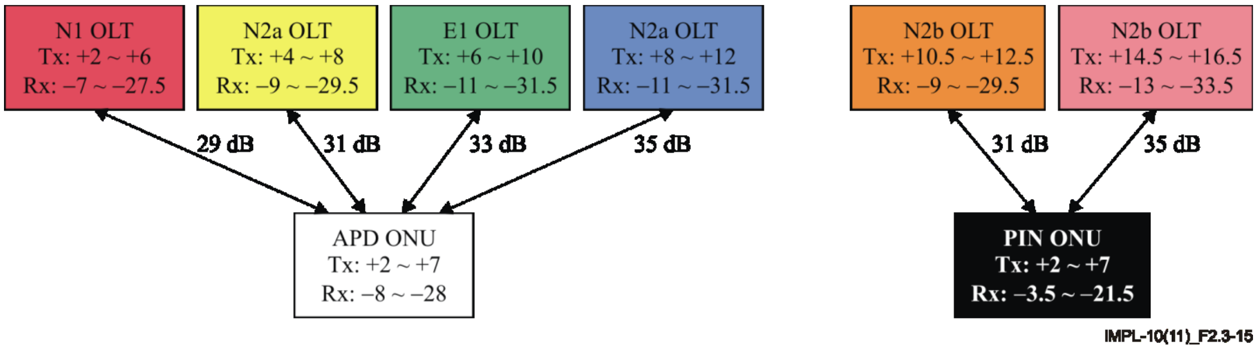


Figure 2.3-15 – Power budgets for optical path loss classes (29, 31, 33 and 35 dB)

An example of the relationship between the path loss and Tx/ Rx values is the following:

(N1 OLT Tx: +2) – (APD ONU Rx: -28) – (Penalty: 1 dB) = (Path Loss: 29 dB)

2.3.3.4 The wavelength plan

The wavelength plan of XG-PON and G-PON allows an XG-PON and G-PON system to coexist on the same ODN at the same time, and allows coexistence with RF video overly. The wavelength plan for XG-PON, G-PON and a typical RF video overlay is shown in Figure 2.3-16.

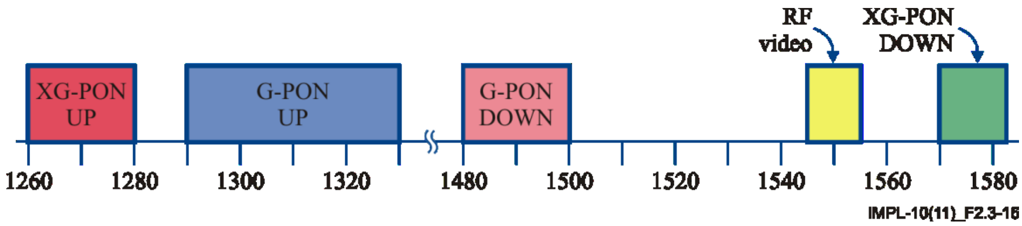
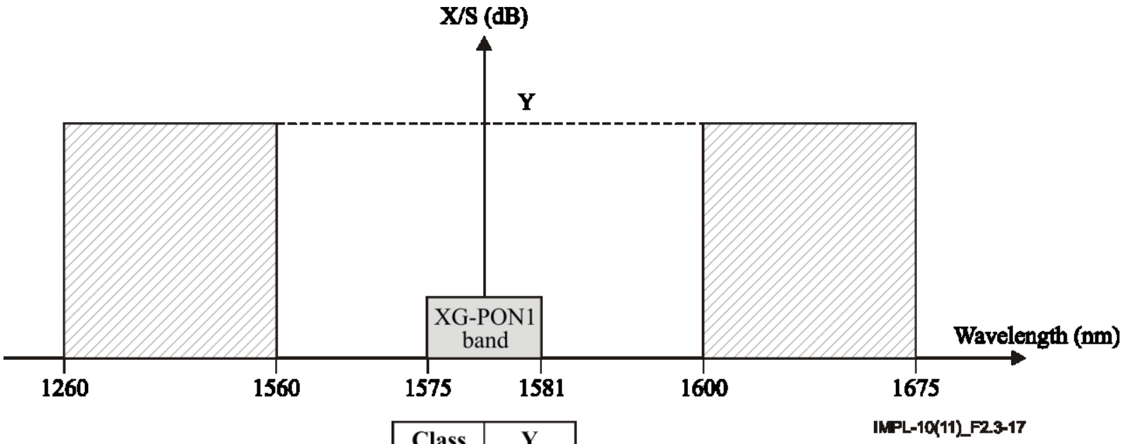


Figure 2.3-16 – Wavelength plan for G-PON and XG-PON

Note that for coexistence to be realized, appropriate filtering at the XG-PON ONUs must be realized. Figure 2.3-17 shows the X/S tolerance mask, where, as measured at the ONU receiver, "X" is the total power of the interfering signals in the specified bands, "S" is the power level of the desired (XG-PON) signal, and X/S is the power ratio in dB, as defined in ITU-T G.987.2 Amendment 1. Implementers must specify the isolation characteristics of the ONU WBF and WDM filters such that the XG-PON sensitivity requirement is met when the interference signals are X/S dB higher than the XG-PON receive signal. The interfering wavelengths and X/S value must fall beneath the mask of Figure 2.3-17 to allow coexistence with XG-PON.



Class	Y
x1, x2a	21.5
x2b	15

NOTE – x1 covers N1, E1. x2a covers N2a, E2a. x2b cover N2b, E2b

Figure 2.3-17 – X/S tolerance mask for ONU (Versatile WDM configuration)

2.3.3.5 Additional definitions

The eye diagram masks for the 10 Gbit/s and 2.5 Gbit/s signals are taken from existing industry standards, and described in ITU-T G.987.2 Clause 9.2.7.6 for convenience.

Similarly the jitter characteristics are leveraged from existing industry standards and described in ITU-T G.987.2 Clause 9.2.9.7 for convenience.

2.3.4 XG-PON transmission convergence layer specifications

Editor: Yuanqiu Luo

(For further information see Recommendation ITU-T G.987.3.)

This section describes the XG-PON transmission convergence (XGTC) layer that is a protocol layer of the XG-PON protocol suite, which is positioned between the physical media-dependent (PMD) layer and the XG-PON clients.

This description, mainly based on the content of Recommendation ITU-T G.987-3, refers to the formats and procedures of mapping between upper layer SDUs on the one hand, and bit streams suitable for modulating the optical carrier on the other hand. In particular this section deals with the following subjects: XGTC layered structure and functionalities, layer framing and service data encapsulation, ONU activation and timing relationships, ONU management, resource allocation, security, power-saving and performance monitoring.

2.3.4.1 XGTC layer structure and functionality

The XGTC layer is present at both the OLT and ONU sides in an XG-PON system. Figure 2.3-18 shows the XGTC layer structure. There are three sublayers: the XGTC service adaptation sublayer, the XGTC framing sublayer and the XGTC PHY adaptation sublayer.

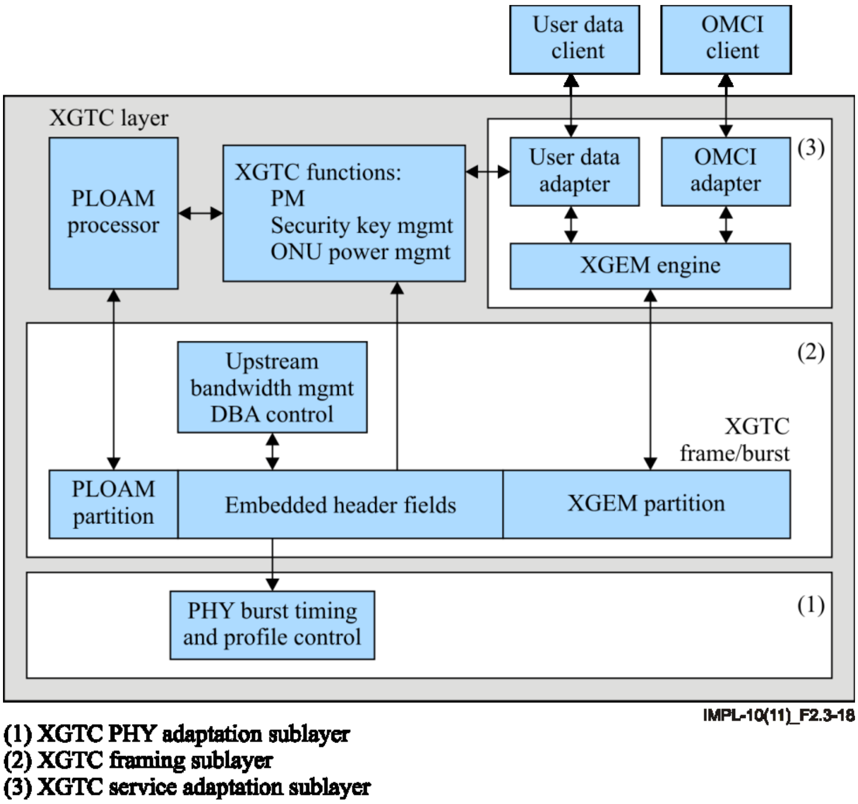


Figure 2.3-18 – XGTC layer structure

XGTC service adaptation sublayer

The XGTC service adaptation sublayer is the top sublayer of the XGTC protocol stack. It provides upper layer service data unit (SDU) encapsulation, multiplexing and delineation. The SDUs in an XG-PON system include user data and OMCI traffic, and the two service adapters in the XGTC service adaptation sublayer are configured to accommodate them, respectively. On the transmitter side, SDUs are fragmented as necessary and encapsulated into XG-PON encapsulation method (XGEM) frames. On the receiver side, XGEM frames are filtered from the XGTC frames or bursts, reassembled to SDUs, and delivered to the user data client or OMCI client. The XGEM engine performs traffic multiplexing and filtering based on the XGEM port identifier (XGEM Port-ID). The XGEM Port-ID identifies XGEM frames that belong to different logical connections. When the XGEM frame payload is optionally encrypted, the XGTC service adaptation sublayer also deals with encryption and decryption.

XGTC framing sublayer

The XGTC framing sublayer is responsible for construction and parsing of the downstream XGTC frame and upstream XGTC burst. The frame and burst formats are devised to align to 4-byte word boundaries whenever possible. The XGEM frames from the service adaptation sublayer form the XGTC payload. The overhead fields in the downstream XGTC frame header or upstream XGTC burst header carry necessary PON management information. Upstream bandwidth management and dynamic bandwidth assignment (DBA) signalling are processed within the framing sublayer to support resource allocation.

XGTC PHY adaptation sublayer

The XGTC PHY adaptation sublayer provides the functions of forward error correction (FEC), scrambling and line coding. The physical synchronization block is prepended to the downstream XGTC frame or upstream XGTC burst, providing timing alignment of the bit stream.

2.3.4.2 Downstream frame and upstream burst

Downstream frame

The XG-PON downstream transmission is partitioned into fixed-size downstream PHY frames. Figure 2.3-19 shows the downstream frame format. Each downstream PHY frame is 125 µs and has the size of 155 520 bytes. A downstream PHY frame consists of a 24-byte downstream physical synchronization block (PSBd) and a 155 496-byte PHY frame payload. The PSBd contains physical synchronization sequence (PSync), superframe counter (SFC) structure and PON-ID structure.

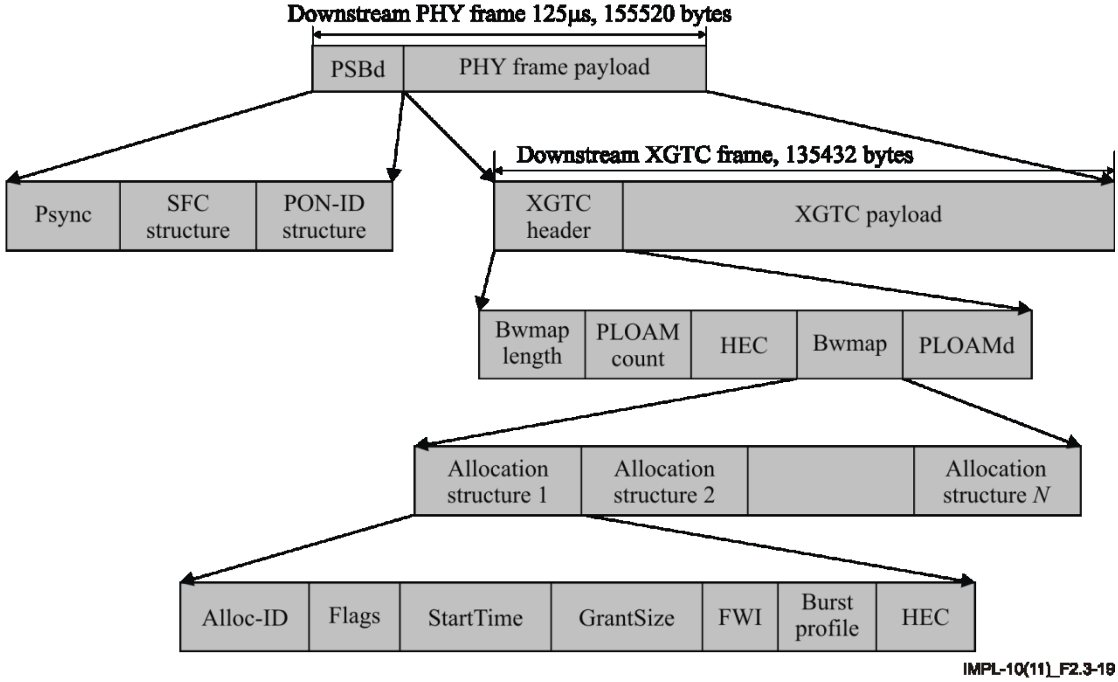


Figure 2.3-19 – XG-PON downstream frame format

The downstream PHY frame payload contains a downstream XGTC frame of 135 432 bytes and FEC parities of 20 064 bytes. The downstream XGTC frame consists of the XGTC header and the XGTC payload section. The XGTC header carries the bandwidth map (BWmap) information and downstream PLOAM messages. The BWmap specifies upstream bandwidth allocations to different traffic-bearing entities (i.e., Alloc-IDs). The XGTC payload contains multiple XGEM frames.

Upstream burst

The OLT employs the BWmap to control timing and duration of the upstream transmissions from ONUs. The upstream bursts have dynamically determined sizes and locations. Figure 2.3-20 shows the upstream burst format. An upstream PHY burst consists of an upstream physical synchronization block (PSBu) and a PHY burst payload. The PSBu contains preamble and delimiter, allowing the OLT optical receiver to adjust to the level of the optical signal and to delineate burst.

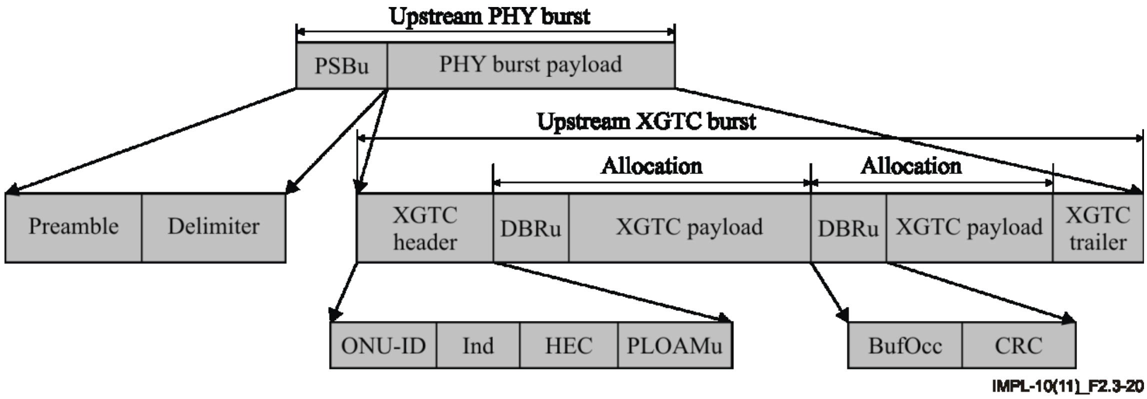


Figure 2.3-20 – XG-PON upstream burst format

The upstream PHY burst payload contains the upstream XGTC burst and may optionally contain FEC parities. The upstream XGTC burst consists of the upstream XGTC burst header, one or more bandwidth allocation intervals, and the XGTC trailer. The XGTC burst header carries identification and unsolicited signalling information. It may contain one PLOAM message as controlled by the OLT. Each bandwidth allocation contains the XGTC payload and may optionally contain a buffer occupancy (BufOcc) report. The XGTC payload contains multiple XGEM frames. The XGTC trailer is a 4-byte bit-interleaved parity (BIP), which provides BER estimation of the upstream link when upstream FEC is turned on.

2.3.4.3 XG-PON encapsulation method (XGEM)

The XGTC payload section in the downstream frame and upstream burst consists of one or multiple XGEM frames. Each XGEM frame contains a XGEM header and a XGEM payload field. Figure 2.3-21 shows the XGEM frame format. The XGEM header is 8 bytes. It contains information on payload size (i.e., payload length indication), data security (i.e., key index), traffic multiplexing (i.e., XGEM Port-ID) and SDU fragmentation (i.e., last fragment).

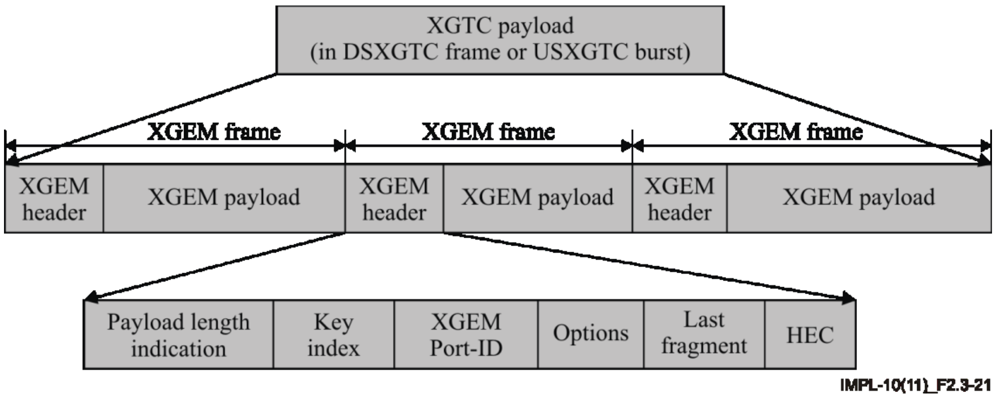


Figure 2.3-21 – XGEM frame format

The XGEM payload is a variable-length field carrying SDUs or SDU fragments. Figure 2.3-22 shows SDU fragmentation. When the SDU or SDU fragment is not equal to a multiple of 4 bytes, the XGEM engine adds one to seven padding bytes in the least significant byte positions. This aligns the XGEM payload at the 4-byte word boundaries.

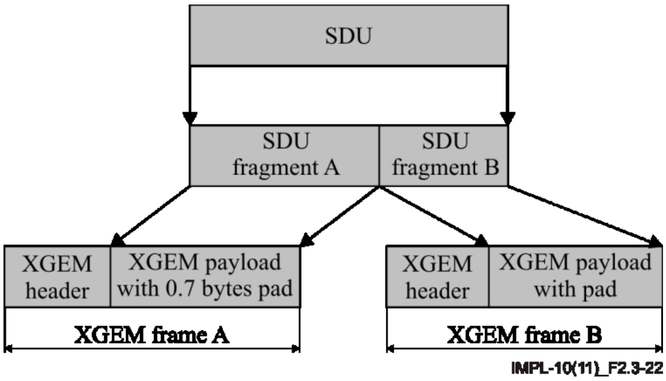


Figure 2.3-22 – SDU fragmentation

2.3.4.4 FEC and scrambling

The downstream FEC code is R-S (248,216), which is a truncated form of R-S (255,223) code. The upstream FEC code is R-S (248,232), which is a truncated form of R-S (255,239) code. FEC support is mandatory for both the upstream and downstream. In the downstream direction, FEC is always on; in the upstream direction, the use of FEC is under dynamic control by the OLT.

The downstream PHY frame is scrambled using a frame-synchronous scrambling polynomial. The polynomial used is $x^{58} + x^{39} + 1$. The shift register used to calculate this polynomial is reset by a preload pattern at the first bit following the PSBd block. It runs until the last bit of the downstream PHY frame. The 58-bit preload is represented by the 51-bit superframe counter transmitted in the PSBd block and 7-bit 1s. The upstream PHY burst scrambling is similar to that of the downstream PHY frame. It is burst synchronous. The scrambler is shown in Figure 2.3-23.

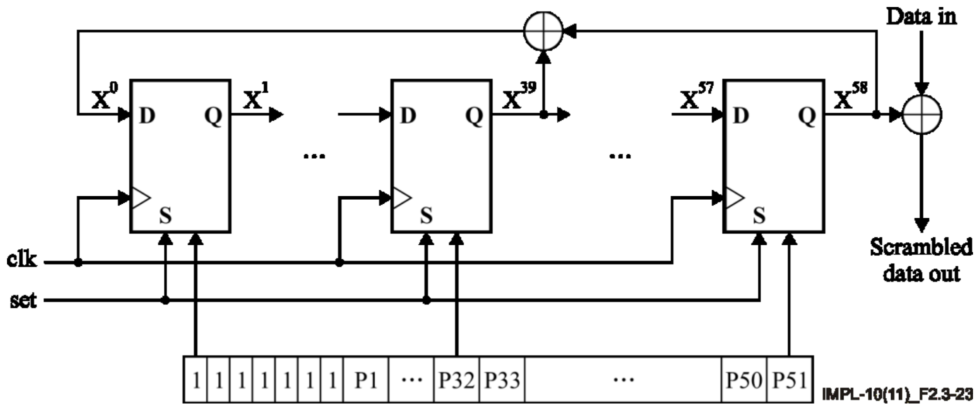


Figure 2.3-23 – XG-PON scrambler

2.3.4.5 XG-PON management

There are three channels to carry the control and management information in XG-PON: embedded OAM, physical layer OAM (PLOAM), and ONU management and control interface (OMCI). The embedded OAM and PLOAM channels manage the functions of the PMD and XGTC layers. OMCI is a uniform system for managing service-defining layers. Embedded OAM and PLOAM are defined in Recommendation ITU-T G.987.3, and OMCI is specified in Recommendation ITU-T G.988. (For further information on OMCI see Section 2.5 of this Technical paper.)

Embedded OAM

The embedded OAM channel is transported by the overhead fields in the downstream XGTC frame and upstream XGTC burst. This channel offers a low-latency path for the time-urgent control information. Examples in the downstream XGTC frame are the StartTime and GrantSize fields for bandwidth allocation, the BurstProfile field for upstream PHY burst timing and delineation, and the forced wake-up indication (FWI) field power management. Examples in the upstream XGTC burst are the dying gasp indication for defects management and the BufOcc field for queue length report.

PLOAM channel

The PLOAM channel is carried in a designated field of the downstream XGTC frame and upstream XGTC burst. This channel supports functions such as burst profile communication, ONU registration, encryption key update and exchange and power management. It is based upon exchange of 48-byte PLOAM messages. The PLOAM message format is shown in Table 2.3-8. Downstream and upstream PLOAM messages are listed in Table 2.3-9.

Table 2.3-8 – PLOAM message format

Octet	Field	Description
1-2	ONU-ID	ONU-ID is aligned at the least significant bit (LSB) end. The six most significant bits are set to 0.
3	Message type ID	This byte indicates the message type.
4	SeqNo	Sequence number.
5-40	Message_Content	Message content.
41-48	MIC	Message integrity check.

Table 2.3-9 – PLOAM messages

Direction	Message type ID	Message name	Description
Downstream	0x01	Profile	To provide upstream burst header information.
	0x03	Assign_ONU-ID	To link a free ONU-ID value with the ONU's serial number.
	0x04	Ranging_Time	To indicate the round-trip equalization delay (EqD); may be used to offset the EqD of all ONUs.
	0x05	Deactivate_ONU-ID	To instruct a specific ONU to stop sending upstream traffic and reset itself. It can also be a broadcast message.
	0x06	Disable_Serial_Number	To disable/enable ONU with this serial number.
	0x09	Request_Registration	To request an ONU's registration ID.
	0x0A	Assign_Alloc-ID	To assign a specified Alloc-ID to a particular ONU.
	0x0D	Key_Control	The OLT instructs the ONU to generate new encryption key of specified length and send it upstream. The same message may be used to confirm an existing key.
	0x12	Sleep_Allow	To enable or disable sleep modes in real time.

Table 2.3-9 – PLOAM messages

Direction	Message type ID	Message name	Description
Upstream	0x01	Serial_Number_ONU	To report the serial number of the ONU.
	0x02	Registration	To report the registration ID of an ONU.
	0x05	Key_Report	To send a fragment of a new encryption key to the OLT. This message can also be used to verify an existing key.
	0x09	Acknowledge	To indicate reception of specified downstream messages; also used for no-op, error and busy responses.
	0x10	Sleep_Request	To signal the ONU's intention to change power-saving modes.

2.3.4.6 ONU activation

The OLT controls the ONU activation. The causal order events of the activation process are: the ONU attains downstream synchronization by listening to the downstream transmission. The ONU listens to the Profile PLOAM messages to learn the upstream burst profiles. The ONU announces its presence with a Serial_Number_ONU PLOAM message once, receiving a serial number grant with a known profile. The OLT discovers the serial number of a newly connected ONU and assigns an ONU-ID to it using the Assign_ONU-ID message. The OLT optionally issues a directed ranging grant to a newly discovered ONU and prepares to measure the response time. The ONU responds with the Registration PLOAM message. The OLT performs authentication of the ONU based on the registration ID, computes the equalization delay and communicates it to the ONU using the Ranging_Time PLOAM message. The ONU adjusts the start of its upstream PHY frame clock based on its assigned equalization delay. The ONU completes activation and starts regular operation. Figure 2.3-24 shows the ONU state diagram.

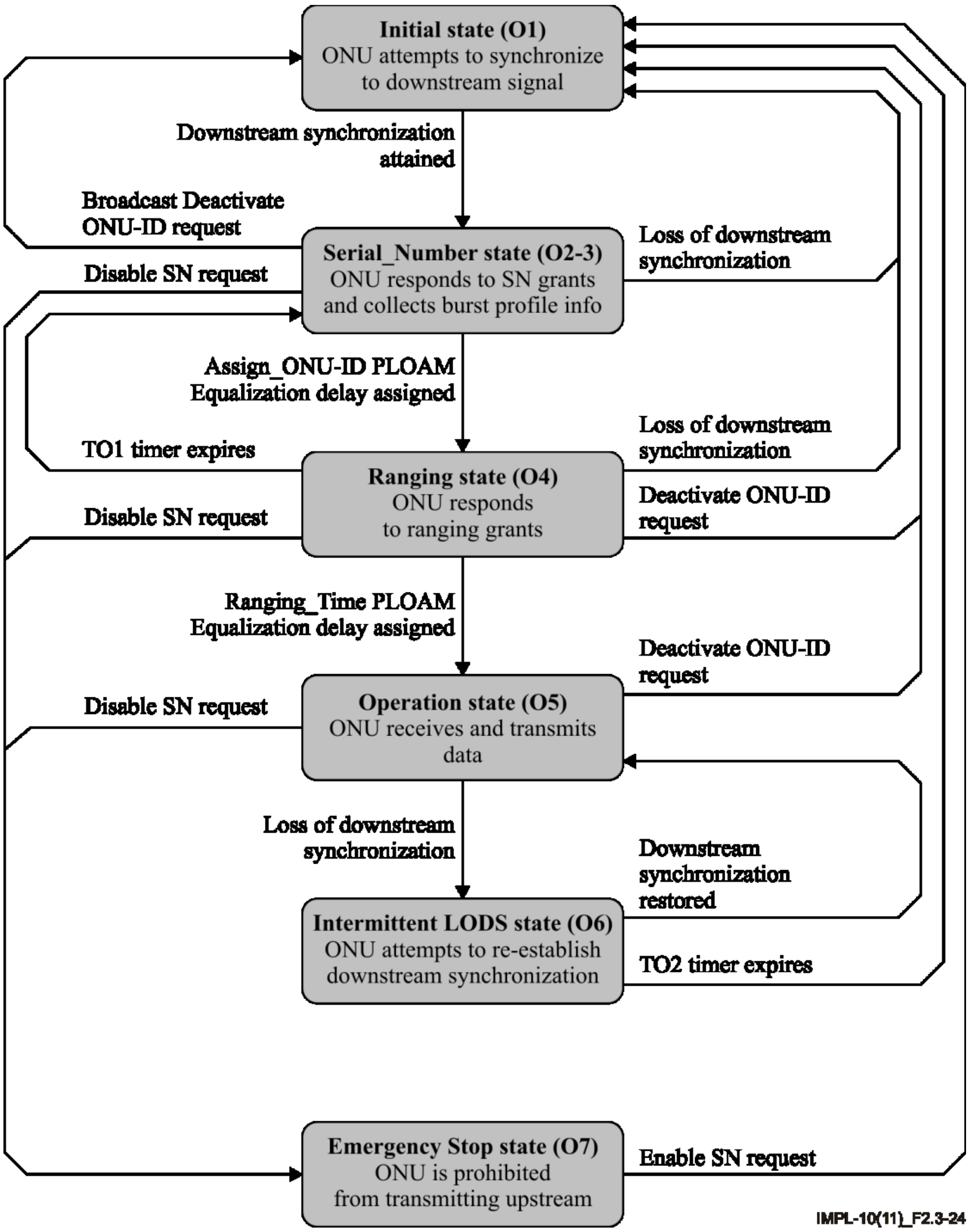


Figure 2.3-24 – ONU activation state diagram

2.3.4.7 Resource allocation

The OLT masters downstream and upstream traffic transmission. In the downstream, the XGEM port is employed to identify different logical connections. The OLT provides TDM-based QoS-aware traffic management. In the upstream, the time division multiple access (TDMA) is employed. The OLT grants upstream bandwidth allocations to allocation IDs (Alloc-IDs) within ONUs. Within each Alloc-ID, the ONU uses the XGEM port to further identify different logical connections. Figure 2.3-25 shows the traffic multiplexing.

The process of OLT allocating upstream bandwidth to Alloc-IDs based on traffic indication and contract is called dynamic bandwidth assignment (DBA). XG-PON supports two methods of DBA: status reporting (SR) DBA based on explicit buffer occupancy reports, and traffic monitoring (TM) DBA based on the OLT's observation of upstream idle XGEM frames. The bandwidth map (BWmap) section in the downstream frame is to inform Alloc-IDs of the upstream bandwidth assignment. The upstream dynamic bandwidth report (DBRu) section in the upstream burst is to provide a buffer occupancy report of an Alloc-ID.

The bandwidth requirements are classified into four strict priorities: fixed bandwidth (highest priority), assured bandwidth, non-assured bandwidth, and best-effort bandwidth (lowest priority). The fixed bandwidth is firstly assigned regardless of the actual load. The assured bandwidth is secondly assigned to satisfy the actual demand. The non-assured bandwidth is assigned in proportion to the sum of that Alloc-ID's fixed and assured bandwidths. The best-effort bandwidth is lastly assigned either by rate proportion or weight factors.

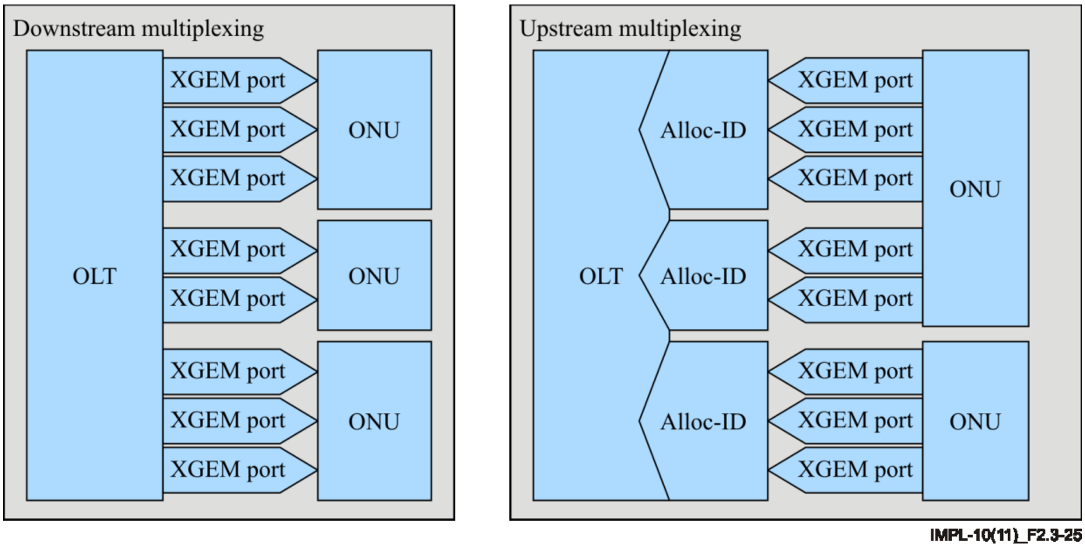


Figure 2.3-25 – Downstream and upstream traffic multiplexing

2.3.4.8 Security

XG-PON supports three authentication mechanisms. The first one is based on the registration ID, which is in the process of ONU activation and provides a basic level of one-way authentication for the ONU. It is mandatory in all XG-PON devices. The two other mechanisms provide mutual authentication to both OLT and ONU. One is based on an OMCI message exchange. The other is based on an IEEE 802.1X message exchange. Support for the two mutual authentication mechanisms is mandatory for implementation at the component level, but optional from an equipment specification perspective.

Key derivation is executed by both the OLT and ONU when the ONU reports its registration ID or a mutual authentication mechanism is completed. Key derivation employs the cipher-based message authentication code (CMAC) algorithm with the Advanced Encryption Standard (AES) encryption algorithm as the underlying block cipher.

The XGEM payloads can be encrypted to provide data privacy. The encryption algorithm is the AES 128 cipher with the counter mode (AES-CTR).

2.3.4.9 Power management

There are various reasons and techniques to reduce the power consumption by an ONU. First, ONU power save follows the natural evolution of technology which tends toward more efficient realizations of given functions. Second, when a subscriber interface is idle, it is desirable to power down the ONU circuitry associated with that interface, while retaining the capability to detect subscriber activity on that interface. Third, the extent of feasible power reduction depends on the acceptable effect on service. The maximum possible savings occur when a subscriber intentionally switches off an ONU, for example, overnight or during a vacation. Forth, during failures of a.c. power, in order to conserve backup battery life, it is desirable to power down the ONU circuitry associated with all interfaces except those considered to provide essential services. The preceding techniques for power management are a matter of ONU design and subscriber and operator practice, and are beyond the scope both of this Technical paper and of ITU-T G.987.3.

However ITU-T G.987.3 addresses two additional means of power management, which do require XGTC layer support. One is doze mode, the other is cyclic sleep mode. All ITU-T G.987.3-compliant implementations are expected to support the doze mode. Support of the cyclic sleep mode is optional for both OLT and ONU. (For further information see Section 2.2.8).

Doze mode is associated with powering off of the ONU transmitter for substantial periods of time on the condition that the receiver remains continuously on. A dozing ONU ignores upstream allocations as long as it has no traffic to send, while avoiding loss of signal declaration by the OLT and keeping the downstream channel open and operational. The dozing ONU may instantaneously wake-up on an OLT request as well as on a local stimulus.

Cyclic sleep mode means that both ONU transmitter and ONU receiver are turned off for substantial periods of time. The ONU power save state consists of a sequence of sleep cycles, each composed of a sleep period and an active period.

The primary signalling mechanism of power management is the PLOAM channel. Relevant PLOAM messages are Sleep_Allow and Sleep_ Request. The secondary signalling mechanism is the embedded OAM. The FWI bit in the BWmap wakes up a sleeping ONU.

2.3.4.10 Performance monitoring and defects

Tables 2.3-10 and 2.3-11 list the performance monitoring (PM) parameters and the defects/required actions, respectively in the XGTC layer.

Table 2.3-10 – Performance monitoring parameters

PM type	Parameters
PHY PM	Corrected FEC bytes, Corrected FEC code words, Uncorrectable FEC code words, Total FEC code words, Total received words protected by BIP-32, BIP-32 errors, PSBd HEC error count, XGTC HEC error count, Unknown profile
XGEM PM	Transmitted XGEM frames, Transmitted XGEM frames per XGEM port, Received XGEM frames, Received XGEM frames per XGEM port, Count of the number of transmitted XGEM frames with LF-bit NOT set, XGEM frame header HEC errors, Count of XGTC frame words lost due to GEM frame HEC error, XGEM key errors
PLOAM PM	SN grant count, PLOAM MIC errors, PLOAM timeouts, DG count, Downstream PLOAM message count, Profile, Assign_ONU-ID, Ranging_Time, Deactivate_ONU-ID, Disable_Serial_Number, Request_Registration, Assign_Alloc-ID, Key_Control, Sleep_Allow, Upstream PLOAM message count, Serial_Number_ONU, Registration, Key_Report, Acknowledge, Sleep_Request
OMCI PM	OMCI baseline message count, OMCI extended message count, Autonomous messages, OMCI MIC errors
Energy conservation	Time spent in each of the OLT/ONU low-power states, respectively

Table 2.3-11 – Defects and actions

Detected at	Defect	Description	Action
OLT	LOBi	Loss of burst for ONU *i*	At the discretion of the OLT; may include waiting extra soak time; changing the allocation schedule; deactivating or disabling the offending ONU, or executing a rogue ONU diagnostic procedure; reporting of the LOBi condition should be qualified by any DG received.
	LOS	Loss of signal	At the discretion of the OLT; may require additional diagnostic to determine whether PON has been lost, and ultimately lead to protection switching event.
	TIW~~i~~	Transmission interference warning for ONI *i*	At the discretion of the OLT; may include deactivating or disabling the ONU, or executing a rogue ONU diagnostic procedure.
	SUFi	Start-up failure of ONU *i*	Send Deactivate_ONU-ID PLOAM message.
	DFi	Deactivate failure of ONU *i*	Mitigating action at the discretion of the OLT; may include rogue ONU diagnostic procedures; the offending ONU-ID and the associated Alloc-IDs may have to be blocked from re-allocation.
	LOPCi	Loss of PLOAM channel with ONU *i*	Mitigating action at the discretion of the OLT; may include ONU re-authentication, ONU deactivation or disabling, or execution of rogue ONU diagnostic procedures.
	LOOCi	Loss of OMCI channel with ONU *i*	Mitigating action at the discretion of the OLT; may include ONU re-authentication, ONU deactivation or disabling, or execution of rogue ONU diagnostic procedures.
ONU	LODS	Loss of down-stream synchronization	Provide necessary visual indication and user-side interface signalling. Execute appropriate transition of the ONU activation state machine.

2.3.5 Extended reach capabilities

Editor: Frank J. Effenberger

(For further information see Recommendation ITU-T G.987.4.)

This section describes the reach extension capabilities currently under development for the XG-PON system. At the most basic level, the reach extenders for XG-PON adapt all the same architectures and functions as those for G-PON (see Section 2.2.5). There are not many areas which required change; most had to do with aligning the reach extender (RE) optical specifications (wavelengths, power levels) with those of XG-PON. Beyond this, several new features were added.

2.3.5.1 Combination reach extenders

Because XG-PON can coexist with G-PON, joint reach extension is needed. There are several methods for providing reach extension for both systems. The most basic uses completely separate reach extender units connected using WDM1 passive filters. However, more integrated combination reach extenders can achieve higher performance and lower costs due to sharing functions and avoiding unnecessary back-to-back multiplexer/demultiplexer steps.

2.3.5.2 Electrical splitting

In the OEO type of RE, there is the opportunity to connect several ODN interfaces into a single OTL interface. In the downstream this is a simple broadcast function. In the upstream, an electrical combining function is performed. This can achieve very high split ratios, as the electrical loss can be offset by very cost-effective electrical gain.

2.3.5.3 Lossless optical combining

In a conventional single-mode splitter, the upstream suffers the same loss as the downstream. A different type of splitter that couples several single-mode fibres to a single multi-mode fibre can ideally achieve no loss. This is limited by the fact that the multi-mode fibre cannot be very long (less than one metre); still, it is a means to produce a large fan out optical interface.

2.4 Point-to-point Ethernet

Editor: Makoto Kadowaki

This section deals with point-to-point Ethernet-based optical access system for the optical access services. In particular this section will deal with Optical Distribution Network (ODN) specification, physical layer specification and the requirements / specifications for the Operation, Administration and Maintenance (OAM). The content of this Section is based on that of Recommendations ITU-T G.985 and ITU-T G.986.

This section is divided in two parts: the first is dedicated to 100 Mbit/s point-to-point Ethernet-based optical access system and the second to 1 Gbit/s point-to-point Ethernet-based optical access system.

For an effective use of optical fibres, only a single fibre bi-directional transmission system is specified, dual-fibre systems being, at present, of no practical interest.

Figure 2.4.1 shows the system configuration of the point-to-point Ethernet-based optical access systems. In the configuration, both UNI and SNI are Ethernet interfaces.

The two directions for optical transmission in the ODN are identified as follows:

– downstream direction for signals travelling from the OLT to the ONT;
– upstream direction for signals travelling from the ONT to the OLT.

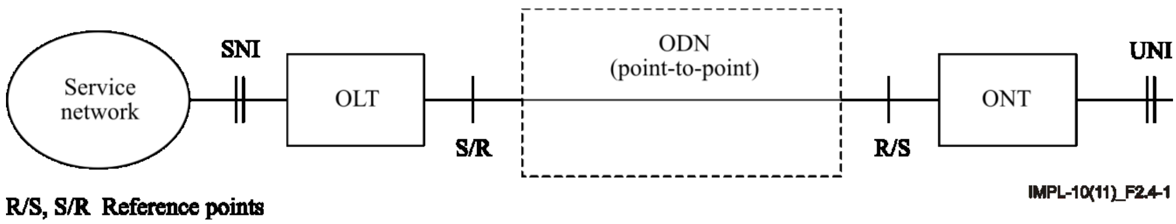


Figure 2.4.1 – Point-to-Point Ethernet system configuration

Bidirectional transmission is accomplished by use of Wavelength Division Multiplexing (WDM) technique allowing the connection to be a point-to-point type ODN. For upstream, the operating wavelength range is 1260-1360 nm for both systems and for downstream, the operating wavelength ranges are 1480-1580 nm and 1480-1500 nm for 100 Mbit/s and 1 Gbit/s systems respectively.

Both systems include the silent start function, in which the transmitter in ONT must be initially disabled, for the purpose to avoid disturbing other access systems in case of misconnection.

2.4.1 100 Mbit/s point-to-point Ethernet-based optical access system

(For further information see Recommendation ITU-T G.985.)

2.4.1.1 Physical layer specification

The optical interface of ONT and OLT follows the transmission and coding specification of Physical Medium Attachment (PMA), Physical Coding Sub-layer (PCS), Media-Independent Interface (MII), Reconciliation Sub-layer (RS) of 100 BASE-FX given in IEEE Standard 802.3, except for the physical layer which is specified in ITU-T G.985.

Physical layer specification is specified for each of the following applicable areas.

– Class S: optical path loss 15 dB, power penalty 1 dB.

– Class A: still to be defined. The transmission distance is assumed to be within 20 km.

– Class B: still to be defined. The transmission distance is assumed to be within 30 km.

NOTE – The distance indicated above are not a standard, but only for classification.

Table 2.4-1– Physical layer specification for ONT

Items	Unit	Specification		
ODN class		**Class S**	**Class A**	**Class B**
Nominal bit rate	Mbit/s	125		
Transmit wavelength	nm	1260-1360		
Receive wavelength	nm	1480-1580		
Line code	–	NRZ Inverted (NRZI) and 4B5B block coding		
Spectral characteristic			TBD	TBD
If MLM laser – Maximum RMS width	nm	7.7		
If SLM laser – Maximum –20 dB width	nm	TBD		
If SLM laser – Minimum side mode suppression ratio	dB	TBD		
Mean launch power MAX	dBm	–8		
Mean launch power MIN	dBm	–14		
Minimum overload	dBm	–8		
Minimum sensitivity	dBm	–30		
Power penalty	dB	1		
Extinction ratio	dB	More than 8.2		
Pulse mask		Conformance with Rec. ITU-T G.957, STM-1		
S/X (Note)			TBD	TBD
Optical return loss condition	dB	More than 14		
Bit error ratio		Less than 10^{-10}		
Optical return loss of the interface	dB	More than 14		
NOTE – S/X (Optical power / Interference signal): the OLT (or ONT) shall receive both signal and cross-talk light from the ONT (or OLT) because of multiple reflections incurred by discontinuity of reflective index on the optical path. The OLT (or ONT) must have applicable S/X against reflection from the optical path which satisfies the specification of optical return loss.				

All parameters are specified in accordance with Table 2.4-1 for an ONT and Table 2.4-2 for an OLT. In particular Table 2.4-1 contains the specifications of the transmitter (upstream) and the receiver (downstream) of the ONT, while Table 2.4-2 contains the specifications of the transmitter (downstream) and the receiver (upstream) of the OLT.

Table 2.4-2 – Physical layer specification for OLT

Items	Unit	Specification		
ODN class		**Class S**	**Class A**	**Class B**
Nominal bit rate	Mbit/s	125		
Transmit wavelength	Nm	1480-1580		
Receive wavelength	Nm	1260-1360		
Line code	–	NRZI and 4B5B block coding		
Spectral characteristic			TBD	TBD
If MLM laser – Maximum RMS width	Nm	6		
If SLM laser – Maximum –20 dB width	Nm	TBD		
If SLM laser – Minimum side mode suppression ratio	dB	TBD		
Mean launch power MAX	dBm	–8		
Mean launch power MIN	dBm	–14		
Minimum overload	dBm	–8		
Minimum sensitivity	dBm	–30		
Power penalty	dB	1		
Extinction ratio	dB	More than 8.2		
Pulse mask		Conformance with Rec. ITU-T G.957, STM-1		
S/X (see Note under Table 2.4-1)			For further study	For further study
Optical return loss condition	dB	More than 14		
Bit error ratio		Less than 10^{-10}		
Optical return loss of the interface	dB	More than 14		

2.4.1.2 Requirements for the OAM

Ethernet-based point-to-point connection is simple to configure, therefore a simple OAM function is required. To provide optical access services using the Ethernet-based point-to-point system, the operator is capable of the following actions from the remote side, which are not defined in the Ethernet protocol. To achieve these actions, the OLT should be able to monitor and test the ONT.

– Identification of the failure point

  The OLT must identify where the failure point is (e.g., in the optical line, inside the ONT and so on). Optical link signal status and ONT status are to be monitored by the OLT in order to identify this failure point. Moreover the ONT should also notify its power status (power-on, power-out) to the OLT.

– Verification of the line

  The loop-back test for the optical access line from the OLT is required.

2.4.1.3 Other requirements

Other requirements should also be satisfied, such as the silent start function. In this function, the transmitter in the ONT is initially disabled for the purpose to avoid disturbing other access systems in case of misconnection. ONT enables the transmitter to enter a handshaking process with OLT only after confirming that the frame structure and/or the line coding of the received downstream signal are matched with those the ONT complies with.

2.4.2 1 Gbit/s point-to-point Ethernet-based optical access system

(For further information see Recommendation ITU-T G.986.)

Table 2.4-3 – Physical layer specification for ONT

Items	Unit	Specification		
ODN class		**Class S**	**Class A**	**Class B**
Nominal bit rate	Gbit/s	1.25		
Transmit wavelength	nm	1260-1360		
Receive wavelength	nm	1480-1500		
Line code	–	8B10B block coding		
Spectral characteristic				
If MLM laser – Maximum RMS width	nm	See Table 59-4 of IEEE 802.3 (Note)	– (Note)	– (Note)
If SLM laser – Maximum –20 dB width	nm	Less than 1 (Note)		
If SLM laser – Minimum side mode suppression ratio	dB	More than 30 (Note)		
Mean launch power MAX	dBm	0	+4	+4
Mean launch power MIN	dBm	–6	–3	–3
Minimum overload	dBm	0	0	–8
Minimum sensitivity	dBm	–22	–24	–29
Damage threshold MAX	dBm	–	+4	–7
Power penalty	dB	1		
Extinction ratio	dB	More than 8.2		
Pulse mask {X1,X2,Y1,Y2,Y3}	UI (Unit Interval)	0.22,0.375,0.2,0.2,0.3 See Figure 59-4 of IEEE 802.3		
S/X (see Note under Table 3-1)				
Optical return loss condition	dB	More than 14		
Bit error ratio	–	Less than 10^{-12}		
Optical return loss of the interface	dB	More than 14		
NOTE – Either MLM laser or SLM laser will be selected for Class S. Only SLM laser will be selected for Class A and Class B.				

2.4.2.1 Physical layer specification

The optical interface of ONT and OLT follows the transmission and coding specification of PMA, PCS, MII, RS of 1000 BASE-X. PMA and PCS are defined in clause 36 of IEEE 802.3. GMII and RS are defined in clause 35 of IEEE 802.3. The physical layer specification has functionalities based on the physical medium dependent (PMD) sublayer defined in clause 59 of IEEE 802.3. The operation of the optical interface is full-duplex.

Physical layer specification is also specified for each of the following applicable areas:

– Class S: optical path loss 15 dB, power penalty 1 dB for transmission within 10 km.
– Class A: optical path loss 20 dB, power penalty 1 dB for transmission within 20 km.
– Class B: optical path loss 25 dB, power penalty 1 dB for transmission within 30 km.

All parameters are specified as in the following Table 2.4-3 for an ONT and Table 2.4-4 for an OLT.

Table 2.4-4 – Physical layer specification for OLT

Items	Unit	Specification		
ODN class		**Class S**	**Class A**	**Class B**
Nominal bit rate	Gbit/s	1.25		
Transmit wavelength	nm	1480-1500		
Receive wavelength	Nm	1260-1360		
Line code	–	8B10B block coding		
Spectral characteristic				
If MLM laser – Maximum RMS width	Nm	– (Note)	– (Note)	– (Note)
If SLM laser – Maximum –20 dB width	Nm	Less than 1 (Note)		
If SLM laser – Minimum side mode suppression ratio	dB	More than 30 (Note)		
Mean launch power MAX	dBm	0	+4	+4
Mean launch power MIN	dBm	–6	–3	–3
Minimum overload	dBm	0	0	–8
Minimum sensitivity	dBm	–22	–24	–29
Damage threshold MAX	dBm	–	+4	–7
Power penalty	dB	1		
Extinction ratio	dB	More than 8.2		
Pulse mask {X1,X2,Y1,Y2,Y3}	UI (Unit Interval)	0.22,0.375,0.2,0.2,0.3 See Figure 59-4 of IEEE 802.3		
S/X (see Note under Table 3-1)				
Optical return loss condition	dB	More than 14		
Bit error ratio	–	Less than 10–12		
Optical return loss of the interface	dB	More than 14		
NOTE – Only SLM laser will be selected for Class S, Class A and Class B.				

2.4.2.2 OAM specification for single domain ONT management

The ONT management and control interface (OMCI) specifications have been optimized for single domain ONT management. The case of a dual domain managed ONT and related OLT requirements are for future study.

The following OAM structure is applied:

– The managed entities are specified in ITU-T G.984.4.

– The OAM functions for link operation, specified in clause 57 of IEEE 802.3, are applied.
– The OAM functions for ONT equipment and service management, optimized in accordance with ITU-T G.986, are applied.

Table 2.4-5 summarizes the OAM functions and indicates whether the specifications from clause 57 OAM of IEEE 802.3, or the OMCI specifications optimized for this section, would be applied to each of them. For OAM for ONT equipment and service management, each ONT management and control protocol packet is encapsulated into the protocol data field as the OMCI message field in a Media Access Control (MAC) frame with the Organizationally Unique Identifier (OUI) extended ethertype in the Length/Type field in clause 2.3 of IEEE 802. The frame is called the OMCI Ethernet frame in the Recommendation ITU-T G.986.

Table 2.4-5 – OAM functions and applicable specifications

<table>
<tr><th colspan="2">OAM functions</th><th>Applicable specifications</th></tr>
<tr><td rowspan="3">ONT status notification</td><td>ANI (Access Node Interface) status</td><td>Clause 57 OAM of IEEE 802.3</td></tr>
<tr><td>ONT vendor code
and ONT model number</td><td>OMCI in ITU-T G.986
ONT-E defined in clause 9.1.13 of ITU-T G.984.4, Amendment 2</td></tr>
<tr><td>UNI status</td><td>OMCI in ITU-T G.986
Physical path termination point of Ethernet UNI defined in clause 9.5.1 of ITU-T G.984.4</td></tr>
<tr><td>ONT remote setting</td><td>UNI status</td><td>OMCI for this section
Physical path termination point of Ethernet UNI defined in clause 9.5.1 of ITU-T G.984.4</td></tr>
<tr><td rowspan="4">Fault management</td><td>Power supply</td><td>Clause 57 OAM of IEEE 802.3</td></tr>
<tr><td>ONT failure</td><td>Clause 57 OAM of IEEE 802.3 and/or OMCI in ITU-T G.986
ONT-E defined in clause 9.1.13 of ITU-T G.984.4</td></tr>
<tr><td>Received signal</td><td>Clause 57 OAM of IEEE 802.3</td></tr>
<tr><td>UNI status</td><td>OMCI for this section
Physical path termination point of Ethernet UNI defined in clause 9.5.1 of ITU-T G.984.4</td></tr>
<tr><td>Loop-back test</td><td>ONT loop-back status</td><td>OMCI in ITU-T G.986
Physical path termination point of Ethernet UNI defined in clause 9.5.1 of ITU-T G.984.4</td></tr>
</table>

2.4.2.3 Other requirements

Other requirements should also be satisfied, such as the silent start function. In this function, the transmitter in ONT is initially disabled for the purpose to avoid disturbing other access systems in case of misconnection. ONT enables the transmitter to enter a handshaking process with OLT only after confirming that the frame structure and/or the line coding of the received downstream signal are matched with those the ONT complies with. This confirmation shall be done with both OLT and ONT being set the auto-negotiation function (defined in IEEE 802.3) disabled.

2.5 ONU management and control interface (OMCI) specification

Editors: Wei Lin and Dave Hood

(For further information see Recommendation ITU-T G.988.)

This Section describes the optical network unit (ONU) management and control interface (OMCI) for optical access networks as defined in Section 2.2, in Section 2.3 and in Section 2.4. The content of this section is mainly based on that of ITU-T G.988.

The OMCI specification addresses ONU configuration, fault management and performance management for optical access system operation, and for several services.

OMCI defines a protocol necessary to support the capabilities identified for these ONUs. It also allows optional components and future extensions.

2.5.1 Reference model of OMCI in the access network

OMCI fits into the overall model for PON system as shown in figure 2.5-1. The dotted line shows a path for OMCI signals between an OLT and ONU.

The OMCI protocol is asymmetric: the controller in the OLT is the master, while the ONU is the slave. A single OLT controller using multiple instances of the protocol over separate control channels typically controls multiple ONUs.

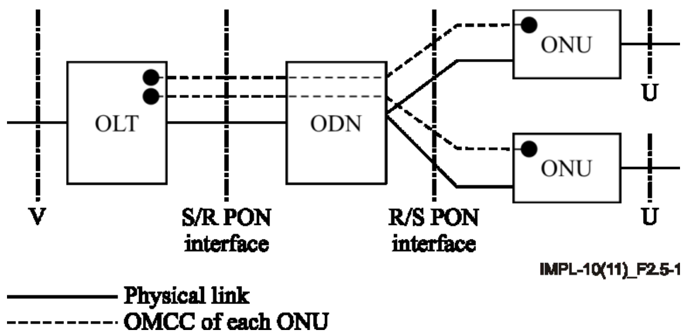


Figure 2.5-1 – Reference model of OMCI

The OMCI protocol runs across a Gigabit-capable passive optical network encapsulation method (GEM) XGEM (see Sections 2.2 and 2.3) connection between the OLT controller and the ONU controller. The GEM connection is established at ONU initialization. OMCI transport in 1 Gbit/s point-to-point Ethernet-based optical access applications is defined in Section 2.4.

The following sub-section will discuss how the ONU Management and Control Channel (OMCC) is established.

2.5.2 ONU functions

As shown in Figure 2.5-2, the functions of the ONU are:

a) access network line termination (AN LT);

b) user network interface line termination (UNI LT), noting that in the fibre-to-the-business case, the UNIs from one ONU may belong to different users;

c) service multiplexing and de-multiplexing.

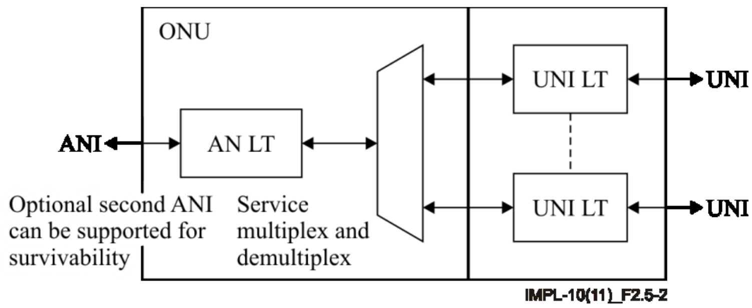


Figure 2.5-2 – ONU functional block diagram

2.5.3 Establishment of the ONU management and control channel (OMCC)

Upon initialization, the ONU creates a virtual OMCI transmission container (T-CONT). Then the establishment of the OMCC follows the process shown in Figure 2.5-3.

During activation, before ranging (see the Note below), the ONU receives a control message from the OLT indicating the assignment of the ONU identifier (ONU-ID). The ONU populates the alloc-ID attribute of its virtual OMCI T-CONT with the ONU-ID. This makes the alloc-ID for OMCI the same as the assigned ONU-ID.

Upon completion of ONU activation in GPON systems, the OLT assigns a GEM port-ID to the ONU for OMCI messages. This is accomplished by a configure_port-ID PLOAM message. The ONU populates the OMCI port-ID attribute of the OMCC structure based on that message, and responds back to the OLT with an acknowledgment. In XG-PON systems, the GEM port for OMCI use is automatically assigned, and is equal to the ONU-ID.

At this point, the OMCC path has been successfully established.

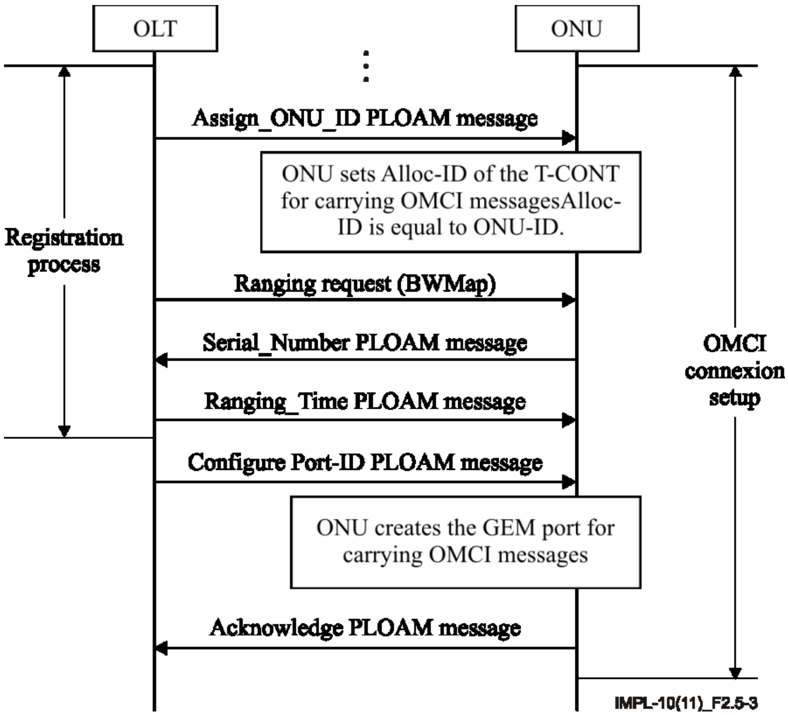


Figure 2.5-3 – OMCC establishment

After the OMCC has been established, it's at the OLT's discretion whether the OMCC GEM/XGEM port is encrypted or not.

NOTE – In order to start a ranging procedure, OLT addresses a ranging request message to ONU and the ONU then response with a Serial_Number PLOAM message. After correct calculation, OLT informs the ONU its own Equalization delay (EqD) by sending a ranging-time PLAOM message.

2.5.4 OMCI management requirements

OMCI is used by the OLT to manage the ONU in the following areas:

a) configuration management;

b) fault management;

c) performance management;

d) security management.

This OMCI interface allows the OLT to:

a) establish and release connections across the ONU;

b) manage the UNIs at the ONU;

c) request configuration information and performance statistics.

The OMCI also allows the ONU to inform the OLT autonomously of alarms, performance threshold crossings and changes to the values of many of the Management Information Base (MIB) attributes.

2.5.5 Protocol-independent MIB for the OMCI

The OMCI is defined such that vendors can offer modular, incremental capabilities to meet different levels of customer needs. ITU-T G.988 defines a protocol necessary to support capabilities specified in GPON (Section 2.2), XG-PON (Section 2.3), 1 Gbit/s point-to-point Ethernet-based optical access applications (Section 2.4) and possibly other access technologies, as well as a variety of services and features. OMCI supports interoperability, yet it allows for optional components and future extensions.

A protocol-independent MIB describes the exchange of information across the OMCI.

NOTE – For more detailed information see Clause 8 of ITU-T G.988 which lists the managed entities and illustrates key relationships between them to implement some of the important features that may be offered by ONUs. Moreover Clause 9 of ITU-T G.988 defines each managed entity in detail.

2.5.6 Managed entities

The protocol-independent MIB is defined in terms of Managed Entities (MEs). Managed entities are abstract representations of resources and services in an ONU. Only a small subset of MEs is mandatory, most of which are used in representing the equipment and the Access Node Interface (ANI) side technical features. The existence of other MEs depends on the architecture and feature set supported by the vendor, e.g. MEs related to layer 2 service. All the MEs are listed in Table 8-1 of ITU-T G.988.

Every managed entity (ME) is described in following aspects:

a) The purpose of the entity

   This offers the reason why this managed entity is introduced and how it will be used in serving a certain service or resource.

b) The relationships of the managed entity with other managed entities

   There are two ways for defining a ME correlated to another one. One way is to explicitly pointing to the other by a pointer; the other way is to implicitly associating to another one by an identical ME ID.

c) The attributes of the entity

An ordered list that specifies both syntax and semantics.

A ME comprises a ME ID attribute and all the other functional attributes. The ME ID attribute is used to indicate which instance of the ME is now under provisioning.

Attributes of a managed entity that is auto-instantiated by the ONU, can be (R), (W), or (R, W).

On the other hand, attributes of a managed entity, that is instantiated by the OLT, can be either (R), (W), (R, W), (R, Set-by-create) or (R, W, Set-by-create).

d) The management operations (actions) that may be performed on the entity.

Generic actions such as create, delete, get, get next, set and get current data are merely listed in the description of a given ME. Specialized actions are described in more detail in the ME description itself.

e) The notifications generated by the managed entity.

These may be attribute value changes (AVCs), alarms or performance monitoring threshold crossing alerts (TCAs). Tables define each of these three classes as needed for each ME type. Alarms, TCAs and failures of autonomous self-tests are all reported via alarm messages. AVCs are reported via attribute value change messages.

NOTE 1 – (R): At instantiation or initialization, the ONU sets the attribute to a default value or to a value that reflects a current state or measurement. During continued operation, the ONU may update the value of the attribute to reflect state or measurement changes. The OLT can only read (R) the value of the attribute. In case of an autonomous attribute value change, the ONU may send an Attribute Value Change notification (AVC) to the OLT.

NOTE 2 – (W): The OLT can only write (W) the value of this attribute type. An attribute of this type is typically used to trigger an action in the ONU. Such an attribute never triggers an AVC notification to the OLT.

NOTE 3 – (R, W): On instantiation of the managed entity, either autonomously or on request of the OLT via a create action, the ONU sets the attribute to a default value. The OLT can both read (R) and write (W) the value of the attribute. In case of an autonomous attribute value change, the ONU may send an AVC notification to the OLT.

NOTE 4 – (R, Set-by-create): On instantiation of the managed entity, by necessity on request of the OLT via a create action, the ONU sets the attribute to the value specified in the create command. Subsequently, the OLT cannot change the value of the attribute. This combination is used mostly for managed entity IDs, but occasionally for other attributes that cannot meaningfully change after ME creation.

NOTE 5 – (R, W, Set-by-create):On instantiation of the managed entity, by necessity on request of the OLT via a create action, the ONU sets the attribute to the value specified in the create command. Subsequently, the OLT can both read and write the value of the attribute. In case of an autonomous attribute value change, the ONU may send an AVC notification to the OLT. In a number of cases, it is logically impossible to change (write) the value of an attribute after the ME is created. However, chicken and egg issues can arise when several such MEs point to each other. Allowing such attributes to be set after creation is intended to avoid these issues.

All the management entities are organized as following:

a) Equipment management;

b) Access Network Interfaces (ANI) management, traffic management;

c) Layer 2 data services;

d) Layer 3 data services;

e) Ethernet services;

f) xDSL services;

g) TDM services;

h) Voice services;
i) Premises networks;
j) General purpose MEs;
k) Miscellaneous services;
l) Mid-span PON reach extender.

2.5.7 OMCI models

As mentioned above, the MIB of OMCI is structured in a modular way. Therefore several chosen MEs will be grouped together. In order to present a certain service as a whole, a ME is connected to another according to their inherent relationship.

NOTE – For any further information about the modular work of OMCI MIB, see clause 8 of ITU-T G.988.

2.5.8 Baseline and extended messages

There are two formats for OMCI messages: baseline and extended. G-PON and XG-PON systems are free to use either the baseline or the extended OMCI message format. The baseline format is the default at initialization. Use of the extended format is then negotiated between OLT and ONU.

The major difference between a baseline message and an extended message is that the former one has a 48-byte fixed length protocol data unit (PDU) while the latter one has a variable length PDU.

All G-PON ONUs and OLTs are required to support the baseline format. During initialization, and whenever the ONU is re-ranged onto the PON, both entities use the baseline format to establish communications and to negotiate their capabilities. While negotiation, OLT queries ONU its capability of supporting extended OMCI messages through issuing a get command to the ONU2-G (see Note) of obtaining its OMCC version attribute (see Note). By reading the get response from ONU, OLT gets to know whether the ONU supports extended message format. If both OLT and the ONU support extended messages, they may or may not choose to conduct all or some subsequent communications in the extended message set. If not, they may only use baseline message set: this is up to OLT's decision. Baseline messages may be used for any transaction, that is, any exchange of one or more related messages such as a get/get-next sequence. However, even if extended message is the negotiation result, OLT can still use baseline message set to communicate with ONU and the ONU must responds with baseline messages. Figure 2.5-4 illustrates this negotiation and the exchange of messages in one or the other message format.

NOTE – ONU2-G is a management entity which contains basic equipment attributes associated with a PON ONU. OMCC version is one of its attributes, which identifies the version of the OMCC protocol being used by the ONU, e.g. extended message set supported or not. OMCC version attribute allows the OLT to manage a network with ONUs that support different OMCC versions.

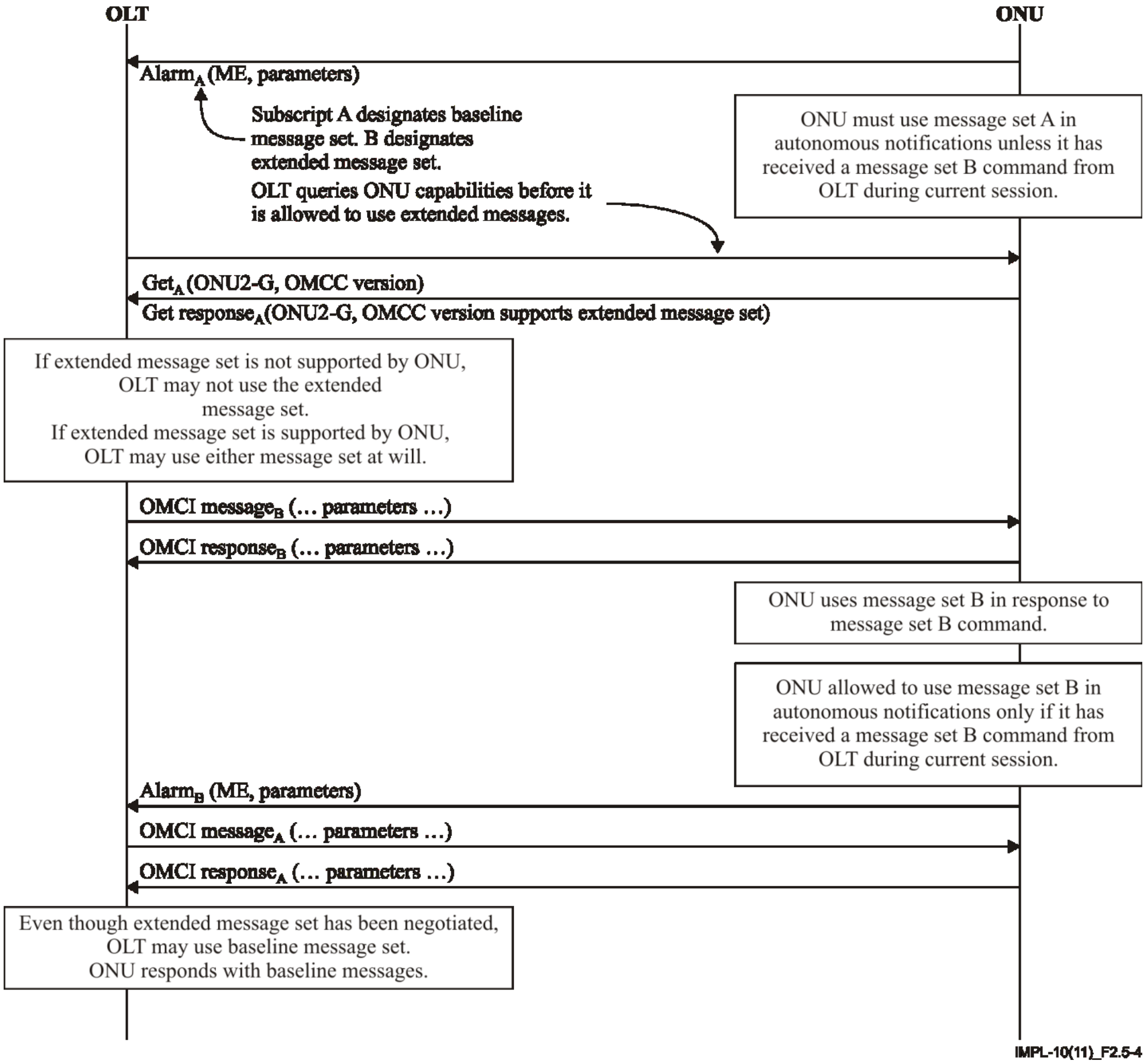


Figure 2.5-4– G-PON OMCI message set negotiation

2.5.9 Common message characteristics

Each OMCI protocol packet is encapsulated directly in one GEM/XGEM frame, or several GEM/XGEM frames if necessary, to satisfy the normal fragmentation rules. The GEM/XGEM frame header contains the OMCC port-ID.

Figure 2.5-5 shows the baseline message format. The packet has a fixed length of 48 bytes.

TCI	Message type	Device identifier	Message entity identifier	Message contents	OMCI trailer
2 bytes	1 byte	1 byte	4 bytes	32 bytes	8 bytes

IMPL-10(11)_F2.5-5

Figure 2.5-5 - Baseline OMCI message format

Figure 2.5-6 shows the extended message format. The packet has variable length N, up to 1980 bytes.

TCI	Message type	Device identifier	Managed entity identifier	Managed contents length	Message contents	OMCI trailer
2 bytes	**1 byte**	**1 byte**	**4 bytes**	**2 bytes**	**N-14 bytes**	**4 bytes**

IMPL-10(11)_F2.5-6

Figure 2.5-6 - Extended OMCI message format

2.5.9.1 Transaction correlation identifier

The transaction correlation identifier (TCI) is used to associate a request message with its response message. For request messages, the OLT selects a transaction identifier, an arbitrary value that should be chosen to avoid the possibility of ambiguous responses from ONUs. A response message carries the transaction identifier of the message to which it is responding.

2.5.9.2 Message type

The message type field is subdivided into four parts, as shown in Figure 2.5-7.

Bit 8	7	6	5 ... 1
0	AR	AK	MT

Bit 8: reserved, is reserved for future use, and is always 0.
Bit 7: acknowledge request (AR), indicates whether or not the message requires an acknowledgement. An acknowledgement is a response to an action request, not a link layer handshake by being correctly set.
Bit 6: acknowledgement (AK), indicates whether or not this message is an acknowledgement to an action request by being correctly set.
Bits 5..1: message type (MT), indicate the message type, i.e. whether it's a set, get or create any possible actions.

Figure 2.5-7 – Message type field subdivision

Table 2.5-1 lists all the OMCI messages that are used in ITU-T G.988. All the syntax details of these commands are listed in Annex A of ITU-T G.988.

2.5.9.3 Device identifier

By being set appropriately, this field is defined to distinguish the baseline OMCI messages from extended OMCI messages.

2.5.9.4 Managed entity identifier

The managed entity identifier comprises four bytes. The most significant two bytes of the managed entity identifier field designate the managed entity class value of the target managed entity. The least significant two bytes of the managed entity identifier field identify the managed entity instance.

2.5.9.5 Message contents length, extended message format

These two bytes contain the length, in bytes, of the message contents field. Its value lies between 0 and 1966, for a 1980-byte PDU limit.

2.5.9.6 Message contents

The layout of the message contents field is specific to each message type.

Table 2.5-1 - OMCI message types

MT	Type	Purpose
4	Create	Create a managed entity instance with its attributes
6	Delete	Delete a managed entity instance
8	Set	Set one or more attributes of a managed entity
9	Get	Get one or more attributes of a managed entity. When directed to a table attribute, get causes the ONU to latch a copy of the table for retrieval with a sequence of get next commands
11	Get all alarms	Latch the alarm statuses of all managed entities and reset the alarm message counter
12	Get all alarms next	Get the active alarm status of the next managed entity or entities from the latched alarm status copy
13	MIB upload	Latch a copy of the MIB. Some MEs and some attributes are not included in a MIB upload
14	MIB upload next	Get the next set of attributes of the managed entity instances included in the latched MIB copy
15	MIB reset	Clear the MIB, re-initialize it to its default, and reset the MIB data sync counter to 0
16	Alarm	Notification of an alarm or a threshold crossing alert
17	Attribute value change	Autonomous notification of an attribute value change
18	Test	Request a test on a specific managed entity
19	Start software download	Start a software download action
20	Download section	Download a section of a software image
21	End software download	End of a software download action
22	Activate software	Activate the downloaded software image
23	Commit software	Commit the downloaded software image
24	Synchronize time	Synchronize PM interval time between OLT and ONU
25	Reboot	Reboot ONU or circuit pack
26	Get next	Get the latched attribute values of the managed entity within the current snapshot
27	Test result	Notification of result initiated by a test command
28	Get current data	Get current counter value associated with one or more attributes of a performance monitoring managed entity
29	Set table	Set one or more rows of a table

2.5.9.7 OMCI trailer, for both baseline message format and extended message format

For baseline messages, the eight bytes of this field are based on the ATM adaptation layer type 5 (AAL5) trailer definition:

a) The first two bytes correspond to Common Part Convergence Sublayer – User-to-user (CPCS-UU) and Common Part Indicator (CPI). They are set to 0 at the transmitter and ignored at the receiver.

b) The length of the Common Part Convergence Sublayer - Protocol Data Unit (CPCS-PDU) field is set to 0x0028 (40 decimal).

c) In G-PON applications, the Message Integrity Check (MIC) is a 32-bit CRC as specified in ITU-T I.363.5.

For extended messages, i.e. in XG-PON applications, the OMCI trailer is a MIC, which is as specified in ITU-T G.987.3.

Chapter 3
Home networking

Introduction

Editor: Tetsuya Yokotani

As optical broadband access networks have been popularized, so has the bundled deployment of Internet access, IP telephony, and IP video distributing services, often marketed as "triple play services". Consumers also expect new services that can improve their quality of life. The provision of guaranteed QoS and highly reliable services by current passive optical networks and by next generation-networks (NGNs) enables the deployment of various home networking services to meet this demand. A key component to enable this is the home gateway which is installed in homes for connecting access networks and home networks.

NOTE – A home gateway is called an access gateway in this chapter because of its focus on transport capability and connectivity with the access network.

This home gateway should comprehend functionalities of the traditional broadband router and should have additional features. The functional requirements of such home gateways have been discussed in standards development organizations (SDOs). That is, the next generation-home gateway generally should have the following four characteristics: high performance for IP processing, compliance with the interface of carrier-grade infrastructure including NGN, a flexible platform for various services, and easy management and maintenance. This chapter describes the standardization of the home gateway and proposes a scenario for its evolution. The chapter also proposes requirements and technologies to comply with the four characteristics described above.

ITU-T has discussed home networking and, in particular, home gateways and has prepared many ITU-T Recommendations on this subject, as shown in Table 3-1. The content of this chapter is mainly based on the content of the Recommendations indicated in that table.

3.1 System level overview

Editor: Tetsuya Yokotani

(For further information see Recommendation ITU-T G.9970.)

Home networking and home gateways have been widely discussed in ITU and other SDOs. For its part, ITU has discussed generic architecture and requirements for home networking, and control protocols for IP-based home networks. This section describes a summary of these technologies. Finally, it provides a standardization map of home networking. This map will be helpful for clarification of relationship among ITU-T Recommendations.

3.1.1 Network architecture

This section describes home networking architecture based on the content of the Recommendation ITU-T G.9970. This section focuses on the transport aspect of home networking, and describes network configuration including definition of components and discussion about demarcation points. Additionally, it touches upon the relationship between the transport aspect and the application aspect.

Table 3-1 – ITU-T Recommendations on home networking

System level	ITU-T G.9970	ITU-T G.9971	ITU-T G.9973
	Network architecture	System level requirements	Home networking topology management
Phone line transceivers	ITU-T G.9951	ITU-T G.9952	ITU-T G.9953
	General aspects	Link layer requirements	Isolation function
HN transceivers	ITU-T G.9954		
	Physical, MAC and DLL requirements		
Narrowband powerline transceivers	ITU-T G.9955	ITU-T G.9956	
	Physical layer	Data link layer	
Unified HN transceivers	ITU-T G.9960	ITU-T G.9961	ITU-T G.9972
	Architecture and physical layer	Data link layer	Coexistence mechanism

3.1.1.1 Home network configuration and definition of components

Figure 3.1-1 shows a generic home network architecture, focusing on the transport path. The home network is shown to include an IP-based home network, which uses IP, and a non-IP-home network, which uses other technologies or protocols. A gateway (GW) between the access network (AN) and the IP-based home network is called the "access gateway transport layer function" (AGTF), while a gateway between an IP-based home network and a non-IP-home network is called a "non-IP gateway". The non-IP terminal at the bottom right of Figure 3.1-1 is a legacy terminal, such as an analogue CPE, which is directly connected to the access network, bypassing the home network.

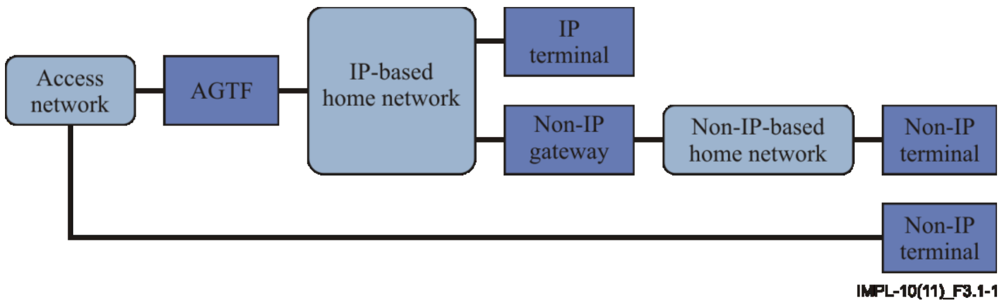


Figure 3.1-1 – Generic home networking functional architecture for the transport layer

Each component shown in Figure 3.1-1 is explained as follows.

1.) The IP-based home network is the network that carries IPv4 or IPv6 data; i.e., it corresponds to the "IPCable2Home domain" described in Recommendation ITU-T J.190 or to the "premises distribution" described in Broadband Forum (BBF) TR-094. Note that the home bridge (HB) in Recommendation ITU-T J.190 can be one of the elements composing the IP-based home network.

2.) A non-IP-based home network is composed of one or more networks, each of which has its own non-IP technology or protocol. A non-IP-based home network corresponds to the "proprietary domain" in Recommendation ITU-T J.190, and also corresponds to the "supplementary application network", or the connectivity between the functional processing device (FPD) and the end-user terminal (EUT), in BBF TR-094. Note that the home decoder

(HD) in Recommendation ITU-T J.190 can be one of the elements composing the non-IP-based home network.

3.) An IP terminal is a terminal function that is directly connected to an IP-based home network, for example an IP-interface-equipped set-top box (STB) or telephone. The IP terminal corresponds to home client (HC) or to the combination of HC and HD in Recommendation ITU-T J.190.

As shown in Figure 3.1-2, there are three types of IP terminals: two primary types, (a) and (b), and one secondary type, (c). IP terminal type (a) retrieves the payload from the received IP packets for the application layer and then sends the non-IP-based layer 3 packets for the application layer. Similarly, IP terminal type (b) sends the IP packets for the application layer. On the other hand, IP terminal type (c) just retrieves the payload from the received IP packets for the application layer. In other words, IP packets are not transferred to other terminals and terminated at this terminal. In BBF TR-094, the application service gateway (ASG) connects to a non-IP terminal, such as a rendering device, via a non-IP-based home network, while the FPD has a point-to-point connection to a non-IP terminal. Since the functional architecture in ITU-T G.9970 does not care about the number of interfaces from the IP terminal type (a) to a non-IP terminal, both ASG and FPD correspond to IP terminal type (a). A BBF TR-094 FPD/T corresponds to either the combined IP terminal type (a) and non-IP terminal, or to the combined IP terminal type (b) and type (c).

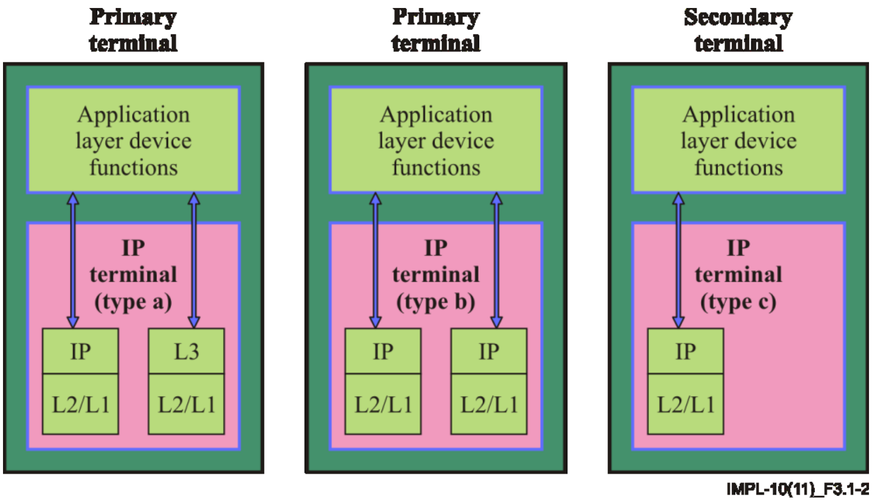


Figure 3.1-2 – Three types of IP terminals

1.) A non-IP terminal corresponds to HD in Recommendation ITU-T J.190 as well as to EUT in BBF TR-094. Examples of customer premises terminal functions that cannot be directly connected to IP-based networks include legacy televisions, telephones and computer peripheral equipment, such as printers. Such terminals are called "non-IP terminals" in Recommendation ITU-T G.9970.

Moreover, an analogue CPE connected directly to the access network – thus bypassing the home network – supporting legacy non-IP services like plain old telephone service (POTS) or broadcast analogue television, is also a "non-IP terminal".

2.) A non-IP GW connects the IP-based home network and non-IP-based home networks.

Contrary to IP terminal type (a), a non-IP GW directly converts the received IP packets to the non-IP layer 3 packets without the application layer, as it is shown in Figure 3.1-3. This corresponds to HC in Recommendation ITU-T J.190.

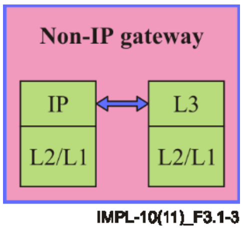


Figure 3.1-3 – Non-IP gateway

3.) The access network is terminated by a network termination (NT) function, as shown in Figure 3.1-4. In general, both IP terminals and non-IP terminals are connected to the access network via an AGTF. Sometimes, however, legacy non-IP terminals are directly connected to the access network. Typical examples are a telephone directly connected to a metallic cable or an STB directly connected to a coaxial cable. In cases in which both directly connected legacy terminals and an IP-based home network share the access line to an access network, a legacy non-IP terminal should be "directly connected" to the access network via a splitter (see Figure 3.1-4).

The splitter separates the signals for legacy services from the aggregate signal stream from the central office. A splitter in Recommendation ITU-T G.9970 corresponds to a POTS splitter (PS) in both Recommendation ITU-T H.610 and BBF TR-094. Moreover, Recommendation ITU-T J.190 implicitly shows the signal splitter function that is connected to an STB.

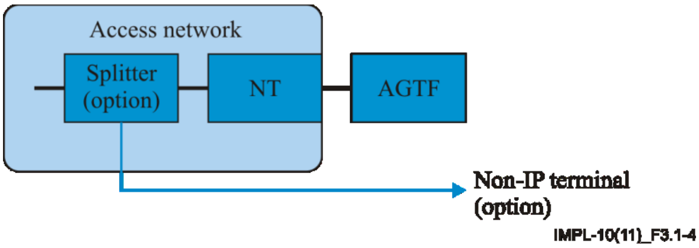


Figure 3.1-4 Access network to support non-IP terminal

4.) The access gateway transport layer function (AGTF) connects the access network to the IP-based home network. Recommendation ITU-T G.9970 describes the relationship between AGTF and the physical access gateway (AGW) device. The manner in which AGTF and AGW are handled by some of the referenced documents are discussed in this section. The detailed implementation aspects are outside the scope of Recommendation ITU-T G.9970.

The AGTF and the access gateway application layer function (AGAF) are shown in Figure 3.1-5. Layers 1 and 2 of the access network are terminated at network termination (NT). The definition of AGAF is addressed in Recommendation ITU-T H.622. AGTF, specified in Recommendation ITU-T G.9970, terminates layers 1 and 2 of the WAN side by using WAN-side termination (WANT), while it terminates layers 1 and 2 of the LAN side by using LAN-side termination (LANT). IP/PPP processing may be executed above these WANT and LANT functions. On the other hand, AGAF, which is specified in Recommendation ITU-T H.622, works above AGTF.

An AGW is a physical device that contains at least AGTF and AGAF, as shown in Figure 3.1-5. Note that it may also contain an optional NT function. In such a case, the WANT is not needed, because the NT also plays the role of the WANT.

Two types of AGW are identified: one is called "aggregate type AGW" and contains NT functionality, while the other is called "separate type AGW" and does not contain NT functionality. This second type of AGW is shown in Figure 3.1-5.

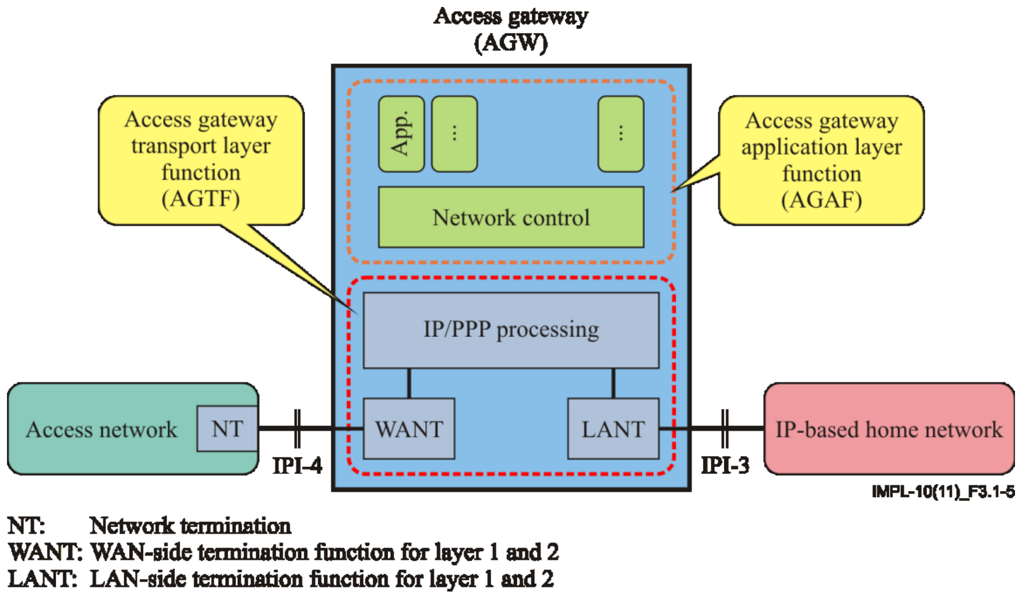


Figure 3.1-5 – Decomposition of access gateway

3.1.1.2 Possible demarcation points

As said in section 3.1.1.1, service is provided to the primary terminal in the application layer, which is supported by either the IP terminal or the non-IP terminal in the transport layer. Therefore, the interfaces to reach each terminal can be specified as potential demarcation points between the user- and operator-domains of responsibility. Possible demarcation points for an IP terminal are described in the following (1) of this section, while those for a non-IP terminal are described in (2). One of these demarcation points would be selected by a user and an operator, considering the service model deployed. Moreover, it has to take into account that there are two types of AGW (aggregation type and separate type).

(1) Possible demarcation points for IP terminals

Points A, B, C, D1 and D2 in Figure 3.1-6 are the possible demarcation points for an IP terminal (type a) and IP terminal (type b), both of which act as a primary terminal. As both non-IP terminals and IP terminals (type c) do not act as primary terminals, the interfaces to reach each of these terminals are shown as dotted lines in order to indicate that they are not possible demarcation points.

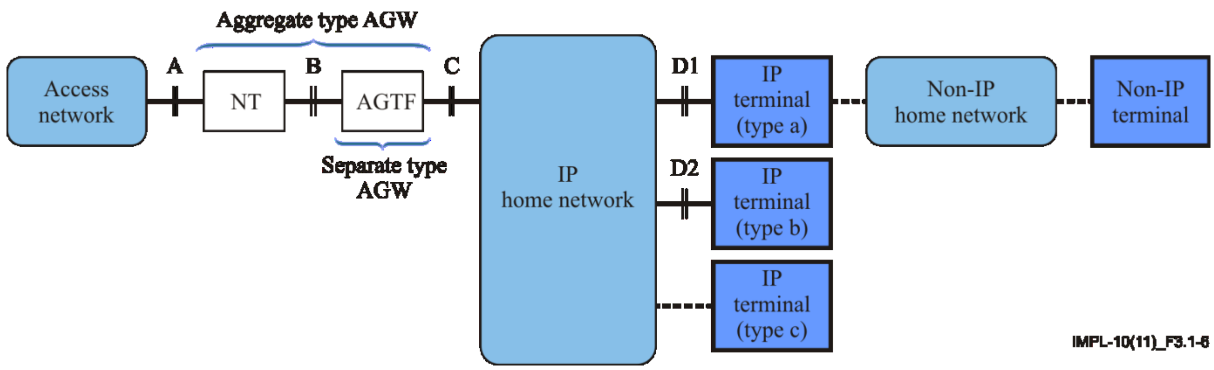


Figure 3.1-6 – Possible demarcation points for IP terminals

(2) Possible demarcation points for non-IP terminals

Existing non-IP services should be provided to the non-IP terminals, such as televisions, telephones, or computer peripherals, etc. Points A, B, C, E, F, G and H in Figure 3.1-7 are the possible demarcation points for non-IP terminals.

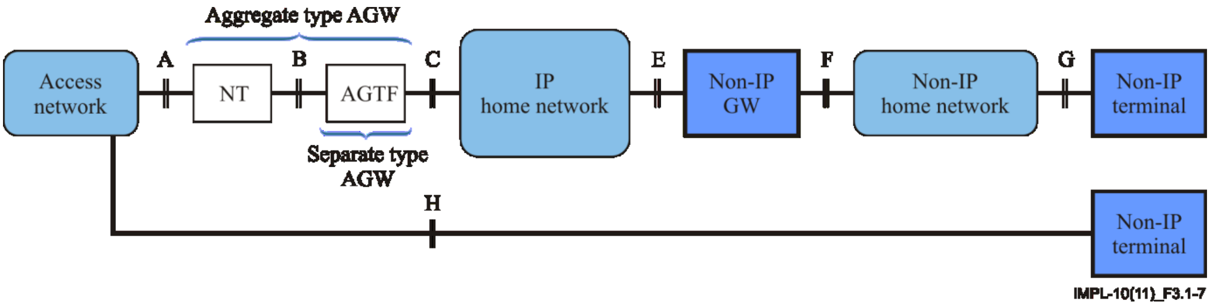


Figure 3.1-7 – Possible demarcation points for non-IP terminals

3.1.1.3 Relationship between transport and application aspects

The main objective of the home networking architecture for the transport layer is to ensure that communication in the application layer can be carried over the transport layer. To better understand the relationship between two home networking architectures, one physical configuration is provided in Figure 3.1-8 that includes the following features:

- The primary terminal contains both an IP terminal type (a) and an application layer device function (ALDF), while the secondary terminal contains both a non-IP terminal and an ALDF.
- AGW, which is the aggregated type in this example, contains NT, AGTF and AGAF.
- AGW terminates the public IP address and interacts with an IP terminal type (a) by a local IP address, while IP terminal type (a) interacts with the non-IP terminal by a non-IP (L3) protocol. Both the IP terminal type (a) and the non-IP terminal lie within the transport layer in the home network.
- On the other hand, ALDF in the primary terminal interacts with functions in the application layer of the carrier's network via the AGAF in the AGW. It also interacts with ALDF in the secondary terminal at the application level.
- The primary domain is provided over an IP-based home network, while the secondary domain is provided over a non-IP-based home network.

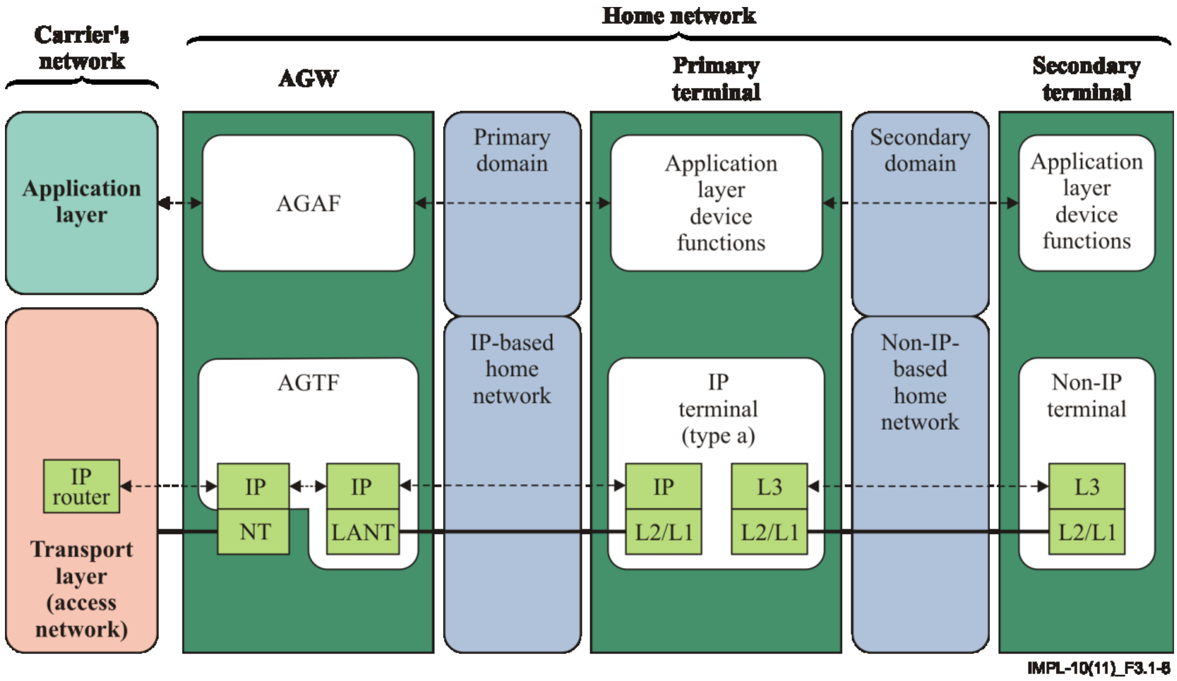


Figure 3.1-8 – One physical configuration based on two generic home architectures

Figure 3.1-9 summarizes the two-layered logical model of home networks. AGW is a physical device that contains at least AGTF and AGAF. Moreover, it may also contain NT function as optional. Both primary terminal and secondary terminal are physical devices that contain application layer device functions as well as transport layer terminal functions, such as IP terminal or non IP terminal. The primary terminal may contain either IP terminal or non-IP terminal. Similarly, the secondary terminal may also contain either IP terminal or non-IP terminal.

3.1.2 System level requirements

(For further information see Recommendation ITU-T G.9971.)

This sub-section specifies the functional requirements of transport functions in an IP-based home network associated with the wireline access network based on the generic architecture described by the previous section 3.1.1. The popularity of broadband services such as FTTH and VDSL and *Data Over Cable Service Interface Specification, version 3.0* (DOCSIS 3.0) is increasing and Recommendation ITU-T G.9971 covers the cases of home networks connecting to wireline access networks such as these. Services on this home network are typically the “triple play” services identified in section 3.1. The incorporation of fixed mobile convergence (FMC) using in-home base stations is for further study. Once a home network is connected to an access network, mechanisms need to exist that allow the access network operator to manage fault detection and reparation, performance, transfer capability, addressing and security for the home network. In many cases, these mechanisms will be the same as those used to manage the access network. Note that, although the NT terminating an access network is also studied from the view point of home network management, only devices connected to the NT through an AGW are within the scope of current specifications. Moreover, the scope only includes the case where Ethernet MAC service (which may be over a variety of physical layers) is provided at the WAN side of NT.

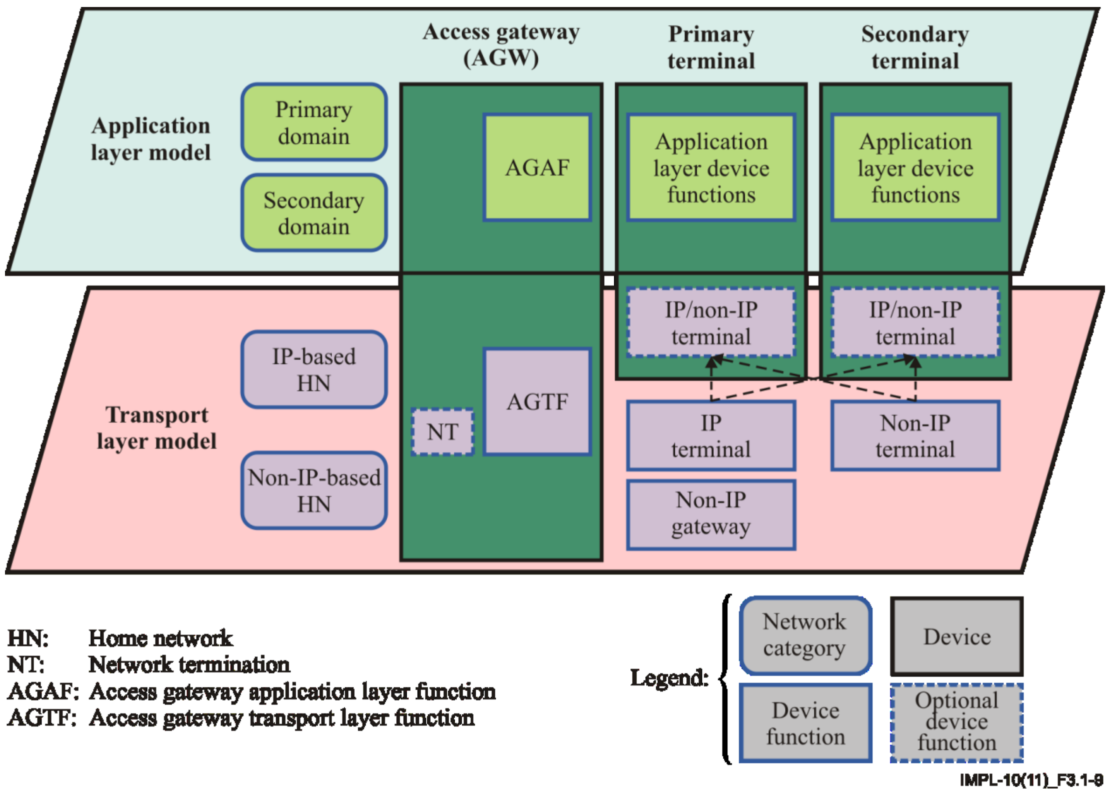


Figure 3.1-9 – Conceptual diagram of two-layered generic model of home networks

This section, based on Recommendation ITU-T G.9971, first clarifies the home networking functional architecture and the position of the home network in end-to-end transport networks, and then provides the functional requirements for the transport capabilities of some key components in home networking, such as the access gateway (AGW) and the IP terminal. Then, it mentions some other functional requirements, such as QoS control, management and security, so that the operators can reliably provide their services all the way to the IP terminal.

3.1.2.1 IP addressing in IP-based home networks

IP addresses should be managed in IP-based home networks. Many models exist for this function. Five of the typical ones are described below.

(1) Model A: Native IPv4/IPv6 connection to AGW

Native IPv4/IPv6 connection to AGW is shown in Figure 3.1-10. The upper figure shows that a native IPv4 address is assigned at the WAN-side port of the AGW by the network service provider's (NSP's) through the use of the Dynamic Host Configuration Protocol (DHCPv4), while local IPv4 addresses are assigned at AGW's LAN-side port and at the IP terminal by the end user through the use of DHCPv4. The lower figure shows that NSP's DHCPv6 prefix delegation (PD) provides an IPv6 prefix for the home network, while IPv6 addresses are assigned at the IP terminal by the end user using DHCPv6 or stateless address auto-configuration (SLAAC) based on the provided IPv6 prefix. A network address translation / network address/port translation (NAT/NAPT) type AGW is used for the former, while an IP router type AGW is used for the latter.

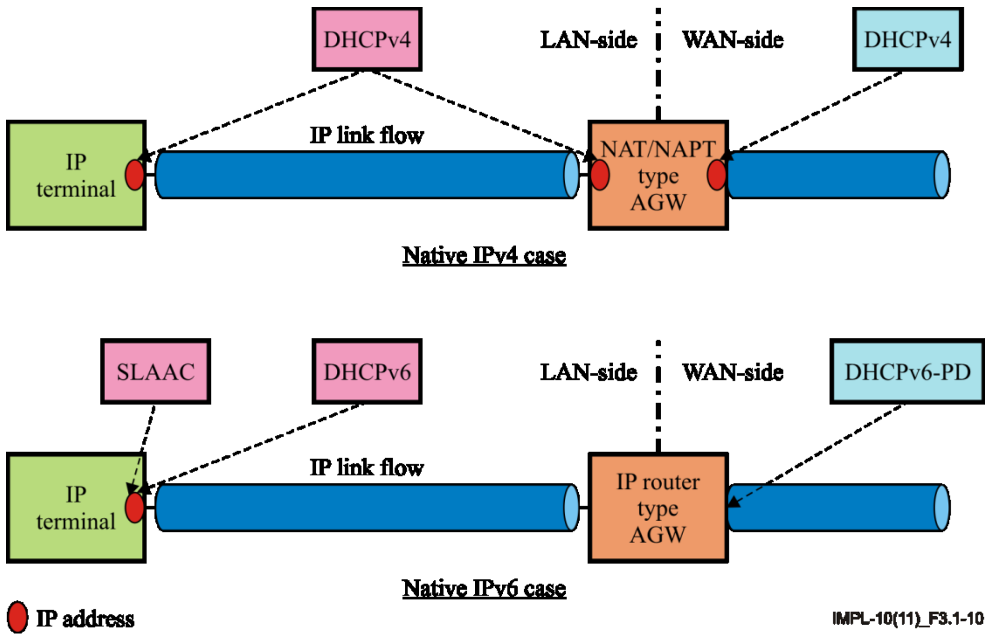


Figure 3.1-10 – Native IPv4/IPv6 connection to AGW

(2) Model B: Either IPv4 over PPP or IPv6 over PPP connection to AGW

Connections to AGW by means of either IPv4 over PPP or IPv6 over PPP are shown in Figure 3.1-11. The upper part of the figure shows that an IPv4 address for IPv4 over a PPP connection is assigned at the WAN-side port of the AGW by using NSP's IPCP, while local IPv4 addresses are assigned at the AGW's LAN-side port and at the IP terminal by using the end-user's DHCPv4, as was the case within Model A. The lower part of the figure shows that unnumbered IPv6 over a PPP connection is established at the WAN-side port of the AGW by using NSP's IPv6CP. Moreover, NSP's DHCPv6-PD provides IPv6 prefix for the home network, while IPv6 addresses are assigned at the IP terminal by using the end-user's DHCPv6 or SLAAC based on the provided IPv6 prefix. As was the case within Model A, an NAT/NAPT type AGW is used for the former, while an IP router type AGW is used for the latter.

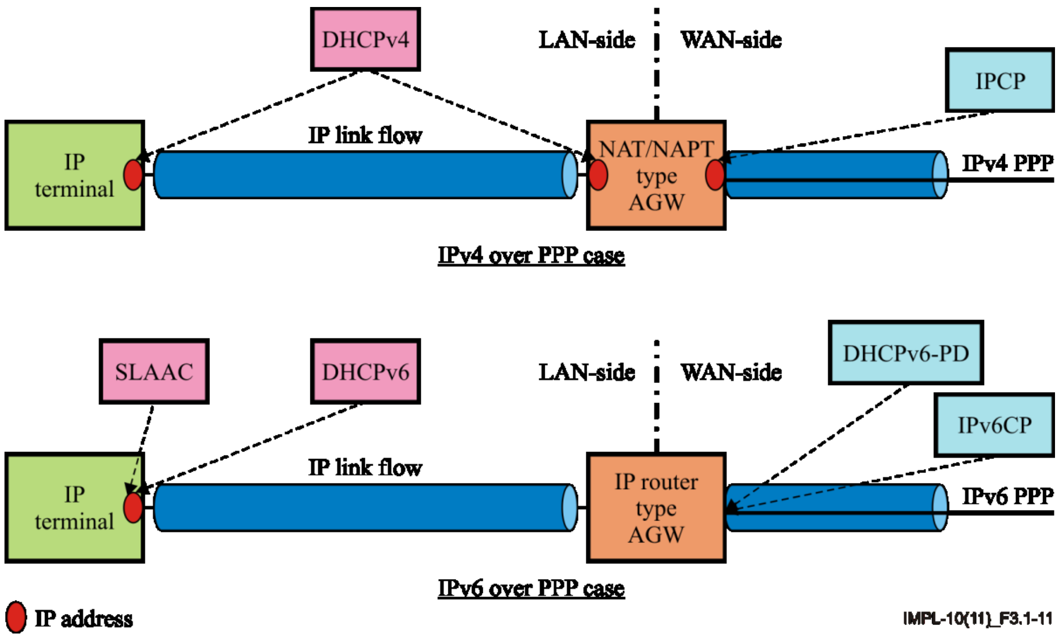


Figure 3.1-11 – Connection to AGW by IPv4 over PPP or by IPv6 over PPP

(3) Model C: Either IPv4 over PPP or IPv6 over PPP connection to IP terminal

Connections to an IP terminal by means of either IPv4 over PPP or IPv6 over PPP are shown in Figure 3.1-12. The upper part of the figure shows that an IPv4 address for IPv4 over a PPP connection is assigned at the IP terminal by using NSP's Internet Protocol Control Protocol (IPCP). In the same way, the lower part of the figure shows that an IPv6 address for IPv6 over a PPP connection is assigned at the IP terminal by using NSP's IPv6CP to establish the PPP session and either SLAAC or DHCPv6 for the IPv6 address. An Ethernet bridge type AGW is used for both cases.

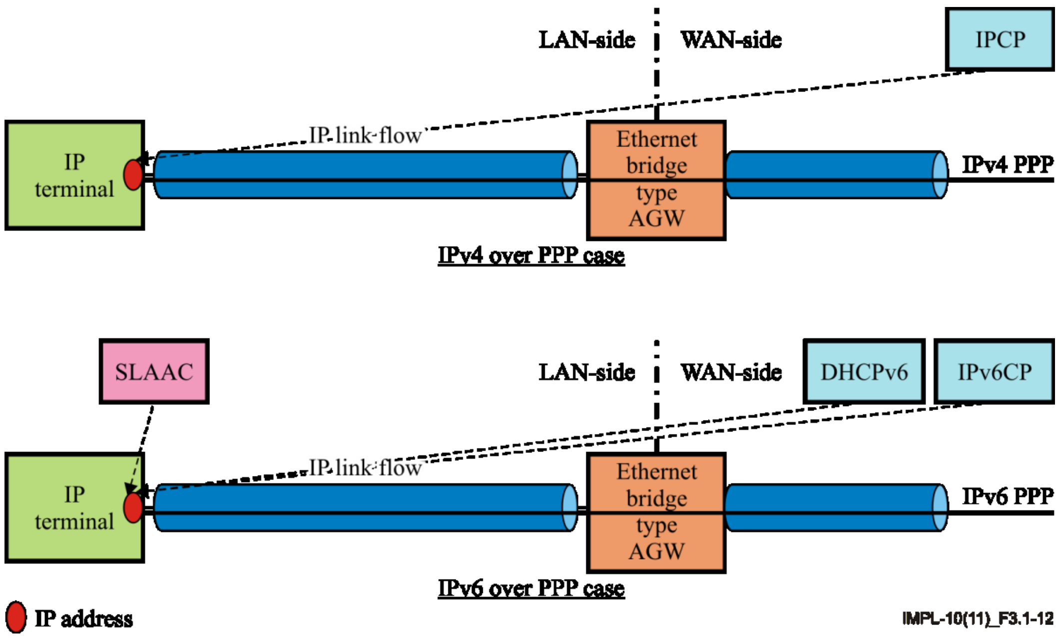


Figure 3.1-12 – Connection to an IP terminal by either IPv4 over PPP or IPv6 over PPP

(4) Model D: IPv6 over L2TP over IPv4 to AGW with IPv6 to IP terminal

This case is IPv6 over IPv4, where an IPv6 terminal wants to communicate with WAN-side IPv6 servers through IPv4 WAN. Figure 3.1-13 shows this in more detail. An IPv4 address of IPv4 over PPP is assigned at the WAN-side port of the AGW first, and then the NSP's DHCPv6-PD over L2TP over this IPv4 provides IPv6 prefix for the home network. IPv6 addresses are assigned at the IP terminal by using the end user's DHCPv6 or SLAAC based on the provided IPv6 prefix. IPv6 IP terminal can communicate with IPv6 servers in the WAN by using IPv6 over IPv4 L2TP.

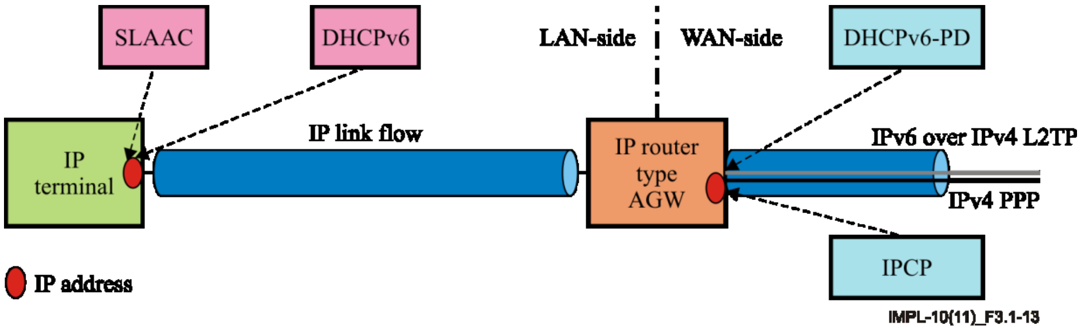


Figure 3.1-13 – IPv6 over L2TP over IPv4 to AGW with IPv6 to IP terminal

(5) Model E: IPv6 over L2TP over IPv4 to AGW with IPv4 to IP terminal

This case is IPv6/v4 network address translation / protocol translation (NAT-PT) where the IPv4 terminal wants to communicate with IPv6 application servers in the WAN. Figure 3.1-14 shows this in more detail. An IPv4 address of IPv4 over PPP is assigned at the WAN-side port of the AGW by using the NSP's IPCP, while local IPv4 addresses are assigned at the AGW's LAN-side port and at the IP terminal by using the end-user's DHCPv4. Moreover, as an IPv6 address over L2TP over IPv4 is assigned at the WAN-side port of the AGW, an IPv4 IP terminal can communicate with IPv6 application servers in the WAN by using this IPv6 over L2TP over IPv4.

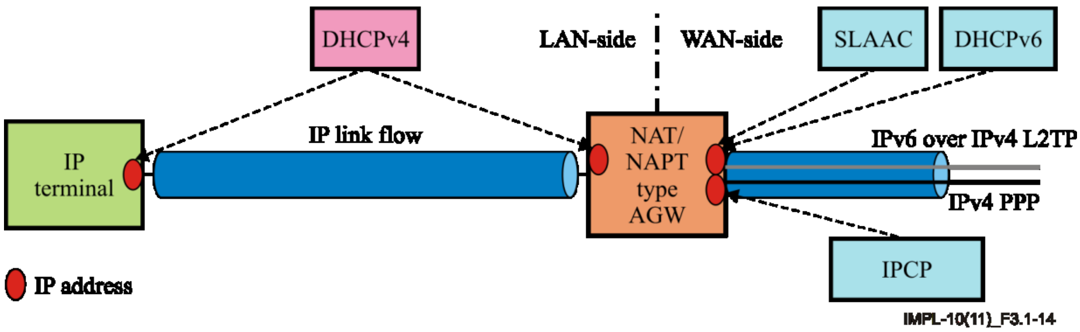


Figure 3.1-14 – IPv6 over L2TP over IPv4 to AGW with IPv4 to IP terminal

3.1.2.2 QoS control

This section describes the architecture for QoS control in an IP-based home network, and then lists the functional requirements for the AGW as well as for other devices. QoS control can be discussed not only for the IP and Ethernet layers but also for other layer 2 protocols, e.g., IEEE 802.11, and lower layer protocols. Therefore, QoS mapping should be specified between each pair of layers. However, as the scope of this description is limited to IP and Ethernet layers, only the QoS mapping between these two layers is shown in Figure 3.1-15.

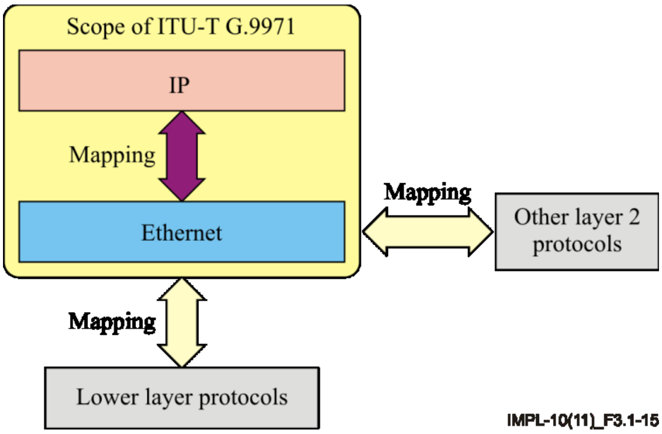


Figure 3.1-15 Scope of QoS control

The detailed requirements of QoS control, QoS control methods and functionalities in the AGW are described below.

(1) QoS control methods

There are three methods to perform QoS control in a home network, depending on the QoS services provided by the WAN and the QoS control supported by the LAN. These are shown in Figure 3.1-16.

- *QoS service type 1*: Best-effort services are provided by the WAN, while the LAN supports non-QoS control. In such a case, there is no way to provide for QoS guaranteed services between two IP terminals.
- *QoS service type 2*: Multiple guaranteed QoS services are provided by the WAN. The LAN also supports QoS control, but the WAN cannot control it. Although QoS control is terminated at the AGW, guaranteed QoS services can be provided between two IP terminals if QoS mapping is used at each AGW. Note that QoS mapping is for L2/L2 or L3/L3; it does not map across layers.
- *QoS service type 3:* Guaranteed QoS services are provided by the WAN. Moreover, the both the LAN and the WAN support QoS control. Accordingly, guaranteed QoS services can be terminated at the IP terminal. The AGW, IP terminal and other devices in the home network will cooperatively perform guaranteed QoS control for the LAN-WAN traffic to use guaranteed QoS services in WAN, taking into account the traffic within the LAN.

(2) Functional requirements and block diagrams in AGW

To provide QoS control, an AGW should have the functional blocks shown in Figure 3.1-17. These blocks can be operated according to QoS control methods in (1) and the operation policy.

- *Policing:* Policing function detects traffic according to certain rules and applies rules to these traffic flows that may cause packets to be dropped, marked, or receive other treatment. Some traffic descriptors for Ethernet and/or IP are provisioned for detecting such traffic flows before user communication is initiated. This function can be located at the ingress of the LAN or WAN sides of the AGW, for example.
- *Classification:* Classification function recognizes the type of each traffic flow and assigns "priority" to each. This recognition is performed according to values of specific fields in the Ethernet frame or IP packet or both of them. This function can be located at the ingress of the LAN or WAN sides of the AGW, for example.

- *Marking:* Marking function writes "priority" in each Ethernet frame or IP packet according to the result of "classification". Otherwise, a specific "priority" value is provisioned. This function can be located at the ingress of the LAN or WAN sides of the AGW, for example.

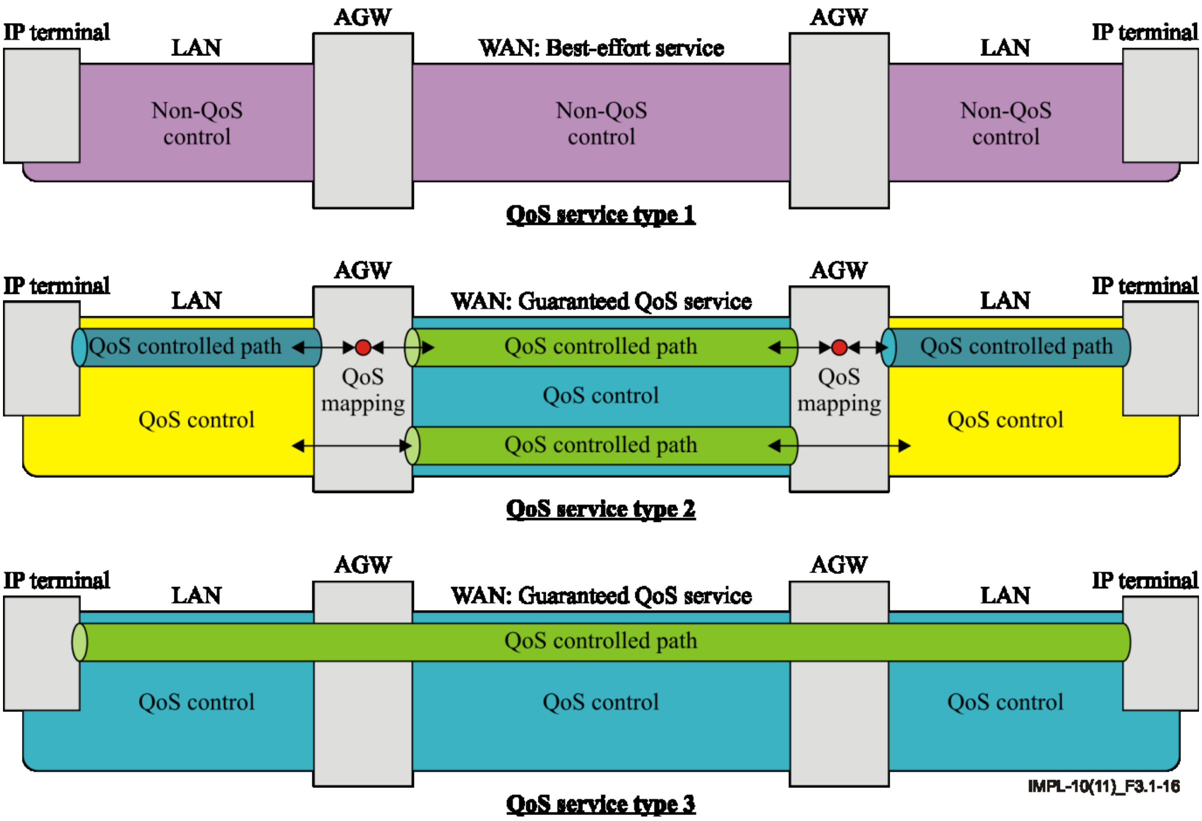


Figure 3.1.16 – Relationship between QoS service types and QoS control

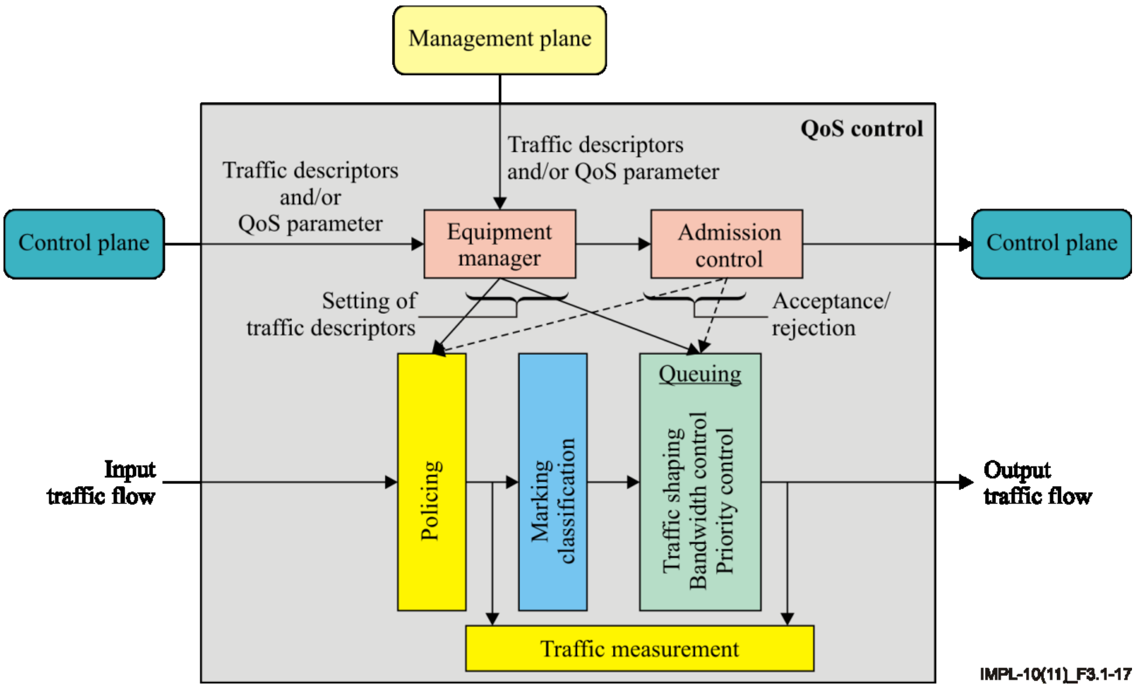


Figure 3.1-17 – Functional architecture for QoS control

- *Priority control:* Priority control function controls input of traffic flows to queues according to the priority level either assigned by "Classification" or written by "Marking". Strict priority (SP) is a typical mechanism for this function.
- *Bandwidth control:* Bandwidth control function controls output of traffic flows from stored queues in order to guarantee a minimum bandwidth based on the committed information rate (CIR) and committed burst size (CBS) of traffic descriptors. Bandwidth control function assigns bandwidth for traffic flows by using scheduling mechanisms, such as weighted fair queuing (WFQ), weighted round robin (WRR), or deficit round robin (DRR).
- *Traffic shaping:* Traffic shaping function also controls output of traffic flows from stored queues, similar to bandwidth control. However, the purposes of this traffic shaping function are the restriction of traffic flows below the maximum transfer rate as well as the reduction of delay variation in every traffic flow.
- *Admission control:* Admission control function manages and judges whether to accept or reject each managed traffic flow for the end-to-end QoS guaranteed services based on the traffic descriptors and QoS parameters before user communication is initiated. One example is the Session Initiation Protocol (SIP) case. The management plane provisions QoS parameters onto the admission control via equipment manager. After admission control receives the traffic descriptors from the control plane via the equipment manager, it judges to accept the traffic flow by comparing the received traffic descriptors with the already-provisioned QoS parameters as well as by analysing whether or not the network resources can be used via another control plane. In case of acceptance, the admission control sends its acceptance message to the policing and queuing controller. Another example is the Resource ReserVation Protocol (RSVP) case. After admission control receives the traffic descriptors and QoS parameters from the control plane via the equipment manager, it judges to accept the traffic flow by analysing whether or not the network resources can be used by another control plane. In case of acceptance, the admission control sends its acceptance message to the policing and queuing controller. Judgement algorithms in admission control are out of scope in Recommendation ITU-T G.9971.
- *Traffic measurement:* Based on Recommendation ITU-T Y.1540, traffic measurement function counts incoming and outgoing traffic to evaluate offered traffic load. Several counting units can be specified, such as the number of bytes, the number of Ethernet frames or the number of IP packets. Examples of counting mechanisms are jumping window and sliding window, as described in Recommendation ITU-T I.371.

3.1.2.3 Home network management

Home network management has two kinds of management schemes (Scheme A and Scheme B) by the remote management server (RMS) as shown in Figure 3.1-18. Scheme A is when RMS directly manages the home network end devices, such as the IP terminal, the non-IP GW and the non-IP terminal. On the other hand, Scheme B is when the RMS manages such devices through an AGW. Scheme A will be applied when the IP terminal is supplied by the NSP in the future, while Scheme B will be applied when some management protocols for the home network, such as universal plug and play (UPnP), are used by the end users. As scheme B is more common than scheme A, Recommendation ITU-T G.9971 describes the requirements for home networking management architecture by focusing on Scheme B.

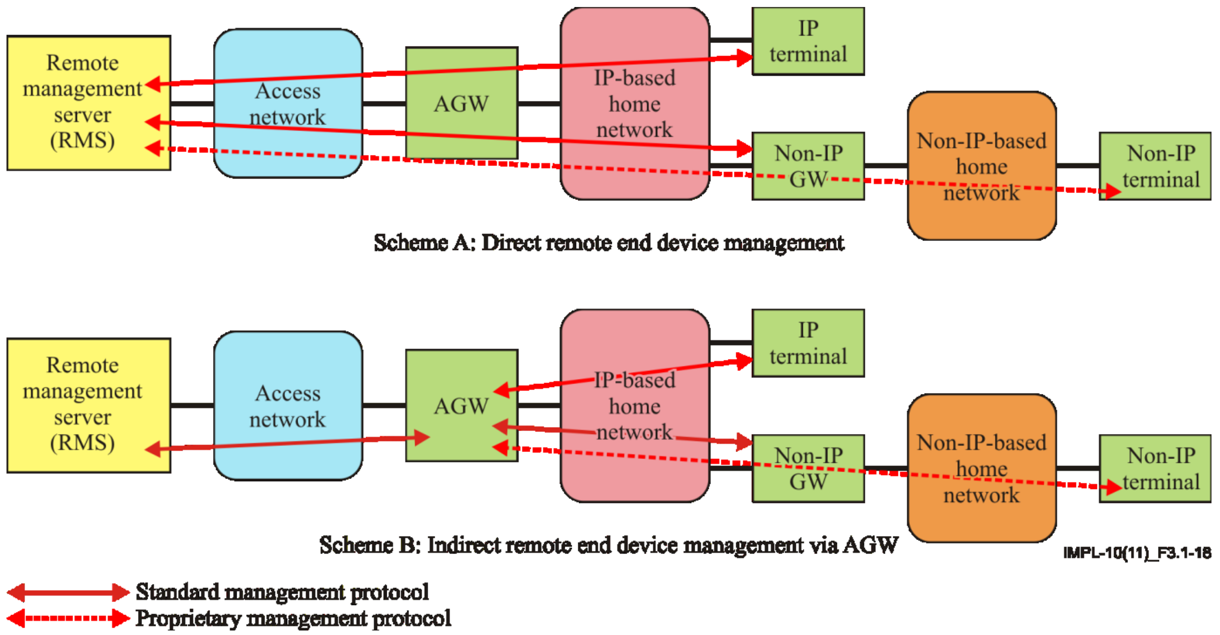


Figure 3.1-18 – Two schemes to home network management

Scheme B has two kinds of management interfaces: one is the management interface between the RMS and the AGW, the other is the one between the AGW and each device in an IP-based home network. In order to handle these two kinds of interfaces, an AGW contains two functions: one is the remote agent processing the former interface, while the other is the local manager processing the latter interface. The following management applications are required for a local manager.

(1) Topology management applications

- To show L3 (IP) network topology in the IP-based home network.
- To show L2 (Ethernet) network topology in the IP-based home network.
- To set, get and show the management information of each device in the IP-based home network.
- To upgrade the function of each device in the IP-based home network.
- To get specific information, such as URLs, of each device in the IP-based home network for logging data.
- To reset or initialize each device in the IP-based home network.

The detailed description of this function is provided in section 3.1.3.

(2) Fault management applications

- To check whether the management interface is set up properly.
- To check whether each device in the IP-based home network is set up properly.

(3) Performance management applications

- To check the network performance of the IP-based home network.

3.1.2.4 Security management

Although security management is categorized into authentication/authorization, encryption and defence, Recommendation ITU-T G.9971 only discusses requirements for encryption and defence relevant to home networking transport layers 2 and 3.

3.1.3 Home networking topology management

Recently, various kinds of IP terminal devices, such as PCs, digital TVs, gaming devices, and portable music devices, are being connected to IP-based home networks. Moreover, their number is increasing and the kinds of transmission media - power line communication (PLC), wireless, unshielded twisted pair (UTP), etc. - used to connect each IP terminal are also becoming more varied. Under such circumstances, most users cannot troubleshoot an IP-based home network by themselves without properly provided network-based services. As a consequence, it is desirable to introduce simple and easy IP-based home networking management that can localize faults to a specific device and network, as well as that can recover from troubles.

The necessity for topology management, fault management, and performance management of IP-based home networks has been already mentioned in 3.1.2.3. This section describes the topology management protocol to perform the topology management applications described in 3.1.2.3 (1). This protocol is used to manage devices in an IP-based home network for the purpose of showing the L2 home network topology only to the users within the home network (behind the AGW).

On the other hand, the customer premises equipment wide area network (CPE WAN) management protocol of BBF TR-069 is the candidate for remote home network management protocol from outside the AGW. Although it may be necessary to study the interaction between this management protocol and CPE WAN management protocol in future, it is out of scope in Recommendation ITU-T G.9973.

3.1.3.1 Concept of protocol for the topology management

Figure 3.1-19 shows concept of the protocol specified in Recommendation ITU-T G.9973. Since this protocol identifies L2 and L3 components, L2 and L3 agents are specified as shown in this figure.

This section describes the interaction between the local manager and the local L3 agent as well as the local manager and the local L2 agent. Management information to identify the IP-based home network topology falls into two areas: device information and media access control (MAC) forwarding table information. One example of device information is the device category, such as Ethernet bridge or PC. Device information resides in the local L3 agent or the local L2 agent, while the MAC forwarding table information resides in the local L2 agent of the Ethernet bridge or the AGW.

Management information can be retrieved by the local manager, which can reside in any device in the IP-based home network. Figure 3.1-19 shows a typical case that the local manager resides in AGW. AGW has both the local L2 and L3 agents, while Ethernet bridge and IP terminal have the local L2 agent and the local L3 agent respectively. The local L3 agent of IP terminal sends device information by using UDA (UPnP Device Architecture), while the local L2 agent of Ethernet bridge sends both device information and MAC forwarding table information by using LLDP (Link Layer Discovery Protocol). Note that the local L2 and L3 agents of AGW locally send device information to the local manager. The local manager can identify the IP-based home network topology by analysing the collection of this management information. By utilizing this IP-based home network topology information, some applications can perform fault localization in response to the failure of network services to be provided properly.

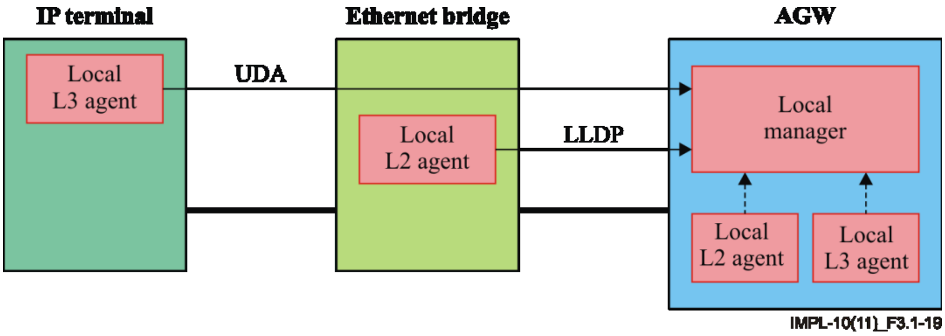


Figure 3.1-19 – The protocol for identifying home network topology

3.1.3.2 Topology management protocol

(For further information see Recommendation ITU-T G.9973.)

The content of this section shortly describes the topology management protocol specified in Recommendation ITU-T G.9973.

(1) Management information

Each local agent of the device, such as IP terminal, Ethernet bridge or AGW, manages device information representing the device. Device information consists of at least the following four kinds of management information.

- *Device category:* It represents the category of the device, such as TV or DVD recorder.
- *Manufacturer code:* It represents the company that produced the device. It is company ID (OUI code) registered by IEEE.
- *Model name:* It represents the device's brand or series name assigned by the manufacturer.
- *Model number:* It represents the device's model number assigned by the manufacturer.

MAC forwarding table information is specified for Ethernet bridge. It represents the pair of Ethernet bridge port and one or more MAC addresses of devices, such as IP terminal or Ethernet bridge or AGW, connected to this port.

(2) Interaction between the local manager and the local L3 agent

The local L3 agent must send device information to the local manager by utilizing the UPnP controlled device function described in ISO/IEC 29341-1.

(3) Interaction between the local manager and the local L2 agent

The local L2 agent must send device information and MAC forwarding table information to the local manager by utilizing Link Layer Discovery Protocol (LLDP). Both types of information are broadcast from all ports via the LLDP agent specified in IEEE 802.1AB. According to IEEE 802.1AB, the local L2 agent hands both types of information to the LLDP agent, which broadcasts it from all managed ports after attaching the device MAC address. The local L2 agent must manage the device information, MAC forwarding table information of the device on which it resides and the chassis ID identifying the local L2 agent. Moreover, the local L2 agent may manage the list of its LLDP agents' MAC addresses. The detailed mechanism to specify the chassis ID is not dealt with in Recommendation ITU-T G.9973. The local L2 agent sends this management information periodically or when it is updated. The detailed specifications for timing or methods must comply with IEEE 802.1AB.

(4) Connectivity check between the local manager and the local agents

The connectivity checks between the local manager and the local agents are executed in L2 and L3.

- *Connectivity check between the local manager and the local L3 agent:* Two connectivity checks are possible in response to a fault. One is that the local manager retries to retrieve device information from the local L3 agent (the number of retries is out of scope of Recommendation ITU-T G.9973). The other is that local manager sends an ICMP echo request message to the local L3 agent and receives an ICMP echo reply message.
- *Connectivity check between the local manager and the local L2 agent:* The local manager can keep the chassis ID as well as TTL by interacting with the local L2 agent. Therefore, the local manager can perform the connectivity check by checking whether or not the next LLDP PDU comes after the previous one within the TTL period.

3.1.4 Standardization map

Figure 3.1-20 shows the relationship among ITU-T Recommendations as an aide in understanding the standardization of home networking.

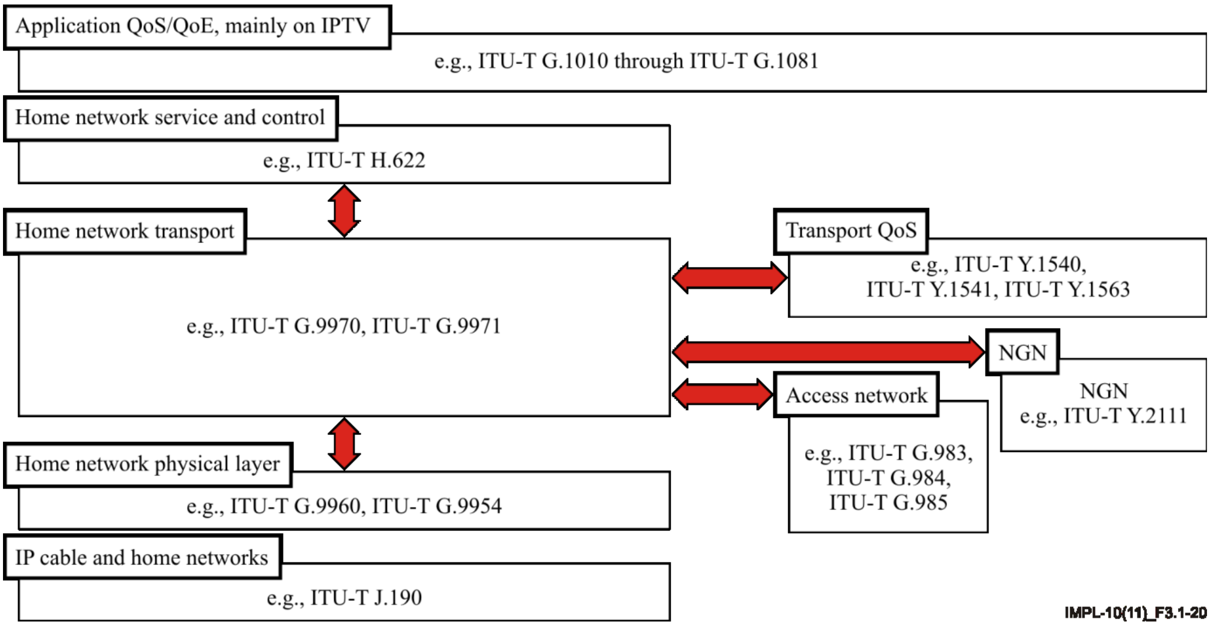


Figure 3.1-20 – Relationship among ITU-T Recommendations for home networking

3.2 Basic home networking transceivers over phone lines

Editor: Erez Ben-Tovim

This section specifies the basic characteristics of devices designed for the transmission of data over in-premises phone line networks.

These devices can be used for in-premises distribution of data provided from wide area access networks such as:

- voiceband data services, e.g. ITU-T V.90;
- ISDN;
- xDSL services (e.g. ADSL, SHDSL, VDSL, cable modems (ITU-T J.112)).

The use of isolation filters between in-premises networks and wide area access networks is addressed in section 3.2.3.

3.2.1 General aspects

(For further information see Recommendation ITU-T G.9951.)

3.2.1.1 Network architecture and reference models

The system reference model for in-home phone line networking transceivers (PNT) shown in Figure 3.2-1 is in accordance with Recommendations ITU-T G.9951, ITU-T G.9952, ITU-T G.9953 (formerly ITU-T G.989.1, ITU-T G.989.2, ITU-T G.989.3, respectively). The model includes physical layer (PHY) and media access control (MAC) functionalities (see section 3.2.2) between the phone line interface and a host interface. The primary interface is the wire-side electrical and logical interface (W1) between a PNT station and the phone wire. Typically the in-premises wiring is connected to the access network. An isolation function (IF) separates the in-home wiring from the access network (see section 3.2.3).

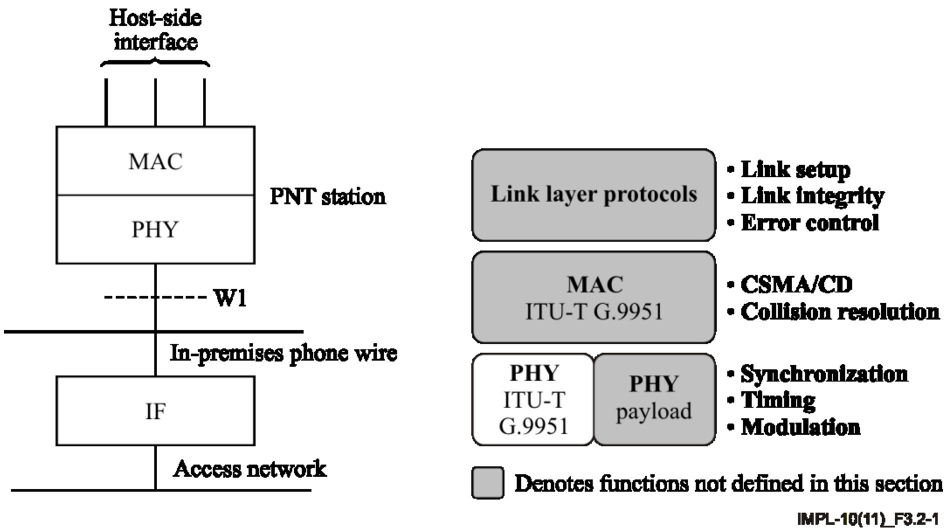


Figure 3.2-1 – Basic reference model and functional view of this model

The PNT system implements a shared-medium single-segment network. All stations on a segment are logically connected to the same shared channel on the phone line. Multiple network segments and other network links can be connected through OSI network layer 2 (L2 or data link) or layer 3 (L3 or network) relays. (See Recommendation ITU-T X.200 and ISO/IEC 7498-1).

In Figure 3.2-2, a layer 3 router is shown as a gateway interconnecting a link to a wide area network and a home network. Such a wide area link might be provided via subscriber line that is implemented as a voiceband modem (e.g. ITU-T V.90), basic rate ISDN, ADSL, VDSL, cable modem, or wireless link. Also shown is an L2 bridge which interconnects the first in-premises network segment with other network segments such as a PNT network.

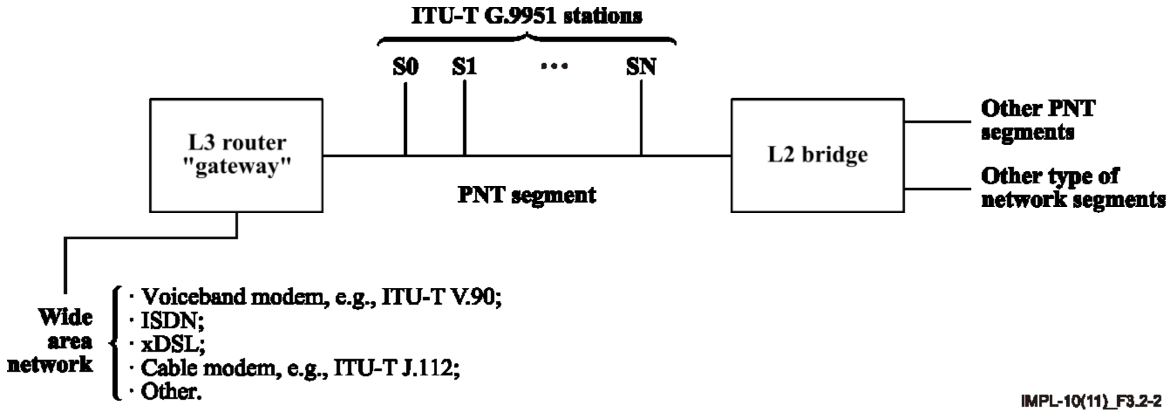


Figure 3.2-2 – Wide area network interworking

Phone line networking transceivers are intended to work over existing in-home wiring. The topologies supported are arbitrary combinations of star, tree and multi-point bus wiring, as illustrated in Figure 3.2-3. Within a topology, each wiring segment may have one or more access points (AP), and variable length extension wiring to the attached POTS or PNT device.

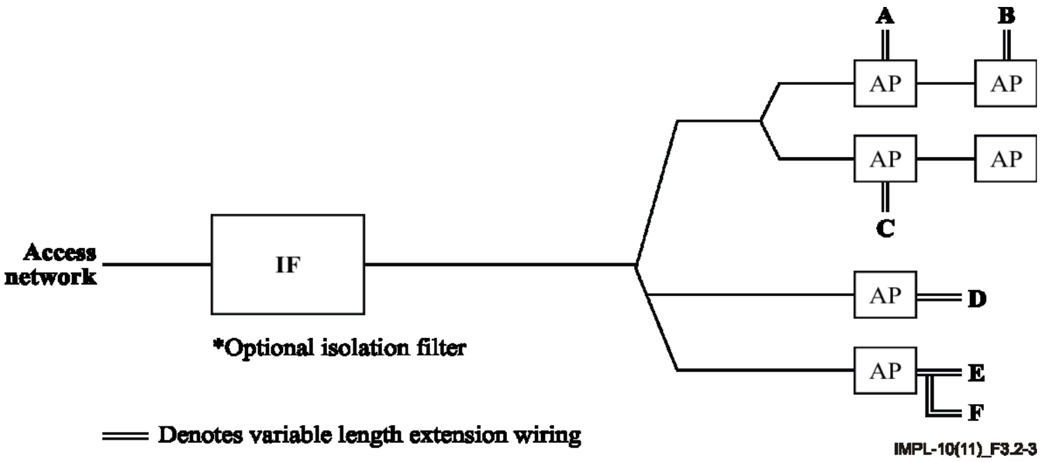


Figure 3.2-3 – Network topology examples

In Figure 3.2-3, stations A and B are on one wiring segment with station B connected in tandem to station A; station C is on a second, unterminated wiring segment; station D is at the end of a direct wiring segment from the access network; and stations E and F share a single access point (AP) via a two-outlet adapter. Many other topologies are possible. Other phone line-based devices may be co-located with the ITU-T G.9951-based stations and connected to the same access points. These may include analogue telephone sets, possibly with an optional low-pass filter in series with each telephone set.

3.2.1.2 Basic frame format

The basic frame format of phone line transceivers complying with Recommendations ITU-T G.9951, ITU-T G.9952, and ITU-T G.9953 is given in Figure 3.3-4. The frame consists of a preamble and frame type (FT) field, the PNT header and payload, and a trailer (End-Of-Frame delimiter, EOF). Each of the fields, except the PNT header and payload, is a fixed sequence for each transmission. A minimum silence gap, referred to as the inter-frame gap (IFG), follows every frame.

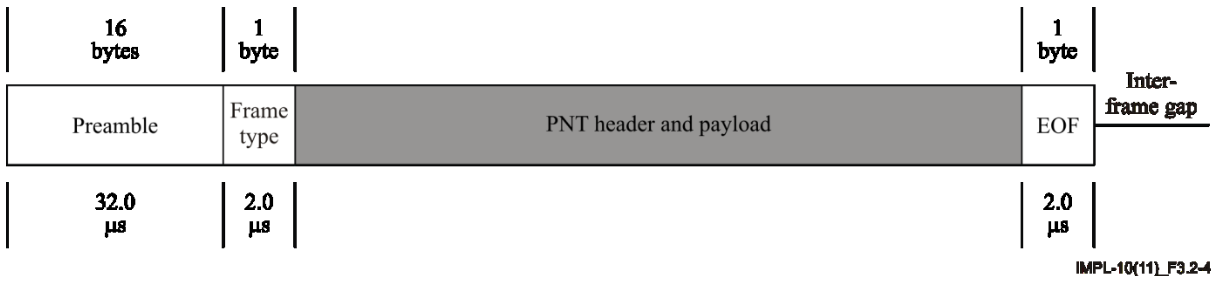


Figure 3.2-4 – Basic frame format

NOTE – The frame type field is not used in the Recommendations ITU-T G.9951, ITU-T G.9952 and ITU-T G.9953 and was designed for future versions.

The maximum frame size is 3122 µs (the total duration of the frame on the phone line network). The minimum inter-frame gap is 29 µs.

3.2.2 Physical, media access and link layer specifications

3.2.2.1 The physical sublayer

(For further information see Recommendation ITU-T G.9952.)

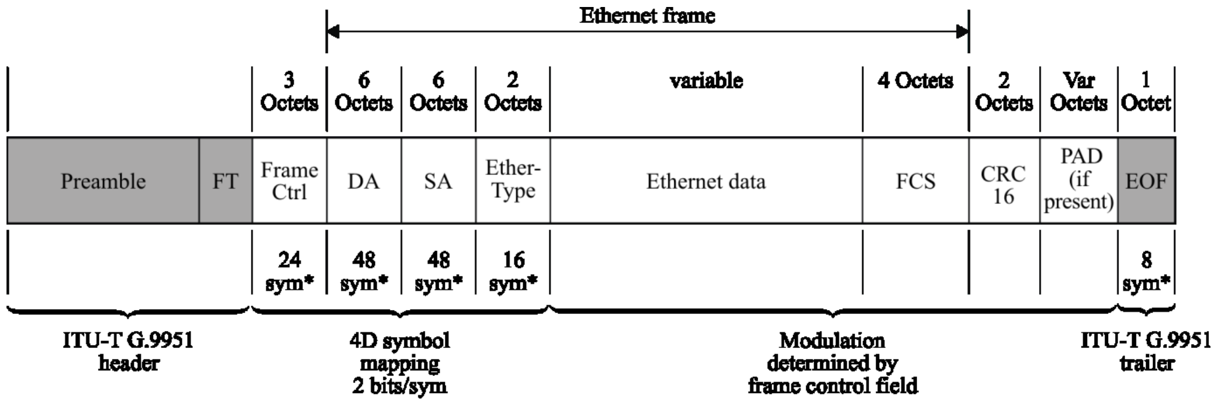
The PHY layer provides payload transmission rates of 4 to 32 Mbit/s, with a nominal effective throughput rate equivalent to 10BASE-T Ethernet, with provision for higher rates in future extensions.

Some of the features of the PHY sublayer are the following:

- Carrier frequency: 7 MHz
- Modulation: Quadrature Amplitude Modulation (QAM) with a symbol rate of 4 Msymbols/s, with a tolerance of ±0.01%.
- Symbol mapping: frames use either:
  - 4D symbol mapping in which each symbol consists of two consecutive, two-dimensional (2D) QAM symbol intervals. The first QAM symbol shall be modulated with 2 to 8 data bits. The second symbol interval shall be transmitted with zero amplitude. This is intended to make possible future enhancements to the standards.
  - Optionally, a portion of the frame may use the 2D symbol mapping, whereby each 2D symbol shall consist of a single QAM symbol, modulated with 2 to 8 data bits.
- Scrambler: the PNT payload contents are scrambled using a frame-synchronized scrambler.
- Transmit filters and transmitted symbol response: (see Recommendation ITU-T G.9952).

The PHY payload in each physical frame is formatted as an Ethernet-type link level frame. In addition, the Ethernet frame is preceded by a 3-octet frame control field, and followed by a 2-octet, 16-bit cyclic redundancy check (CRC-16) field and, possibly, a variable-length pad field.

The frame format is shown in Figure 3.2-5. It consists of a low bit-rate header section, a variable-rate data section, and a low bit-rate trailer. Some parts of the frame are not scrambled.



* Number of 2D symbols in this field

FT	Frame type	FCS	Frame check sequence
Frame Ctrl	Frame control	CRC	Cyclic redundancy check
DA	Ethernet destination address	PAD	PAD field
SA	Ethernet source address	EOF	End-of-frame delimiter

Figure 3.2-5 – PHY frame format

The frame control field contains information on the frame's priority, scrambler initialization bits, payload encoding, and a header check sequence.

3.2.2.2 The medium access sublayer

(For further information see Recommendation ITU-T G.9951.)

The Medium Access Control (MAC) protocol shares media access between users of the spectrum by a distributed CSMA/CD (Carrier Sense Multiple Access with Collision Detection) protocol. Each station on the network segment executes the media access protocol to coordinate access to the shared media. To transmit, a station waits (defers) for a quiet period on the channel (that is, no other station is transmitting) and then sends the intended message in accordance with the appropriate physical-layer specification. To support more than one quality of service (QoS), the transmission deferral is ordered by eight priority levels, implementing absolute priority among the stations contending for access. If, after initiating a transmission, the message collides with that of another station, then each transmitting station ceases transmission and resolves the collision by choosing a backoff level, deferring to other stations that have chosen a lower backoff level.

NOTE – Backoff level is an integer value in the range 0-15 used in collision resolution to determine which of the originally colliding stations will transmit.

3.2.2.3 The link layer protocol

(For further information see Recommendation ITU-T G.9952.)

The link layer includes the following main features:

- **Link layer frame format:** These link functions use control frames to carry protocol messages between stations. Control frames are data link layer frames that are identified by a specific Ethertype value in the type/length field of the frame, and further distinguished by individual sub-types. Link control frames are not seen by layer 3 (IP) of the network stack, and are not bridged between PNT network segments. The link control frame contains a header, data and trailer parts. The header part includes information such as: the Ethernet destination address (DA), the Ethernet source address (SA), the frame type (SSType), the frame length (SSLength), and the SSVersion field (specifying which format version of the control information is used).

- **Rate negotiation:** The rate negotiation function in a destination station uses rate request control frames (RRCFs) to provide information to a source station about the payload encoding that the source station should use to encode future frames sent to this destination, and to generate test frames to assist a receiver in selecting the most appropriate band to use. The policy which the destination station uses to select the desired payload encoding, and the policy it uses to decide when to transmit RRCFs, is vendor discretionary. In general, the usable encoding is a function of the channel quality between source and destination; this generally differs between each pair of stations depending on the wiring topology and specific channel impairments.
- **Link integrity:** The purpose of the link integrity function is to provide a means for the station to determine whether it is able to receive frames from at least one other station on the network. In the absence of other traffic, a station periodically transmits a link integrity control frame (LICF) to the broadcast MAC address, with the interval between such transmissions governed by the method described below.
- **Limited Automatic Repeat reQuest (LARQ):** LARQ is a protocol that reduces the effective error rate when frame errors occur. Its primary distinction from similar, sequence number-based protocols is that it does not guarantee reliable delivery of every frame, but instead conceals errors in the physical layer through fast retransmission of frames. The goal is to significantly enhance the usability of networks that may, at least occasionally, have frame error rates (FER) of 1 in 10^{-2} or worse. Protocols such as TCP are known to perform poorly when FER gets high enough, and other applications, such as multimedia over streaming transport layers, are also susceptible to poor performance due to high FER conditions.

  The protocol provides a negative acknowledgment (NACK) mechanism for receivers to request the retransmission of frames that were missed or received with errors. There is no positive acknowledgment mechanism. There is no explicit connection set-up or tear-down mechanism. A reminder mechanism gives receivers a second chance to detect missing frames when relatively long gaps (in time) occur between frames.
- **Minimal link protocol support profile:** This profile allows for less complex implementations of the link layer protocol. While each of the component protocols serves an important function in the operation of the network, it is possible to implement minimal support for some of the more complex protocols while maintaining compatibility with fully functional implementations, without detracting from the overall performance of other stations. The alternative is full support of all the link protocols, called the full link protocol support profile, or full profile for short.

3.2.3 Isolation function

(For further information see Recommendation ITU-T G.9953.)

This section describes the characteristics and applications of an isolation function which is based on Recommendation ITU-T G.9953 (formerly ITU-T G.989.3) for use with phone line networking transceiver devices described in sections 3.2.1 and 3.2.2. It describes how the isolation function may be used in the system reference model for in-premises phone line networking transceivers (PNT), provides examples of usage of the isolation function, and specifies the characteristics of an isolation function which performs spectral isolation by means of a filter.

3.2.3.1 The isolation function and the phone line networking transceiver reference model

The system reference model for in-premises phone line networking transceivers (PNT) is shown in Figure 3.2-6. The reference model includes physical layer (PHY) and media access control (MAC) functionality between the phone line interface and a host interface. The primary interface is the wire-side electrical and logical interface (W1) between a PNT station and the phone wire. Typically the in-premises wiring is connected to the access network (AN). An isolation function (IF) separates the in-premises wiring from the access network.

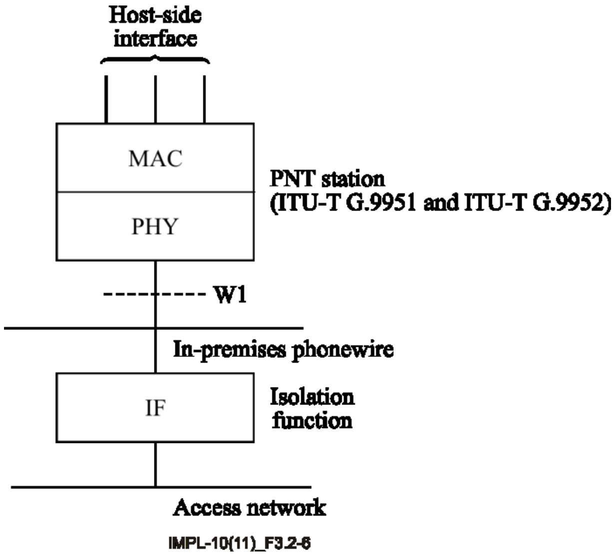


Figure 3.2-6 – Basic reference model

An isolation function shall be implemented, when necessary, to prevent interference between PNT devices operating on in-premises wiring and access network where technologies that use an overlapping frequency spectrum e.g., VDSL, are used. An IF may provide:

- Spectral isolation with wide area network access technologies;
- Known termination impedance;
- Additional lightning and over-voltage suppression.

3.2.3.2 Isolation function usage models

Figure 3.2-7 shows the simplest configuration using an isolation function. Spectral isolation between the access network and premises wiring is achieved by means of a filter. POTS and ADSL signals pass through the filter largely unaffected. Signals above the ADSL band should be blocked. In this configuration, ADSL transceivers present in the premises may be connected to either side of the filter. VDSL transceivers that use downstream frequency bands which overlap with PNT frequencies are not expected to be connected to the in-premises side of the IF, and further, are not recommended to be connected to the access network side of the IF without additional filtering (e.g., using a splitter).

In Figure 3.2-8, an ADSL splitter is also present. Note, in many cases, the ADSL splitter itself will isolate signals above the ADSL band at the POTS port, in effect incorporating the functionality of the isolation function.

In Figure 3.2-9, a pass-through gateway performs the IF function. If voice service is provided in-band over xDSL and POTS service is not supported, then the IF filter is not required and the xDSL to PNT gateway performs itself the IF function.

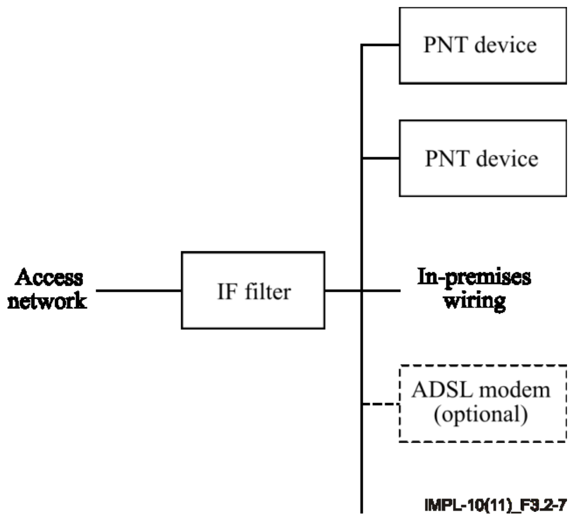


Figure 3.2-7 – Basic configuration using an isolation function

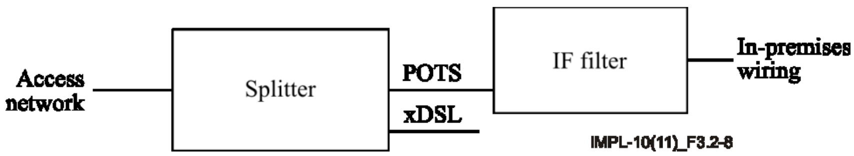


Figure 3.2-8 – Splittered configuration

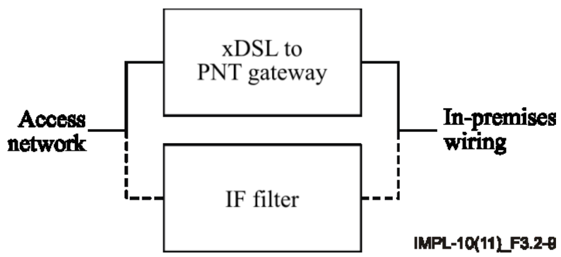


Figure 3.2-9 – Gateway

In Figure 3.2-10, a gateway along with an ADSL splitter is present. As was the case in Figure 5.2-9, the ADSL splitter often will isolate itself signals above the ADSL band at the POTS port, in effect incorporating the functionality of the isolation function.

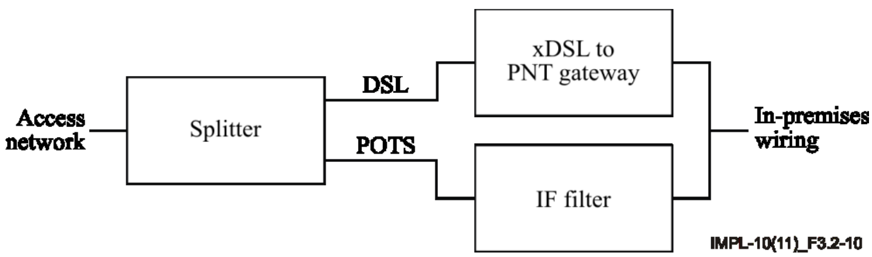


Figure 3.2-10 – Splitter plus gateway

Figure 3.2-11 shows an IF used with a cable-to-PNT gateway. The IF filter provides isolation between signals placed on the premises wiring by the cable gateway and signals on the Telephone access network. Optionally, if the output from the cable gateway contains energy in the ADSL or POTS band, then the POTS or ADSL devices (if any) would need to connect to the telephone access network side of the IF.

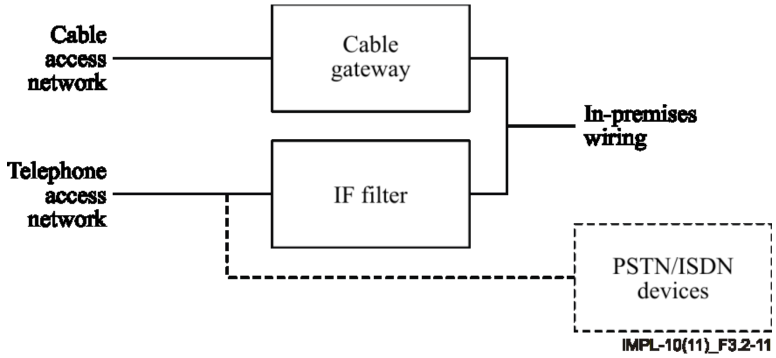


Figure 3.2-11 – IF in conjunction with cable gateway

3.2.3.3 Electrical characteristics of the isolation function (the IF filter)

An isolation function which performs spectral isolation by means of a filter should have the following characteristics specified:

- Stress withstand, meaning that the filter shall remain functional when a certain voltage and current are applied at the access network port of the filter;
- Isolation between wires, and the wire-ground isolation;
- DC resistance;
- Reference impedance, which is the nominal reference impedance of the filter;
- Differential insertion loss;
- Common mode insertion loss;
- Differential mode return loss;
- Differential mode impedance;
- Balance at various frequency bands;
- Noise levels measured at the access network port of the filter;
- Distortion between voiceband and PNT frequencies.

The required values for the characteristics listed above are given in Recommendation ITU-T G.9953.

3.3 Enhanced home networking transceivers over phone lines and coaxial cable

Editor: Erez Ben-Tovim

3.3.1 Overview

This section describes the PHY, MAC, DLL and convergence protocol stack layers for the HN transceivers operating over phone line and coaxial cable based on Recommendation ITU-T G.9954. These transceivers have the following features:

- Operation over phone line or over coaxial cable;
- PHY layer payload transmission rates of 4 to 320 Mbit/s;
- Rate adaptive transceivers that optimize data rates and packet error rates for dynamically varying channel conditions on a per-packet basis;

- QAM modulation technique for communication over phone wire or coaxial cabling;
- Spectrum notching over phone line for compatibility with amateur radio services;
- Synchronous MAC protocol controlled by a dynamically elected master employing a collision avoidance media access strategy;
- Support for constant and variable bit-rate data services;
- Peer-to-peer communication within a master-controlled network;
- Packet aggregation (packetization) performed within the ITU-T G.9954v2 protocol stack layer up to latency limits of the service flow and available transmission bandwidth;
- Quality of service guarantees for bandwidth, jitter, latency and BER;
- QoS support for services with explicit traffic and rate specifications providing a link layer that is well suited for streaming audio and video;
- Protocol-specific convergence layers;
- Backward compatibility with transceivers specified in Recommendations ITU-T G.9951 and ITU-T G.9952 (mode A) over phone line using ITU-T G.9951/ITU-T G.9952 asynchronous MAC protocol;
- Coexistence and interoperability between ITU-T G.9954v1 and ITU-T G.9954v2 nodes in a mixed network;

NOTE – ITU-T G.9954v1 refers to the HNT technology proposed in Recommendation ITU-T G.9954 (2005), while ITU-T G.9954v2 refers to the enhanced HNT technology proposed in Recommendation ITU-T G.9954 (2007).

- Compatibility with other phone line services such as POTS, ITU-T V.90, ISDN, ADSL and ADSL2;
- Compatibility with other coaxial services such as VDSL, VDSL2 and cable-TV channels;
- Interoperability between phone and coaxial PHY layers using spectral modes A and B, thus allowing a mixed phone line/coaxial cable network (see section 3.2);
- Local and remote management of ITU-T G.9954v2 nodes;
- Provisions for future security extensions.

Some of the above features are described in subsequent sections; for the others, see Recommendation ITU-T G.9954.

3.3.2 The ITU-T G.9954 home network (architecture, reference models and network features)

3.3.2.1 The home networking architecture and topology

Figure 3.3-1 illustrates the home networking (HN) architecture reference model. The model assumes a home network connected to an external access network via a residential gateway (RG) or (Internet gateway). The home network is composed of a number of network nodes all communicating over a shared media infrastructure within the home premises. In this model, management of the home network can be performed remotely, from the broadband service management entity, using the residential gateway as the access point into the home network. In Figure 3.3-1, the RG assumes the role of network master and is responsible for coordinating media access within the home network. Although the RG is a natural candidate for being network master, it should be noted that this represents only one possible configuration since any node can assume the role of master without changing the network model. In the network model, each network node of the home network is assumed to be running an instance of the home networking transceiver (HNT) protocol stack.

The HN system implements a shared medium, single-segment network, as shown in Figure 3.3-2. All stations on a segment are logically connected to the same shared channel either on the phone line or the coaxial cable or both. Multiple HN network segments and other network links can be connected through ISO network layer 2 (L2 or data link) or layer 3 (L3 or IP) relays. (The reference model of the HN transceiver and the relation to the ISO reference models is explained in section 3.3.2.2.) Layer 1 relays (PHY layer repeaters) are not defined in this Technical paper.

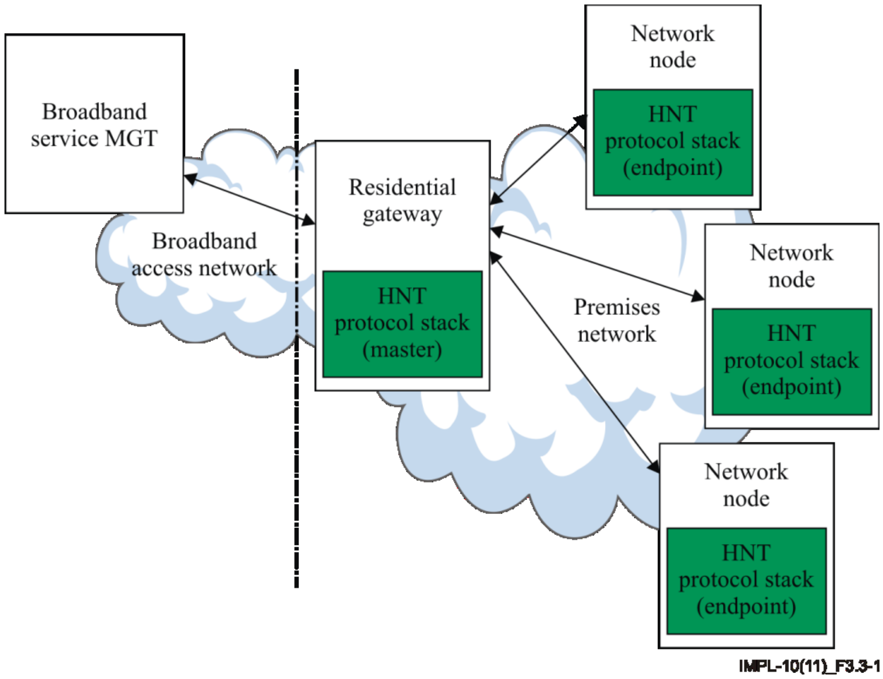


Figure 3.3-1 – Network architecture reference model

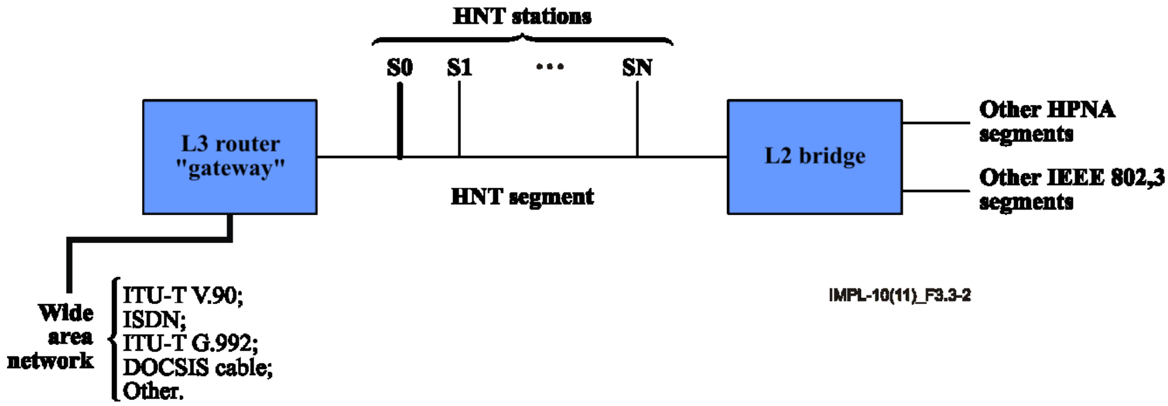


Figure 3.3-2 – HNT shared medium network segment on the coaxial cable

As seen in Figure 3.3-3, the ITU-T G.9954v2 network model assumes a home network composed of a variety of types of network nodes, connected to the shared media home phone line and coaxial cable network backbone. It assumes a single broadband connection (e.g., using phone line xDSL services) to an external access network, through an Internet gateway and possible bridges to other home network segments, possibly based on other home networking technologies (e.g., wireless, power-line).

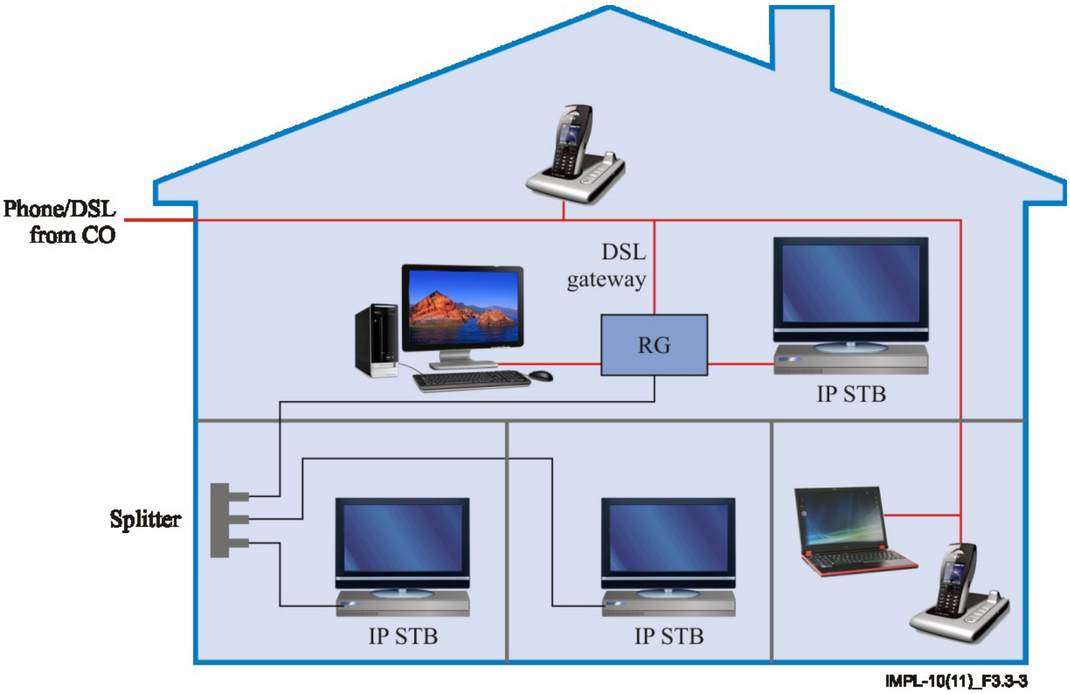


Figure 3.3-3 – ITU-T G.9954v2 home network with several types of network nodes

In Figure 3.3-2, a layer 3 router/gateway is shown which interconnects a wide area network link to the in-house HN network. Such wide area link might be provided via subscriber line (V.90, ISDN, xDSL), coaxial cable (DOCSIS, Data Over Cable Service Interface Specifications) or wireless link. Also shown in figure 3.3-2 is a L2 bridge that interconnects the first HN network with other HN network segments or IEEE 802.3 (10BASE-T, 100BASE-T) networks.

NOTE – Where multiple HN network segments exist, they should not share the same cables infrastructure unless the segments are properly isolated in the HNT frequency band.

The HNT network standard is designed to work over "as is" customer premise wiring or coaxial cabling.

The topologies anticipated on the phone line are random combinations of star, tree and multipoint bus wiring: see Figure 3.3-4 for an example. Here, the "plain old telephone service" (POTS) network interface device (NID) is shown with the outside subscriber loop to the left, and the premises wiring splitting in a "star" from the NID to several wiring runs. Each run may have one or more modular connectors at wall plates, and variable length extension wires (shown as double lines) run from the wall plates to the attached POTS or HNT node. In the example, stations A and B are on one bus; station C is on a second bus, which is unterminated at the end; station E is at the end of a direct run from the NID; and stations F and G share a single wall plate via a two-outlet adapter. Many other topologies are possible.

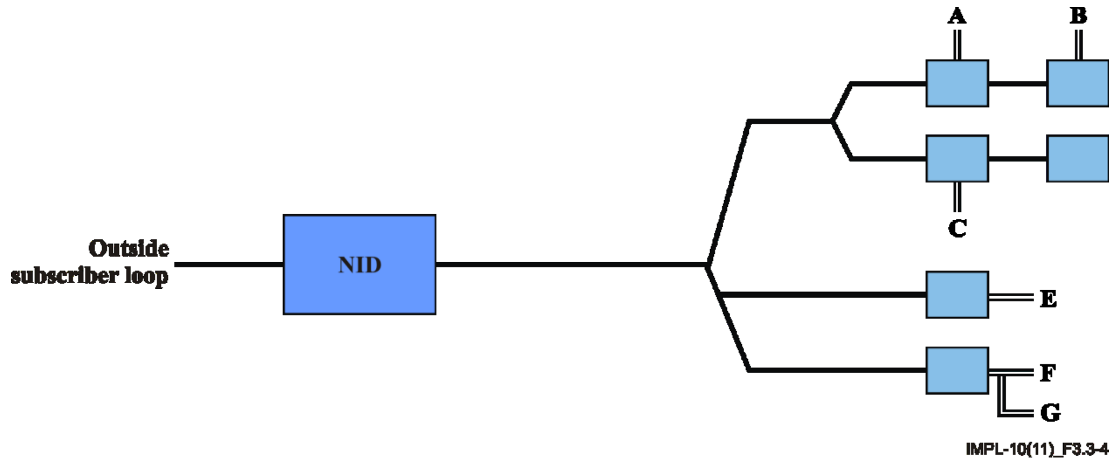


Figure 3.3-4 – Reference wiring topology over phone line

The topologies anticipated on the coaxial cable are various combinations of tree and bridged-tap cabling, usually built for a distribution of signals from the outside cable to the coaxial outlets; see Figure 3.3-5 for an example. Here the outside subscriber cable is connected to the input of a main splitter with three output ports. The signal splits to three output paths where two of them are connected directly to outlets while a third path goes into a second splitter with two ports. Each output of the two-port splitter is connected to two bridge-taped outlets. The outlets close to the two-port splitter also serve as non-symmetric splitters since they split the signal between the local outlet and the other chained outlets in the bridge topology. In the example, stations A and B are on the same bridge-tap chain; station C is on a second chain; and station D is connected directly to one of the output ports of the main splitter. Many other topologies are possible.

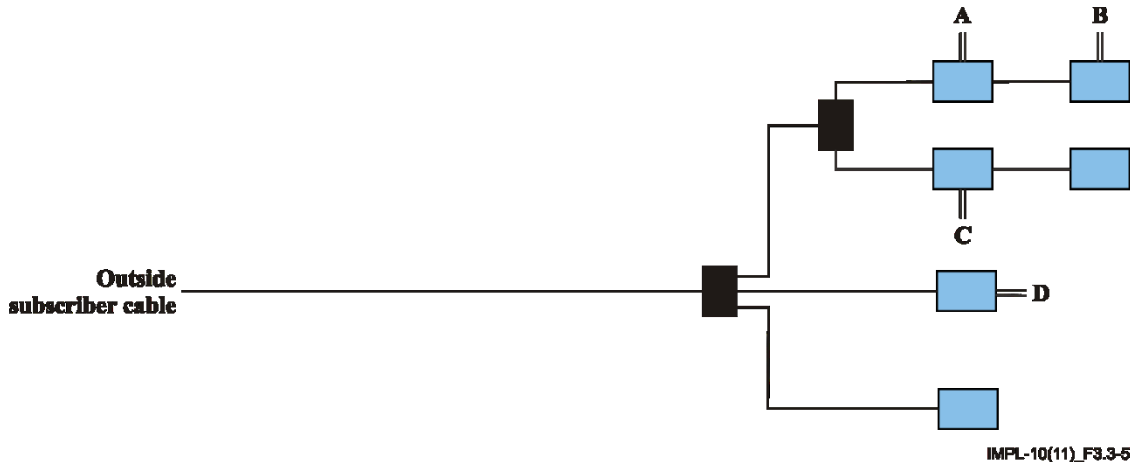


Figure 3.3-5 – Reference wiring topology over coaxial cabling

The ITU-T G.9954v2 protocol is based on a master-controlled network model. The master-controlled network model assumes the existence of a master node that provides the timing on the network and synchronizes media access to all ITU-T G.9954v2 network nodes.

Although media access in a master-controlled network is controlled by the master, communication between two nodes does not traverse the master, but nodes communicate directly (peer-to-peer) at the master-designated time. Any node on the network can potentially act as the master, although it is a role most naturally assumed by a gateway or server.

3.3.2.2 The home networking transceiver protocol reference model

Figure 3.3-6 shows the HN transceiver reference model and the relationship to the Open Systems Interconnection (OSI) reference model.

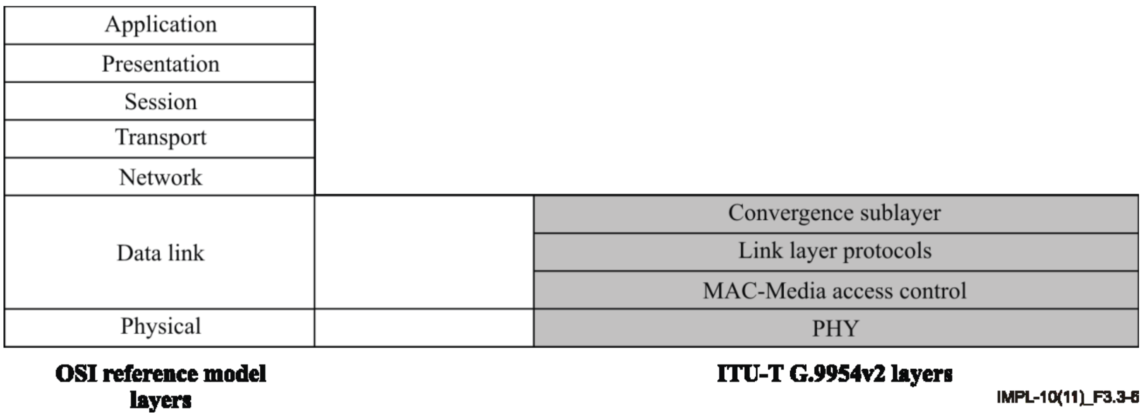


Figure 3.3-6 – The relationship between ITU-T G.9954 and OSI reference models

The ITU-T G.9954v2 protocol stack provides layer 1 (PHY) and layer 2 (DLL or data link layer) services for transmitting and receiving packets over a wired media using the ITU-T G.9954v2 protocol. The protocol stack used by the ITU-T G.9954v2 is illustrated in Figure 3.3-7. The DLL is composed of the MAC, LLC and convergence sublayers. In addition the ITU-T G.9954 protocol stack includes a management layer (for more details see section 5.3.1.2.3.6). The layers above the convergence sublayer are beyond the scope of Recommendation ITU-T G.9954.

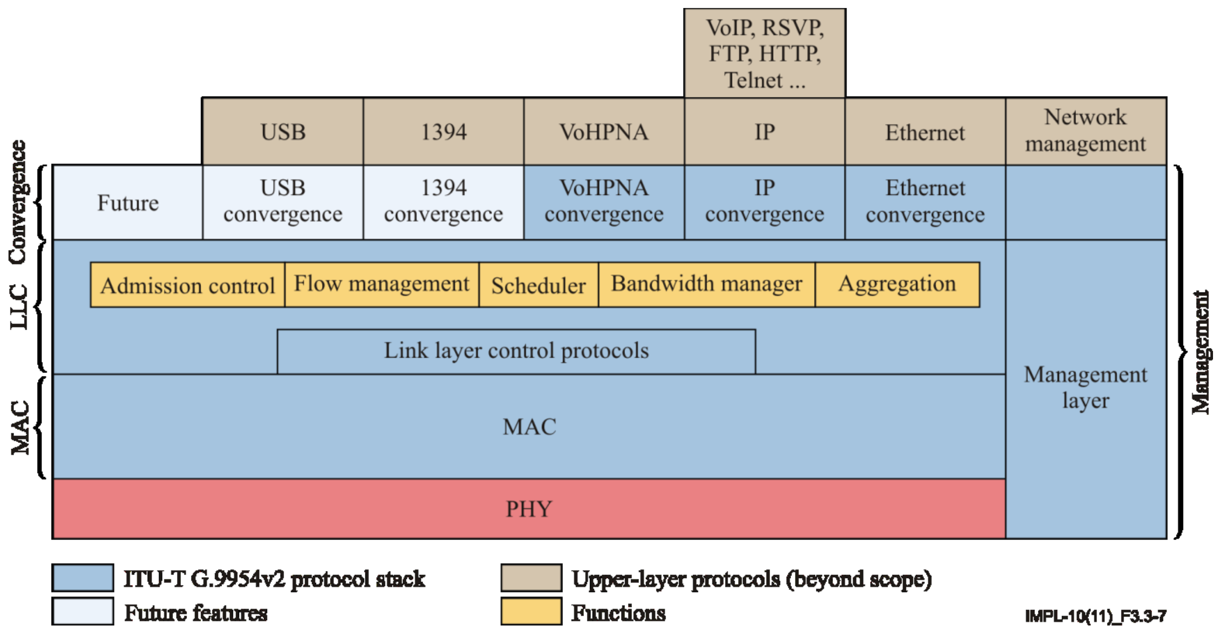


Figure 3.3-7 – ITU-T G.9954v2 protocol stack

The media access method depends on the existence of an ITU-T G.9954v2 node on the network that is able to assume the role of network master. Such a node is referred to as the master node or just master. A node that is able to assume the role of master on the network is referred to as a master-capable node. A master-capable node is a regular ITU-T G.9954v2 node that also supports functional capabilities that allow it to assume the role of master, in the absence of an active master on the network.

The master is responsible for controlling media access by planning media access timing on the network and periodically advertising the media access plan to all nodes on the network. The periodic timing is referred to as a MAC cycle. ITU-T G.9954v2 nodes synchronize with the periodic MAC cycle and time their transmissions in accordance with the transmission timing described in the media access plan (MAP).

3.3.2.3 The home networking transceiver interfaces

The primary interface specified is the wire-side electrical and logical interface (W1) between an ITU-T G.9954v2 station and the phone wire or the coaxial cable as shown in Figure 3.3-8. This figure also shows host-side interfaces in terms of example interfaces such as IEEE 802.3 logical link level frame formats, addressing and broadcast/multicast behaviour. Several options exist for host-side interfaces, with the medium-independent interface (MII) described in Appendix II of Recommendation ITU-T G.9954.

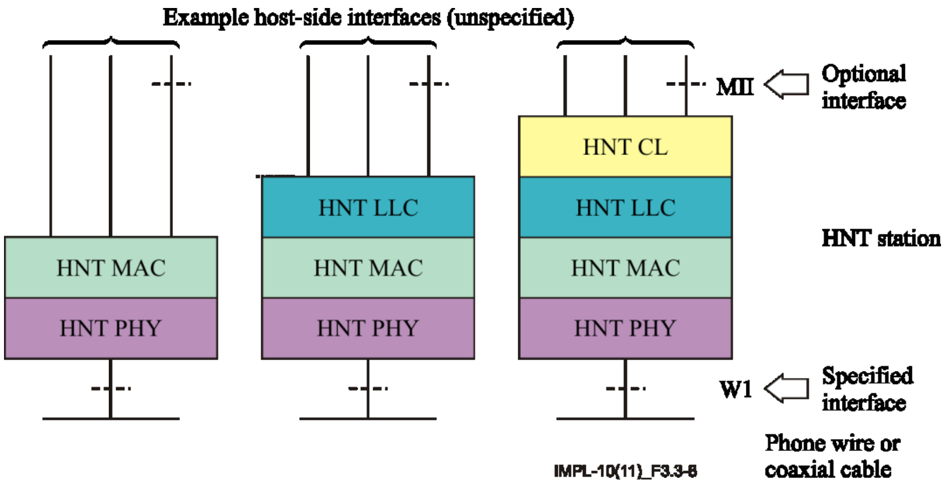


Figure 3.3-8 – Interfaces

3.3.3 Network level features

3.3.3.1 Media access method

The ITU-T G.9954v2 MAC protocol is a synchronous MAC protocol that coordinates media access under master control. The protocol is synchronous in the sense that all ITU-T G.9954v2 nodes on the network are synchronized to a periodic MAC cycle and transmissions are pre-planned and accurately timed.

The ITU-T G.9954v2 MAC protocol is used to support different kinds of services including asynchronous best-effort data services and isochronous constant and variable bit-rate streaming services such as required by telephony, audio and video.

In an ITU-T G.9954v2 network, media access is pre-planned and a collision avoidance (CA) strategy is used during normal data-transfer operations. Collision avoidance, together with packet aggregation, provides efficient use of the media and provides the infrastructure for supporting quality of service (QoS) guarantees.

The ITU-T G.9954v2 MAC protocol supports bridging to other synchronous protocols, such as IEEE 1394, USB, etc., and to broadband access protocols such as DOCSIS and IEEE 802.16, using the protocol convergence sublayer. Furthermore, the master-controlled network model, used in the ITU-T G.9954v2 MAC, is a natural model for broadband access networks and is well suited to an architecture containing a residential gateway.

3.3.3.2 Functions of a master node and endpoint nodes

An ITU-T G.9954v2 master-capable node is an ITU-T G.9954v2 node that, in addition to supporting all of the required capabilities of an ITU-T G.9954v2 "endpoint" node (a regular node), is also able to assume the role of master in the absence of an active master on the network. Following is a list of master-related MAC and link layer functions:

1) **Network admission** – Manage the admission of ITU-T G.9954v2 nodes to the network;
2) **Dynamic master selection** – Detect the presence or absence of an operational master on the network and assume the role of network master, if required;
3) **Flow and bandwidth management** – Manage the setup, modification and teardown of service flows and the allocation of associated media bandwidth resources in accordance with the services QoS constraints;
4) **Scheduling** – Plan the media cycle and schedule transmissions such that QoS bandwidth, latency and jitter constraints are met;
5) **MAP generation and distribution** – Generate a media access plan (MAP) that represents the output (“plan”) of the bandwidth management and scheduling functions and distribute the MAP during each MAC cycle.

Only a single master node shall exist on the network at any one time. It is not a requirement that every ITU-T G.9954v2 node be capable of becoming a master.

An ITU-T G.9954v2 endpoint node shall detect the existence of an ITU-T G.9954v2 master node on the network and operate according to the media access rules for a managed network. As a minimum requirement, an ITU-T G.9954v2 endpoint node shall support the following MAC functions:

1) **MAC cycle synchronization** – An ITU-T G.9954v2 endpoint shall synchronize with the master-generated MAC cycle in a managed network.
2) **Synchronized transmissions** – An ITU-T G.9954v2 endpoint node shall comply with the transmission directives in the current MAP and guarantee that it shall only transmit within a transmission opportunity (TXOP) that is allocated exclusively to it, a contention-free TXOP (CFTXOP), or to a group to which it belongs, a contention TXOP (CTXOP), or within an unallocated TXOP (UTXOP).

The above minimum requirement represents the core functionality upon which the higher-level protocol functions (e.g., registration, flow set up etc.) can be bootstrapped. In order to support QoS contracts of bandwidth reservation for flows, an ITU-T G.9954v2 endpoint node shall support the following ITU-T G.9954v2 MAC and link layer functions:

1) **Registration** – Once an endpoint node has synchronized with the master, the endpoint shall REGISTER with the master. REGISTRATION is the process whereby an endpoint requests entry to the network and, if authorized, is supplied a network Device_ID and network configuration data.
2) **Flow signalling** – In order to manage QoS flows, an endpoint shall support the flow signalling protocol. The flow signalling protocol is used to set up, modify or tear down flows.

3.3.3.3 Quality of Service

The ITU-T G.9954v2 MAC supports both priority-based and parameter-based QoS methods.

Priority-based QoS supports priority classification using eight priority levels and provides a basic QoS mechanism for differentiating between different kinds of services. This mechanism is compatible with IEEE 802.1D specifications, the VLAN priority tag (IEEE 802.1P) and the PRECEDENCE bits defined in the original interpretation of the type of service (TOS) field found in an IP packet using the differentiated services (Diffserv) protocol.

Parameter-based QoS supports traffic specifications defined in terms of rate, latency, jitter and other parameters. This provides controls to a finer level of detail than just a relative ordering of packets as supported by the priority-based scheme.

The ITU-T G.9954v2 QoS mechanism is based on the concept of a flow, which represents a unidirectional flow of data between network nodes based on well-defined QoS parameters that allow strict control over network throughput, latency, jitter and BER (Bit Error Ratio) parameters.

Flows are set up and torn down on a service-by-service basis. The ITU-T G.9954v2 link layer control (LLC) and MAC sublayers are responsible for scheduling the transmission of packets on flows in such a way so as to enforce respective traffic/QoS parameters. Bandwidth is reserved for a flow during its lifetime and this is reflected in the media access plan (MAP) prepared by the master ITU-T G.9954v2 node. Bandwidth requirements for a flow may also be modified throughout its lifetime in order to support changing bandwidth requirements that are characteristic of "bursty" and variable bit-rate (VBR) data streams.

It is the responsibility of the convergence sublayer to map incoming data streams onto an appropriate flow in order to meet QoS requirements.

Flows may be set up automatically upon service invocation or they may be established at initialization time according to a predefined specification (e.g., part of the convergence layer) or configuration data. Flows may similarly be torn down automatically upon detection of inactivity in order to free network resources associated with the flow.

3.3.3.4 Performance

The ITU-T G.9954v2 protocol improves on the performance of the ITU-T G.9951/ITU-T G.9952 and ITU-T G.9954v1 asynchronous mode MAC protocol by using a pure collision avoidance media access method. In addition, the ITU-T G.9954v2 MAC protocol improves on network utilization compared to that of ITU-T G.9951/ITU-T G.9952 by supporting aggregation of multiple MAC protocol data units (MPDUs) into a single PHY layer burst (frame).

The above performance gains are related to the ITU-T G.9954v2 MAC protocol itself and further performance gains and advantages may be expected in implementations themselves.

3.3.3.5 Security and privacy

An ITU-T G.9954v2 network node must register with the master in order to connect to the network and to initiate data transfer. This centrally controlled network model provides the necessary infrastructure for network admission control, security and privacy.

In the network admission control model, a node authorization list defines which nodes are able to connect to the master and gain access to the network and its resources. Node identification is performed using the node's hardware MAC address. Network access may be denied on the basis of authorization information accessible to the master. The management of the node authorization list and its physical location are beyond the scope of the Recommendation ITU-T G.9954 and, therefore, of this Technical paper.

Privacy of data is supported using shared private-key encryption methods. Link layer privacy controls ensure that only nodes with knowledge of the shared key are able to communicate and receive network data. The actual key management and distribution protocols are beyond the scope of Recommendation ITU-T G.9954 and, therefore, of this Technical paper.

Privacy may be required in the home in order to protect home content from exposure to unauthorized collection and monitoring caused by crosstalk. Encryption can be used to protect data in ITU-T G.9954v2 transmissions rather than relying only on security mechanisms based on restricting receiver sensitivity.

Network admission controls, security and privacy support are all optional features.

3.3.3.6 Management support

Given a home networking model based on a residential gateway through which services are delivered into the home, the need to be able to both locally and remotely manage, configure, monitor and troubleshoot home networks becomes critical. In this model, the RG is the primary means for collecting and reporting information about the state and health of the home network.

To support this functionality, ITU-T G.9954v2 nodes provide the following management functions:

- Configure, control and monitor all ITU-T G.9954v2 nodes on the network;
- Provide local and remote access to all nodes;
- Access to all nodes through the gateway (master);
- Support diagnostics using a standard message-based protocol (certification and diagnostics protocols);
- Support BBF TR-069 data model.

  NOTE - BBF TR-069 specifies the CPE WAN Management Protocol (CWMP) and is a de facto standard used by many service providers. It describes the protocol intended for communication between a CPE and an auto-configuration server (ACS). It defines a mechanism that encompasses secure auto-configuration of a CPE, and also incorporates other CPE management functions such as troubleshooting, diagnostics, status and performance monitoring, and upgrading software and firmware within a common framework.
- Support other higher-level management interfaces (e.g., SNMP, HTTP, etc.).

The management facilities are intended to provide access to the following management information:

- PHY information;
- Network information;
- Node statistics;
- QoS information;
- Node information;
- Configuration information;
- Authorization and security information;
- Version information.

3.3.3.7 Compatibility and interoperability

The ITU-T G.9954v2 PHY layer includes two alternatives, where one is specified for phone line networks and the other is specified for coaxial cable-based networks. Each maintains compatibility with existing services on the same network.

The PHY layer over phone line maintains backward compatibility with ITU-T G.9954v1 (HomePNA V3.0) using spectral mode A. It is also compatible with other phone line services such as POTS, V.90, ISDN and xDSL.

Compatibility with amateur radio services is due to spectrum notching.

The PHY layer over coaxial cable is compatible with other coaxial services such as VDSL, VDSL2 and cable-TV channels.

The two PHY layers enable optional interoperability with each other using spectral modes A and B (see section 3.3.4.3.1), thus allowing a mixed phone line/coaxial cable network.

An ITU-T G.9954v2 node operating in mode A over phone line will be backward compatible with an ITU-T G.9951/ITU-T G.9952 node. At this mode, when an ITU-T G.9954v2 node detects an ITU-T G.9951/ITU-T G.9952 node it will return to work as an ITU-T G.9951/ITU-T G.9952 node.

3.3.3.8 External interfaces and protocols

The ITU-T G.9954v2 protocol supports interfaces and bridging to external protocols through the convergence sublayer in the protocol stack.

It is the responsibility of the protocol convergence sublayer to map data packets arriving from a particular interface onto the flows appropriate for the particular data service.

The ITU-T G.9954v2 protocol stack does not assume the existence of an external host processor and is able to directly interface, in hardware, to an external chip, possibly running a different protocol. In this configuration, the protocol convergence sublayer is assumed to co-reside with the MAC and link layers in an integrated ITU-T G.9954v2 chip. Alternatively, the ITU-T G.9954v2 convergence sublayer may actually execute, in part or entirely, on an external host processor.

The external protocols addressed explicitly in the ITU-T G.9954v2 convergence sublayer description include the IEEE 802.3 Ethernet protocols and Internet protocol (IP). Additional protocols are also supported by the convergence layer through a generic packet classification mechanism.

Protocol mapping and convergence at an explicit level of the protocol stack supports synchronization between external and home networks. This is described in more detail in Appendix III of Recommendation ITU-T G.9954. Given that the QoS of the home network is defined in terms that are similar to those of the external network, the extension of QoS methods from external networks into the home network is supported.

3.3.4 The PHY layer

3.3.4.1 General

The PHY layer provides transmission and reception of physical layer frames using QAM (quadrature amplitude modulation) technique over phone line media or coaxial cabling.

The PHY layer over phone supports 2-, 4-, 8-, 16-Mbaud symbol rates with 2 to 10 bits-persymbol constellation encoding. The PHY layer over coaxial cable supports 2-, 4-, 8-, 16- and 32-Mbaud symbol rates with 2 to 10 bits-per-symbol constellation encoding. This provides a PHY layer data rate in the range of 4 to 320 Mbit/s within an extended 4 to 36 MHz power spectral density (PSD) mask supporting up to a 32-MHz bandwidth.

3.3.4.2 The transmitter reference model for transmission over phone lines / coaxial cable

The transmitter block diagram is shown in Figure 3.3-9. This block diagram is common to both the PHY specified for phone lines and the PHY specified for coaxial cabling, although the constituent blocks for the two media are not identical. This block diagram consists of a frame processor, data scrambler, bit-to-symbol mapper, and QAM modulator.

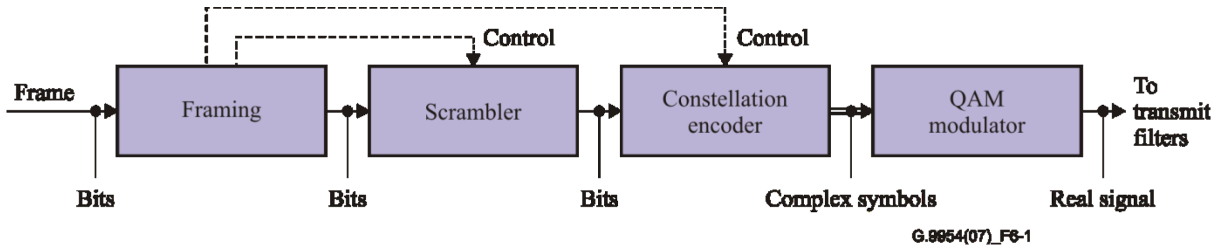


Figure 3.3-9 – Transmitter block diagram

3.3.4.3 Media-specific PHY specifications for phone line or coaxial cable

3.3.4.3.1 PHY specifications over phone lines

The ITU-T G.9954v2 PHY layer over phone lines supports two spectral modes. Each spectral mode supports a different band range while both supporting the same baud rates set:

- Spectral mode A: 4 to 20 MHz; 2, 4, 8, 16 MBaud;
- Spectral mode B: 12 to 28 MHz; 2, 4, 8, 16 MBaud.

The actual spectral mode to be used in the network is pre-configured according to considerations of coexistence with other services and line characteristics. The pre-configuration technique is implementation dependent and is out of the scope of Recommendation ITU-T G.9954 and therefore of this Technical paper. The network configuration is limited to a homogenous spectral mode for all nodes.

Constellation sizes range from 2 to 10 bits per symbol, specifying PHY layer payload modulation rates that range from 4 Mbit/s to 160 Mbit/s.

Information is transmitted on the channel in bursts. Each burst or physical layer frame consists of PHY-layer payload information encapsulated with PHY preamble, header and postamble. The PHY-layer payload refers to the portion of the link level frame that is modulated at the payload rate, which is typically higher than the header rate. Hereafter, "payload" refers to the PHY-layer payload unless otherwise specified.

The frame format is shown in Figure 3.3-10. This consists of a low-rate header section, a variable-rate payload section, and a low-rate trailer. Some parts of the frame are not scrambled.

3.3.4.3.2 PHY specifications for coaxial cable

The ITU-T G.9954v2 over coaxial cable PHY layer supports four spectral modes. Each spectral mode supports a different band range along with its corresponding payload baud rates set:

- Spectral mode A: 4-20 MHz; 2, 4, 8, 16 Mbaud;
- Spectral mode B: 12-28 MHz; 2, 4, 8, 16 Mbaud;
- Spectral mode C: 36-52 MHz; 2, 4, 8, 16 Mbaud;
- Spectral mode D: 4-36 MHz; 2, 4, 8, 16, 32 Mbaud.

The actual spectral mode to be used in the network is pre-configured according to considerations of co-existence with other services and line characteristics. The pre-configuration technique is implementation dependent and is out of the scope of Recommendation ITU-T G.9954. The network configuration is limited to either a homogenous spectral mode for all nodes or a dual spectral mode D+A or D+B.

Constellation sizes range from 2 to 10 bits per baud, specifying PHY layer payload modulation rates that range from 4 Mbit/s to 320 Mbit/s.

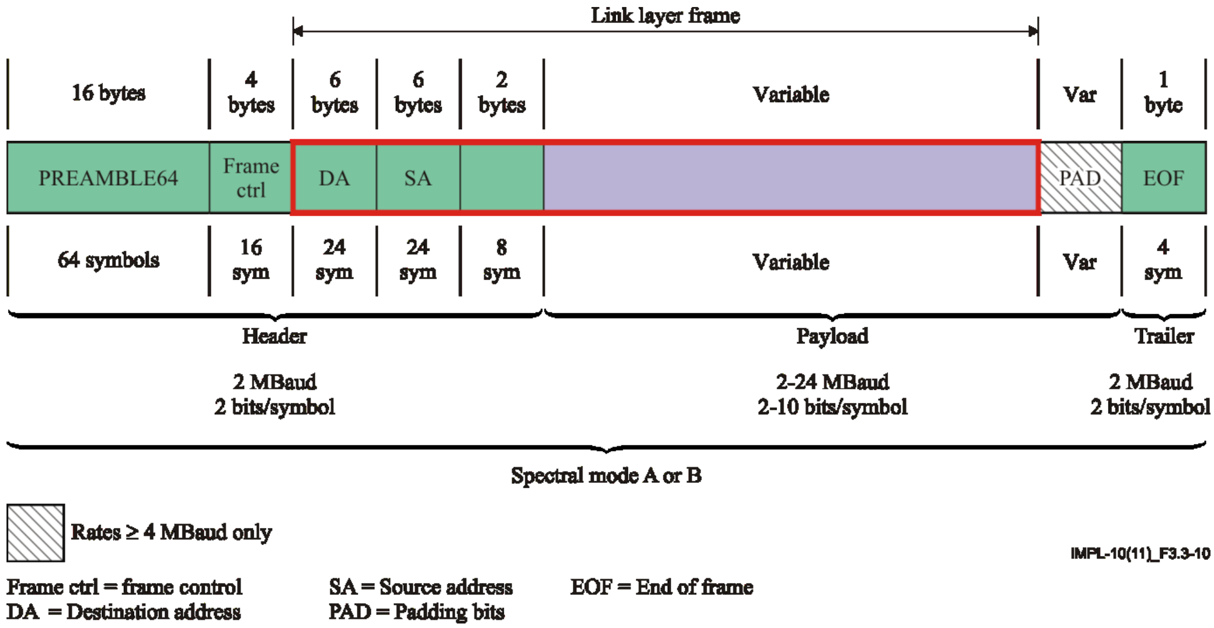


Figure 3.3-10 – PHY frame format for transmission over phone lines

Information is transmitted on the channel in bursts. Each burst or physical layer frame consists of PHY-layer payload information encapsulated with PHY preamble, header and post-amble. The PHY-layer payload refers to the portion of the link level frame that is modulated at the payload rate, which is typically higher than the header rate. Hereafter, "payload" refers to the PHY-layer payload unless otherwise specified.

The frame format for transmission over coaxial cable is very similar to the one shown Figure 3.3-9 with some minor variations (e.g. the payload has a max. of 32 Mbaud, the spectral modes are A, B, C or D).

3.3.5 The DLL (Data-link layer)

The data-link layer is composed of three sublayers: the MAC, LLC and convergence sublayers.

3.3.5.1 The MAC sublayer

The ITU-T G.9954v2 media access protocol is a synchronous protocol that uses Carrier Sense Multiple Access with Collision Avoidance methods (CSMA/CA) to coordinate access to a shared media amongst a set of ITU-T G.9954v2 nodes. The ITU-T G.9954v2 MAC protocol is suitable for shared media networks composed of phone lines, coaxial cable or hybrid phone line/coaxial cable wiring.

The ITU-T G.9954v2 MAC uses a resource reservation scheme to guarantee media resources to network devices and to prevent collisions between multiple network nodes contending for access to the media.

3.3.5.1.1 Master node and Endpoint nodes

An ITU-T G.9954v2 network is composed of at least two network nodes. One of the network nodes takes the role of the network "master" and is referred to as the master while the other nodes are referred to as "endpoints". An ITU-T G.9954v2 network node comprises of, amongst other items, a carrier sensor and a transceiver. The master also includes a scheduler. The master's scheduler sends to each node on the network a media access plan (MAP) at the beginning of each transmission cycle. The transceiver either transmits, or both transmit and receive data transmissions over the network.

3.3.5.1.2 Media Access Plan (MAP) and transmission opportunities (TXOPs)

Transmissions are performed within the context of a transmission cycle, called a MAC cycle. The MAP that starts the transmission cycle describes the schedule of future transmission opportunities (TXOPs) that are available to specific network nodes in the upcoming transmission cycle at specific and non-overlapping times. The start time and length of each scheduled TXOP in the upcoming transmission cycle, as well as the network nodes and flows to which each TXOP is assigned, is determined by the scheduler and defined in the MAP.

After the publication of the MAP, network node transmissions may begin. Each node recognizes, according to the MAP, a particular TXOP within which it is allowed to transmit and either utilizes (transmits within) the TXOP or passes on it.

Figure 3.3-11 shows an example of a network with 3 nodes. DEV-1 is the domain master, transmitting the MAP periodically. DEV-2 is transmitting bursts of data composed of sub-bursts (explained later on), while DEV-0 is trying to register to the network by sending a Registration Request message (shown in blue) in a special "Registration TXOP".

The following types of TXOPs are defined.

- Contention-free TXOP (CFTXOP) – allocated to a dedicated (single) network node.
- Contention TXOP (CTXOP) – A TXOP for which contention-based access is defined amongst a group of network nodes.
- Unallocated TXOP (UTXOP) – An unallocated TXOP is a type of contention-based TXOP where any network node may transmit if the media is sensed as being idle.

The internal structure of a MAC cycle is illustrated in Figure 3.3-12. It shows an example MAC cycle composed of transmission opportunities (TXOPs) of different types.

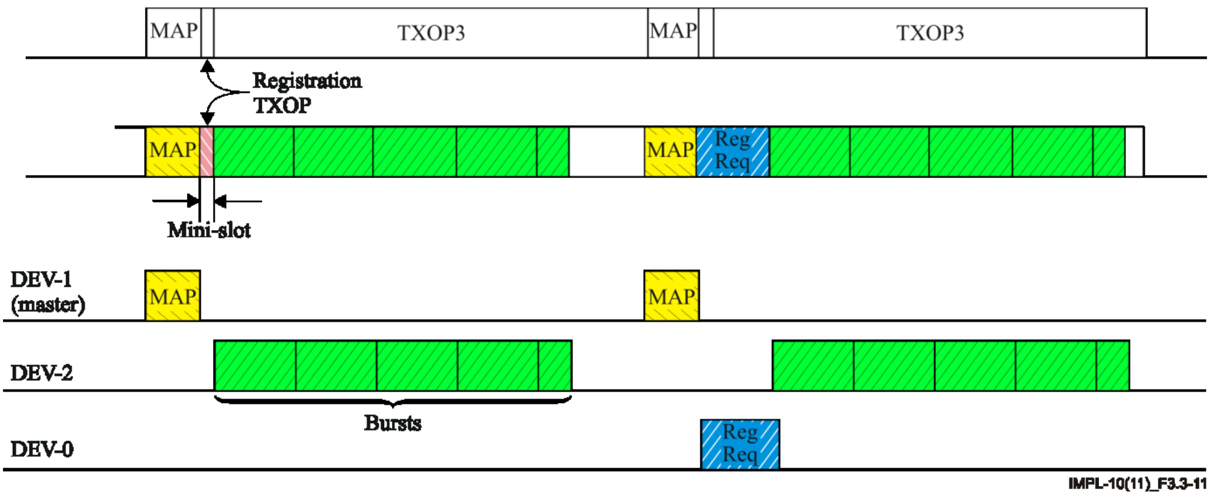


Figure 3.3-11 – Example to the operation of an ITU-T G.9954 network

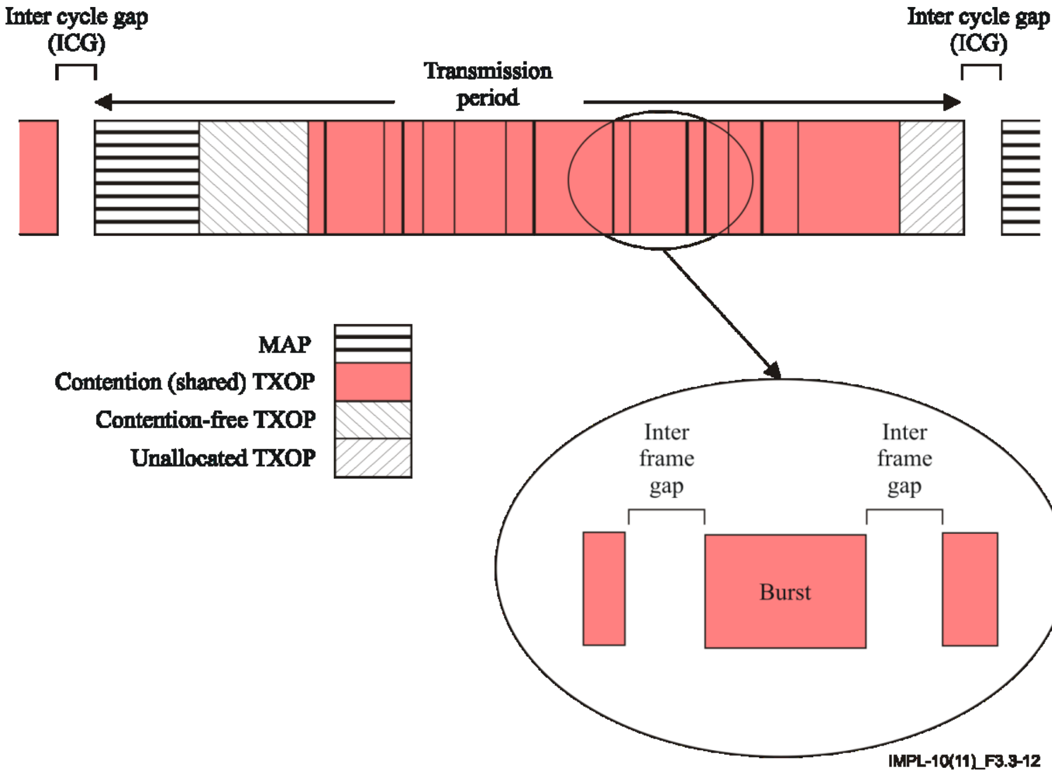


Figure 3.3-12 – MAC cycle structure

3.3.5.1.3 Association of nodes and flows to TXOPs

A TXOP may be assigned to a single or multiple network nodes and/or flows. When a TXOP is assigned to a single network node, the network node is considered to have exclusive access to the TXOP and media access is necessarily collision-free. When a TXOP is assigned to multiple network nodes, the media access method based on carrier-sensing and collision-avoidance techniques is also used to allow collision-free burst-like media access within the shared TXOP.

3.3.5.1.4 Media access to shared TXOPs (either CTXOPs or UTXOPs)

To allow multiple network nodes to perform collision-free media access within a shared TXOP, the ITU-T G.9954v2 MAC defines a TXOP to be composed of a grid of smaller time-slots (sub-burst slots) which represents an opportunity for the initiation of a data transmission by a network device. The sub-burst slot is appreciably smaller in size than the containing TXOP and is smaller than a minimal-sized transmission burst. The advantage of the small sub-burst slot structure can be appreciated when a network node does not use its assigned sub-burst slot. In this case, only the sub-burst slot time is wasted before the opportunity to transmit is passed to the node assigned the next sub-burst slot. The assignment of nodes and flows to sub-burst slots is defined by the scheduler and published in the MAP.

In order for an ITU-T G.9954v2 network node to act on an opportunity to transmit within an assigned sub-burst slot, it must initiate its transmission at the beginning of the sub-burst slot opportunity. The size (duration) of a sub-burst slot opportunity is small and configurable by the ITU-T G.9954v2 master in the range of 8-64 µs. The window for acting upon the opportunity to initiate a transmission within a sub-burst slot shall be within 4 µs of the start of the sub-burst slot. The size of a sub-burst slot opportunity is defined by the ITU-T G.9954v2 master and communicated to all nodes on the network through the MAP.

In the event that a sub-burst slot opportunity S_n is not utilized by the network node to which the slot is assigned, the node assigned the next sub-burst slot in the sub-burst slot grid sequence, S_{n+1} is given the opportunity to transmit. When a sub-burst slot is utilized for a transmission, the sub-burst slot in which the transmission occurs can be thought of as expanding to allow the completion of the transmission burst started within it. Upon completion of the transmission burst, the sub-burst slot grid pattern continues in accordance with the MAP and with sub-burst slot grid timing adjusted relative to the end of the transmission.

The length of a transmission burst within a sub-burst slot, in general, is bounded only by the maximum transmission burst size. However, towards the end of the containing TXOP, the length of the transmission burst may also be bounded in time by the end of the containing TXOP. A transmission burst may extend beyond the end of the TXOP, extending the length of the TXOP if the transmission starts before the end of the TXOP and the attributes of the TXOP allow its length to be extended. By default, the length of a TXOP is strictly bounded.

At the beginning of each cycle, network nodes receive a schedule of transmission opportunities (i.e., a MAP) detailing the timing of the TXOPs, an ordering of sub-burst slots within the TXOP and an assignment of sub-burst slots to nodes and data flows. While the order of sub-burst slots in the grid is known to all nodes on the network, the timing of the sub-burst slots in the grid changes, due to and in direct accordance with the transmissions that occur and the duration of the transmission. Consequently, following each transmission, the sub-burst slot grid aligner function in each network node on the network must recalculate the timing of the sub-burst slot grid so that each network node knows what time its next transmission opportunity is scheduled.

3.3.5.2 The ITU-T G.9954v2 LLC sublayer

The Link Layer Control (LLC) sublayer is responsible for performing link control functions. In particular, it is responsible for managing information concerning network connections, for enforcing quality of service (QoS) constraints defined for the various system data flows and for ensuring robust data transmission using rate negotiation, Reed-Solomon coding techniques and automatic repeat request (ARQ) techniques.

In addition, the ITU-T G.9954v2 MAC protocol requires the support of link control protocols that manage network admission and flow setup and teardown procedures. These protocols are used to manage the information about connected nodes and their associated service flows.

In addition to the link layer control protocols required by the ITU-T G.9954v2 MAC, the following link layer control functions are required: scheduling, bandwidth management, flow management, network admission and packet aggregation. All these link functions use control frames to carry protocol messages between stations. ITU-T G.9954v2 includes a standardized mechanism for link layer network control and encapsulation. Individual sub-types further distinguish control frames.

Following are some more details on the key link-layer functions.

3.3.5.2.1 Various levels of link layer protocol support profiles

While all control protocols serve an important function in the operation of the network, it is possible to implement different subsets (profiles) of link layer Protocols. The profiles specified in Recommendation ITU-T G.9954 are:

- An ITU-T G.9954v2 node supporting the "Full link protocol support profile": Full support of all the link protocols.
- An ITU-T G.9954v2 node supporting the "Minimal profile": a minimal subset of link layer protocols (allows less complex implementations of the ITU-T G.9954v2 specification) that are compatible with fully functional implementations and does not detract from the overall performance of other stations. The protocols that are included in this profile:
  - Rate negotiation (see section 3.3.1.4.2.4);

  - Link integrity (see section 3.3.1.4.2.5);
  - Capability announcement (see section 3.3.1.4.2.6);
  - MAC cycle synchronization (see section 3.3.1.4.2.8);
  - Frame bursting;
  - Certification protocol;
  - Minimal LARQ (see section 3.3.1.4.2.7);
  - Network admission (see section 3.3.1.4.2.9).
- An ITU-T G.9954v2 node supporting QoS contracts: In addition to the link layer protocols in the minimal profile a node supporting QoS contracts shall also support the following LLC protocol:
  - Flow signalling (endpoint node) (see section 3.3.1.4.2.11).
- An ITU-T G.9954v2 master-capable node: a master-capable node shall, in addition to the link layer protocols described above also support the following LLC protocols:
  - Dynamic master selection;
  - MAC cycle generation;
  - Flow signalling (master node);
  - Timestamp reporting (master clock reference).
- ITU-T G.9954v2 optional link layer protocols: The following link layer protocols are optional for all ITU-T G.9954v2 nodes:
  - Full dynamic master selection;
  - Timestamp reporting (endpoint slave);
  - Reed-Solomon encapsulation.

Some of the different subsets (profiles) of link layer protocols are described in the following sub-sections. For the others see Recommendation ITU-T G.9954.

3.3.5.2.2 Basic link layer frame format

The basic link layer frame format is described in Table 3.3-1.

Table 3.3-1 – Basic link layer format

Field	Length	Explanation
DA	6 octets	Destination address
SA	6 octets	Source address
Ethertype	2 octets	Ethernet ethertype. Arbitrary value. If equal to 0x886c (HNT link Protocol Frame assigned by IEEE), then frame is for link protocol control frame.
Data	Variable	Payload data
Pad	Variable	Padding (if required to meet minimum length frame)
FCS	4 octets	Frame check sequence
CRC-16	2 octets	HNT frame check sequence

The ITU-T G.9954v2 basic link layer frame format is based on the IEEE 802.3 specification of the Ethernet frame format (not including the IEEE 802.3 preamble and start frame delimiter (SFD) fields) with an additional CRC-16 frame check sequence.

IEEE assigned Ethernet MAC addresses shall be used for destination address (DA) and source address (SA). An additional CRC-16 is appended after the frame check sequence.

In the frame formats defined above, before transmission, the link control frame shall be converted into an ITU-T G.9954v2 physical layer frame by adding preamble, frame control, PAD and EOF as shown in Figure 4.3.9.

3.3.5.2.3 Link-layer control frames

Link-layer frames with ethertypes equal to 0x886c are link layer control frames. These frames are not based on the specification IEEE 802.3 Ethernet frame format. There are two basic formats for a link control frame: a long subtype and a short subtype. The long subtype format is provided for future specified control frames where the amount of control information exceeds 256 octets. The control and encapsulation frames described in the Recommendation ITU-T G.9954 use the short subtype format.

NOTE – Ethertype is a two octet field in an Ethernet frame. It is used to indicate which protocol is encapsulated in the payload of an Ethernet frame. The Ethertype numbering starts generally starts from 0x800.

Before transmission the link control frame shall be converted into a physical layer frame by adding preamble, frame control, PAD and EOF as shown in Figure 3.3-10.

3.3.5.2.4 Rate negotiation control function

The PHY payload modulation can use 2- to 8-bits per symbol constellations and one of several defined *bands* which are associated with symbol rates. For some bands 8-, 9- and 10-bits per symbol constellations optionally exist.

The payload encoding (PE) that can be achieved is a function of the channel quality between source and destination, and the channel quality generally differs between each pair of stations depending on the wiring topology and specific channel impairments. Therefore the rate negotiation function in a destination station uses rate request control frames (RRCF) to provide information to a source station as to the payload encoding that the source station should use to encode future frames sent to this destination, and to generate test frames to assist a receiver in selecting the most appropriate band to use.

The policy that the destination station uses to select the desired payload encoding and the policy it uses to decide when to transmit rate request control frames are implementation dependent. Stations should avoid transmission policies that can result in excessive RRCF traffic.

Rate negotiation in ITU-T G.9954v2 is defined over a logical channel where a logical channel is defined by the ordered list of elements (tuples) {source address, destination address, priority} and/or {source address, destination address, flow ID}. This allows a fine degree of control over the selected rate for a logical channel by allowing different rates to be negotiated per logical channel, even when the different channels are over the same source-destination pair. Since each logical channel represents a different service or flow, possibly with distinct bit error ratio (BER) / frame error ratio (FER) requirements, rate negotiation is adaptive per service.

The goal of rate negotiation is to select the payload encoding that achieves the highest raw bit rate while still meeting the BER/FER requirements for the logical channel.

3.3.5.2.5 Link integrity function

The purpose of the link integrity function is to provide a means for hardware and/or software to determine whether or not this station is able to receive frames from at least one other station on the network. In the absence of other traffic, a station periodically transmits a link integrity control frame (LICF) to the broadcast MAC address, with the interval between such transmissions governed by a method detailed in the Recommendation ITU-T G.9954.

3.3.6.2.6 Capability and status announcement

A mechanism is defined for network-wide negotiation, capability discovery and status announcement. It is based on periodic broadcast announcements, called capabilities and status announcements (CSA) sent in CSA control frames (CSACFs). The defined status flags allow determination of a station's HNT version, optional feature support, and link layer priority usage, as well as communication of network configuration commands.

The purpose of the protocol is to distribute to all stations the complete set of status flags in use on the network, so that stations can make operational decisions based on those flags with no further interaction.

3.3.5.2.7 Limited automatic repeat request protocol

Limited automatic repeat request (LARQ) is a protocol that reduces the effective error rate when frame errors occur. Its primary distinction from similar, sequence number-based protocols is that it does not guarantee reliable delivery of every frame, but instead conceals errors in the physical layer through fast retransmission of frames. The goal is to significantly enhance the usability of networks that may, at least occasionally, have frame error rates (FER) of 1 in 10^{-2} or worse. Protocols such as Transmission Control Protocol (TCP) are known to perform poorly when FER gets high enough, and other applications, such as multimedia over streaming transport layers, are also susceptible to poor performance due to high FER conditions.

The protocol provides a negative acknowledgment (NACK) mechanism for receivers to request the retransmission of frames that were missed or received with errors. There is no positive acknowledgment mechanism. Stations implement LARQ per "LARQ channel", where a LARQ channel is identified by either the tuple {source address, destination address, priority}, referred to as a LARQ-Priority Channel or by the tuple {source address, destination address, flow id}, referred to as a LARQ-Flow Channel. Stations may enable or disable LARQ processing on a channel dynamically, based on information about network frame error rates. However, LARQ should be left enabled at all times, since the per-packet processing overhead is quite low, and the complexity associated with enabling and disabling the protocol (including determination of appropriate parameters) probably outweighs any likely performance gains.

Stations should implement LARQ, and if they do so, they shall use the specified control frame formats and should use the procedures defined in Recommendation ITU-T G.9954.

3.3.5.2.8 MAC cycle synchronization

MAC cycle synchronization shall be performed using the master-generated media access plan (MAP). The MAP indicates the beginning of the MAC cycle and contains the media access plan for the following MAC cycle. All ITU-T G.9954v2 stations shall implement the MAC cycle synchronization function in order to implement the ITU-T G.9954v2 media access method in a master-controlled network.

3.3.5.2.9 Network admission control (Registration) protocol

Registration opportunities

Once a node is synchronized with the MAC cycle, the node is required to locate transmission opportunities that will allow it to bootstrap the registration process. Such transmission opportunities are identified in the MAP by an unallocated TXOP (UTXOP) also known as a REGISTRATION TXOP. The master guarantees to allocate a REGISTRATION TXOP periodically (The period is defined in Recommendation ITU-T G.9954). The REGISTRATION transmission opportunity is used to advertise an intention to register. This intention is expressed by sending a REG_REQUEST message to the master. Nodes contend for access to the REGISTRATION transmit opportunities.

Registration and authorization control

Registration is the process performed to allow an ITU-T G.9954v2 node to request media access bandwidth. Only after a node has registered with the master can it reserve bandwidth through explicit flow set-up requests with the master.

The registration procedure involves a request-response sequence, whereby an ITU-T G.9954v2 node requests to be registered with the master by sending a REG_REQUEST message containing the node's MAC address as well as other identifying characteristics, such as authentication key and a set of capability parameters. Upon receiving a REG_REQUEST message, the master is responsible for authorizing the entry of the requesting node and, if authorization is successful, for allocating resources to the registered node.

Authorization is performed by checking that the node, identified by its MAC address and possibly other identifying information (e.g., authentication key), is valid and the node is authorized to join the home network controlled by the master. The details of the authorization procedure are implementation dependent.

Once a node is admitted to the network, it is assigned a unique device ID. This device ID is subsequently used as part of the addressing scheme used to allocate transmission opportunities to nodes and flows in the media access plan.

The network admission protocol is illustrated in the sequence diagram in Figure 3.3-13.

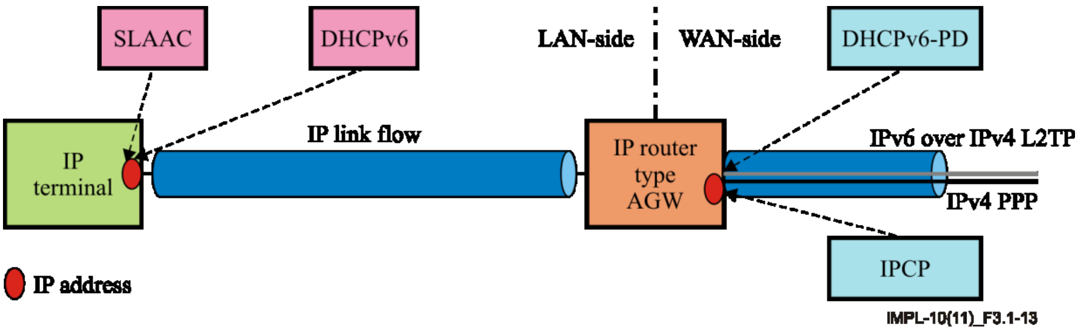


Figure 3.3-13 – Network admission protocol sequence diagram

3.3.5.2.10 Master selection protocol

An ITU-T G.9954v2 network requires the existence of a network node that takes the role of master in order to coordinate and schedule media transmissions. Although a master is required for an operational Recommendation ITU-T G.9954v2 network, not all network nodes necessarily have the functionality to become a master. Amongst those that *do* have the required capabilities, any one of them can potentially become master.

A home network that contains more than one network node that is capable of becoming the master allows for quick recovery from master failure and is inherently more fault/failure tolerant. A master selection protocol shall be used to dynamically select a single master in the presence of multiple potential masters. ITU-T G.9954 contains the following procedures:

- Detection of a managed network: trying to detect the presence of a master in the network;
- The master selection procedure: selecting a master among master-capable nodes based on priorities;
- Detection of master failure and recovery.

3.3.5.2.11 Flow signalling protocol

The flow signalling protocol is used to dynamically establish and manage service flows with QoS parameters and traffic classification filters defined by upper-layer protocols. More specifically, the flow signalling protocol is used to perform the following flow-related functions:

- Set up a flow and traffic classification filters;
- Modify flow parameters and add or remove classification filters;
- Tear down flows;
- Query QoS parameters for a flow or class-of-service.

The flow signalling protocol shall be performed between ITU-T G.9954v2 nodes at the source and destination of a flow and will be used to establish QoS parameters for the flow. In a master-controlled network, flow signalling shall also be performed between the ITU-T G.9954v2 node at the source of the flow and the master, if reserved bandwidth is required. The flow signalling protocol may be initiated by either source or destination nodes involved in a unicast flow, or by the source node in a broadcast/multicast flow or by the master.

3.3.5.2.12 Various levels of link layer protocol support profiles

Packet aggregation is used to concatenate multiple MPDUs, within a single PHY layer frame. This concatenation technique is used to increase the size of the PHY frame in order to reduce the overall per-packet protocol overhead. However, the degree of aggregation performed is a function of the latency requirements of services and the size of the allocated transmission opportunity. The LLC sublayer is responsible for performing this framing and de-framing and for maximizing the size of a burst within the constraints defined by the media access plan.

3.3.6 The ITU-T G.9954v2 convergence sublayer

The ITU-T G.9954v2 protocol stack supports interfaces and bridging to external network protocols through the convergence layer. The protocol convergence sublayers available on an ITU-T G.9954v2 node are advertised using the link layer capability and status announcement protocol.

It is the responsibility of the protocol convergence layer to map data packets arriving from a particular interface onto the *flows* appropriate for the particular service. Flows defined for a particular convergence layer are set up by the convergence layer itself in an implementation-dependent way, possibly during initialization, on receipt of data from upper layers, on network admission or upon demand. The flow traffic and rate parameters for a flow may be also defined in an implementation-dependent way, perhaps by upper-layer protocols, or configured using management operations or configuration data held in non-volatile storage.

ITU-T G.9954v2 convergence sublayers considered for the ITU-T G.9954v2 protocol stack include the IEEE 802.3/Ethernet, IP protocols, USB and IEEE 1394. In addition, bridging interfaces to broadband access protocols, such as DOCSIS and wireless access protocols, such as IEEE 802.11 and IEEE 802.16, are envisioned, as are application-level convergence sublayers for delivery of Moving Pictures Expert Group (MPEG) transport streams.

Protocol mapping and convergence at a well-defined level of the protocol stack enables a degree of synchronization between external and home protocols. Furthermore, being the QoS of the home network defined in terms that are similar to those of the external network, this further supports the extension of QoS from external networks into the home network.

The convergence layer may perform the following functions:

- Interface to higher layer protocols and receives PDU from the upper layers.

- Signal the set-up of traffic flows and classifiers in local and peer MAC, link layer and convergence layer entities.
- Classify upper-layer PDUs, using built-in knowledge of the protocols, and map the PDUs to underlying flows.
- Perform address bridging and translation functions.
- Perform any special PDU processing before passing them onto the link/MAC layers (e.g., removal of payload header information).
- Send upper-layer PDUs to HNT link/MAC layers.
- Receive PDUs transported by the HNT PHY/MAC layers and performs any protocol specific processing before delivery to upper protocol layers.
- Perform peer-to-peer convergence sublayer signalling.
- Perform data sampling and synchronization control.

No assumptions should be made as to the system partitioning of link and convergence layer functions as it is possible to implement both of these protocols both on-chip or in external host drivers. Figure 3.3-14 illustrates the convergence layer to link layer interface.

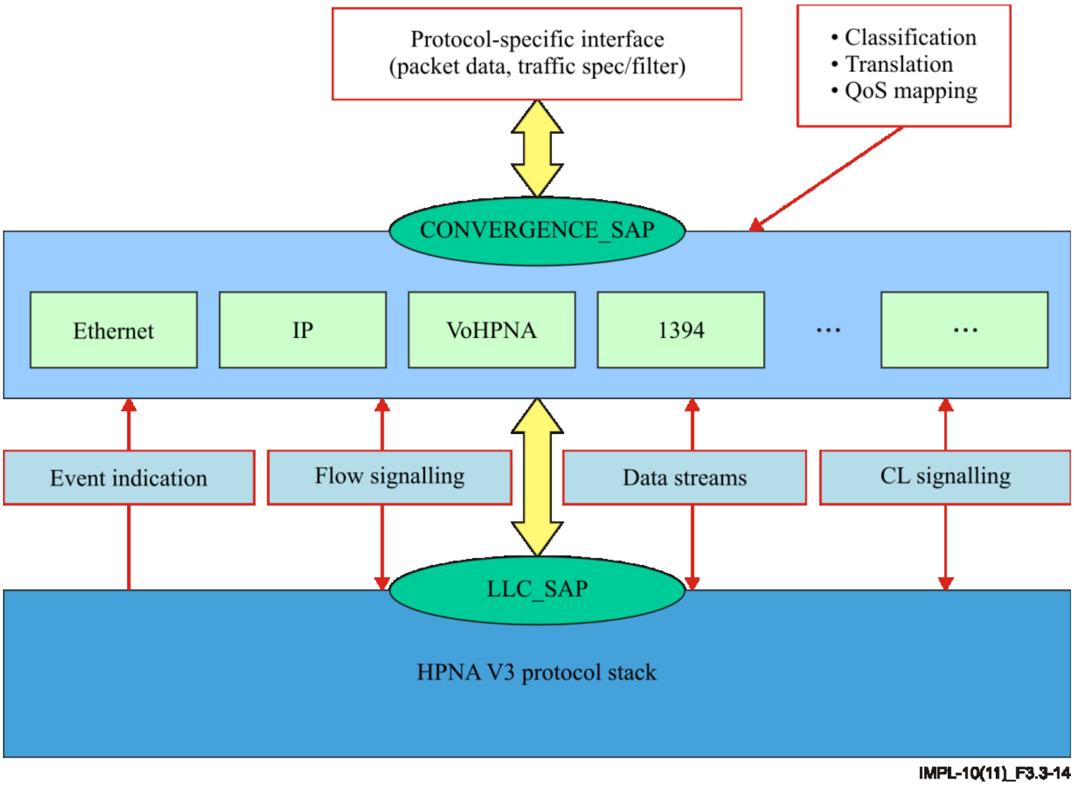


Figure 3.3-14 – Convergence layer – link layer primitives

3.3.7 The management layer

The management layers described in the protocol stack in Figure 5.3-7 includes both network layer management and ITU-T G.9954v2 management facilities. Network layer management operates on network and transport layers, using higher-level management protocols and frameworks such as Simple Network Management Protocol (SNMP) or TR-069 and as such is beyond the scope of Recommendation ITU-T G.9954 and therefore of this Technical paper.

ITU-T G.9954v2 management includes all those facilities that are required in order to collect information from the PHY, MAC, link and convergence layers of the ITU-T G.9954v2 node or remote nodes and to exercise control over them. ITU-T G.9954v2 management supports both local and remote management capabilities. This means that management operations may be performed from a local host interfacing to the ITU-T G.9954v2 node from the host side or from a management entity interfacing with the ITU-T G.9954v2 node from the network (wire) side using a peer management protocol.

3.4 Narrowband power line transceivers

Editor: Stefano Galli

This section gives an overview of the narrowband power line (NB-PLC) transceivers which are specified in the Recommendations ITU-T G.9901, ITU-T G.9902, ITU-T G.9903, and ITU-T G.9904. These Recommendations define technologies that support indoor and outdoor communications over direct current and alternating current power lines (including low and medium voltage lines), through transformer communications, for both urban and long distance rural communications and at frequencies below 500 kHz. These Recommendations include three separate and self-contained NB-PLC specifications:

a) a new NB-PLC technology developed by ITU-T in cooperation with members of the G3-PLC and PRIME Alliances (in Recommendation ITU-T G.9902);

b) an established and field-proven NB-PLC technology contributed by members of the G3-PLC Alliance(in Recommendation ITU-T G.9903);

c) an established and field-proven NB-PLC technology contributed by members of the PRIME Alliance(in Recommendation ITU-T G.9904).

Recommendation ITU-T G.9901 specifies the control parameters that determine spectral content, power spectral density (PSD) mask requirements, a set of tools to support the reduction of the transmit PSD, the means to measure this PSD for transmission over power line wiring, as well as the allowable total transmit power into a specified termination impedance. It complements the system architecture, physical layer (PHY) and data link layer (DLL) specifications in Recommendations ITU T G.9902, ITU-T G.9903 and ITU-T G.9904.

These standards are also an ideal platform for smart grid applications because of their use of power lines as a communications medium which is under the direct and complete control of power utilities. In addition, because the two Recommendations support popular protocols like Ethernet, IPv4 and IPv6, smart grid networks can easily be integrated with IP-based networks. The standards incorporate electromagnetic compatibility (EMC) and mitigation techniques defined in collaboration with ITU's Radiocommunication sector (ITU-R) that ensure a high degree of protection of radio services from PLC emissions.

The approved standards will enable cost-effective smart grid applications such as distribution automation, diagnostic and fault location, smart metering, demand response, self-healing grid, energy management, smart appliances, grid-to-home communications and advanced recharging systems for electric vehicles.

The new generation NB-PLC transceivers defined in the ITU-T G.990x Recommendations are optimized for the various topologies and characteristics of power grids around the world. Standardized transceivers will provide a 'smart' link between electricity and communications networks through their support of the use of power lines as a communications medium. PLC exploits electricity networks' existing wired infrastructure, greatly reducing the cost of deploying a dedicated communications channel.

The salient aspects of the power spectral density are as follows:

- Single PHY/MAC solution operating over A-D bands defined by the European Committee for Electrotechnical Standardization (CENELEC) and those defined by the United States Federal Communications Commission (FCC);

NOTE – CENELEC band: frequency band between 3 kHz and 148.5 KHz allowed to be used for power line communications (PLC). Four CENELEC bands are defined – A: 3-95 kHz, B: 95-125 kHz, C: 125-140 kHz, and D: 140-148.5 kHz.

NOTE – FCC band: frequency band between 9 kHz and 490 KHz allowed to be used for power line communications.

- ITU-T G.9903 specifies a G3-PLC solution for CENELEC A band;

NOTE – G3 indicates a power line communication system based on the orthogonal frequency division multiplexing (OFDM) modulation technique. The G3-PLC specifications were developed by members of the G3-PLC Industry Alliance.

- ITU-T G.9903 also includes an FCC extension to the G3-PLC solution;
- ITU-T G.9904 specifies the PoweRline Intelligent Metering Evolution (PRIME) solution for CENELEC A band.

NOTE – The PRIME specifications were developed by members of the PRIME Industry Alliance.

3.4.1 Network architecture and reference models

(For further information see Recommendation ITU-T G.9902.)

The basic principles of ITU-T G.9902 network architecture are the following:

1. The network is divided into domains:
   - The division of physical network into domains is logical; no physical separation is required. Therefore, domains may fully or partially overlap; that is, some nodes of one domain may communicate directly (on the physical layer) with some nodes of another domain.
   - The number of domains within the physical network may be up to *N* domains.
   - Each domain is identified by a domain ID that is unique inside the network.
   - Nodes of different domains can communicate with each other via inter-domain bridges (IDB). The IDB functions are provided by one or more nodes dedicated to operate as IDB.
   - Besides ITU-T G.9902 domains, a network may include alien domains. Connection between ITU-T G.9902 domains and alien domains is via L3 bridges.
   - Operation of different domains in the same network may be coordinated by the global master (GM). The function of the GM is associated with one of the nodes in one of the network's domains.

2. The domain is a set of nodes connected to the same medium:
   - One node in the domain operates as a domain master.
   - Each domain may contain up to *M* nodes (including the domain master).
   - Each node in the domain is identified by a node ID that is unique inside the domain.
   - All nodes that belong to the same domain identify that by using the same domain ID. A particular single node can belong to only one domain.

- Nodes of the same domain can communicate with each other either directly or via other nodes of the same domain, called relay nodes. Domains where not all nodes can directly communicate to each other are called "partially connected".

3. Nodes of different ITU-T G.9902 networks:

- Can communicate via inter-network bridges (INB). The INB function is an L3 bridging function associated with one or more dedicated nodes on network domains.

Generic network architecture of an ITU-T G.9902 network is presented in Figure 3.4-1.

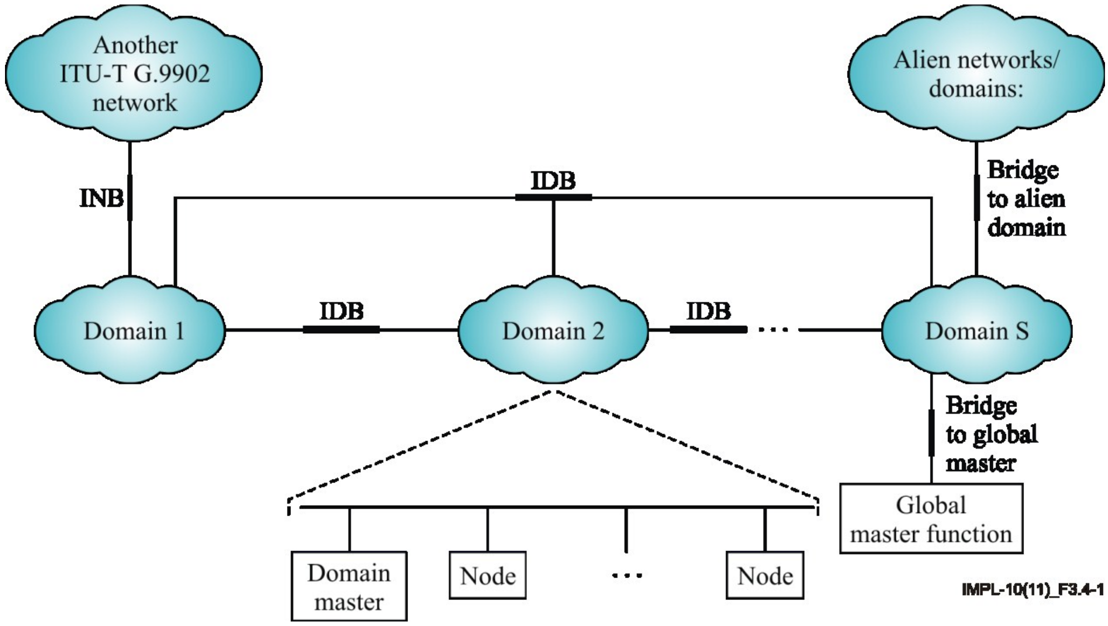


Figure 3.4-1 – Generic network architecture

The details of domain operation rules, types of communications inside a domain, and functionalities of domain master and endpoint nodes are described in Recommendation ITU-T G.9902. The ITU-T G.9902 network supports a mesh topology, that allows each node to communicate with any other node either directly, or via one or more relays, or via relays and IDBs. This allows support of any type of network topology on L3 and above, such as star, tree, multiple trees, and others. Number of domains (*N)* and number of nodes per domain (*M)* depend on the particular type of the network.

Recommendation ITU-T G.9902 contains the physical layer (PHY) and the data link layer (DLL) specifications for the ITU-T G.9902 narrowband orthogonal frequency division multiplexing (OFDM) power line communication transceivers, operating over alternating current and direct current electric power lines over frequencies below 500 kHz.

Recommendation ITU-T G.9903 contains the physical layer (PHY) and data link layer (DLL) specification for the G3-PLC narrowband orthogonal frequency division multiplexing (OFDM) power line communication transceivers for communications via alternating current and direct current electric power lines over frequencies below 500 kHz.

Recommendation ITU-T G.9904 contains the physical layer (PHY) and data link layer (DLL) specification for PRIME narrowband orthogonal frequency division multiplexing (OFDM) power line communication transceivers for communications via alternating current and direct current electric power lines over frequencies in the CENELEC A band.

3.4.2 Physical layer specification

(For further information see Recommendations ITU-T G.9902, ITU-T G.9903, and ITU-T G.9904.)

The PHY layer of ITU-T G.9902 transceivers are capable of operating either with extended capabilities (e.g., domain master, relay node, or combinations thereof) or without extended capabilities, as endpoint nodes.

The functional model of the PHY is presented in Figure 3.4-2. The physical medium-independent interface (PMI) and medium-dependent interface (MDI) are, respectively, two demarcation reference points between the PHY and MAC and between the PHY and transmission medium. Internal reference points δ and α show separation between PMD and the physical medium attachment (PMA), and between the physical coding sub-layer (PCS) and PMA, respectively.

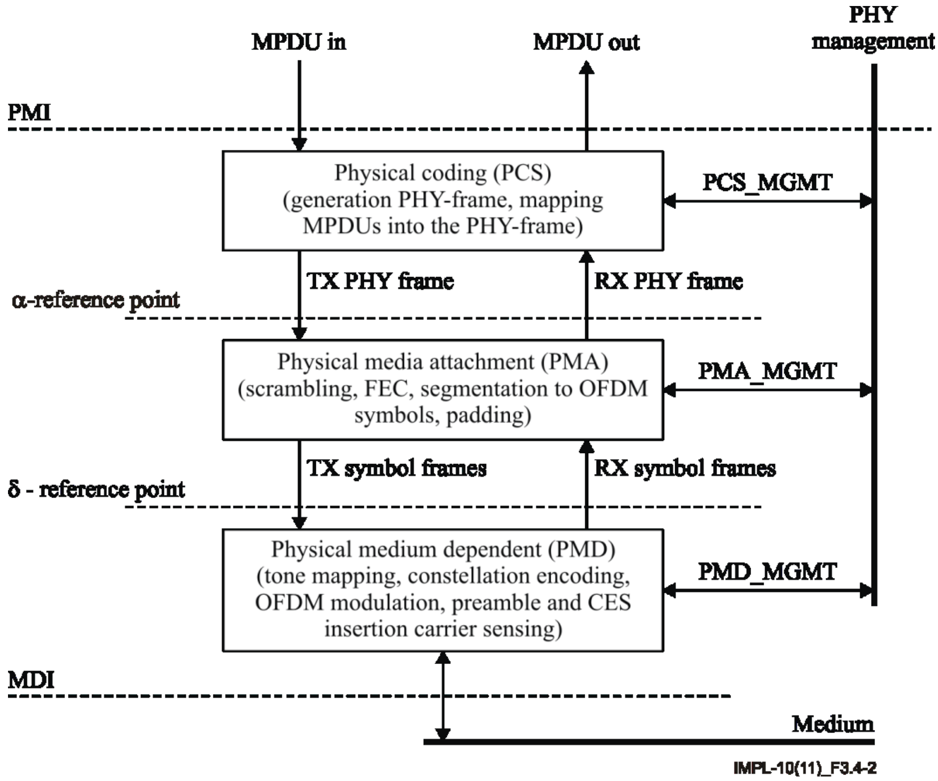


Figure 3.4-2 – Functional model of PHY

In the transmit direction, data enters the PHY from the MAC via the PMI by blocks of bytes called MAC protocol data units (MPDUs). The incoming MPDU is mapped into the PHY frame originated in the PCS, scrambled and encoded in the PMA, modulated in the PMD, and transmitted over the medium using orthogonal frequency division multiplexing (OFDM) modulation with relevant parameters. In the PMD, a preamble and channel estimation symbols (CES) are added to assist synchronization and channel estimation in the receiver.

In the receive direction, a frame entering from the medium via the MDI is demodulated and decoded. The recovered MPDU is forwarded to the MAC via the PMI. The recovered PHY frame header (PFH) is processed in the PHY to extract the relevant frame parameters.

3.4.2.1 PHY characteristics overview

ITU-T home networking uses windowed OFDM with the following set of programmable parameters to address various applications and different types of wiring:

- Number of carriers: 128, 256;

- Carrier spacing: 1.5625 kHz, 3.125 kHz;
- Carrier modulation: Quadrature Amplitude Modulation (QAM) ;
- Guard-interval: 0 for the frame header and 30µs, 60µs, 120µs for the payload;
- Window size: 8, 16 samples.

For payload, two guard-intervals are defined for both 1.5625 kHz and 3.125 kHz carries spacing: 60/120 µs and 30/60 µs, respectively. Double guard-interval is used for QAM-16 that is more sensitive to inter-symbol interference (ISI).

3.4.2.1.1 Bandplans

ITU-T Recommendations specifying ITU-T home networking define several bandplans to address various regulations and applications worldwide. Each bandplan is a set of carriers with consecutive indices, characterized by its start and end carriers, and is used with a particular carrier spacing and guard-interval. The CENELEC band (3 kHz – 148.5 kHz) is divided into the A, B, and C+D bandplans and uses carrier spacing of 1.5625 kHz. Three bandplans currently defined over the FCC band are FCC, FCC-1, and FCC-2, all with carrier spacing of 3.125 kHz. For compliance with ITU-T Recommendations on home networking, a device shall support at least one bandplan from the set indicated within Table 3.4-1.

Table 3.4-1 – Bandplans for ITU-T home networking

Bandplan	ITU-T G.9902	ITU-T G.9903	ITU-T G.9904
CENELEC A	✓	✓	✓
CENELEC B	✓		
CENELEC C	✓		
CENELEC D	✓		
FCC	✓		
FCC-1	✓	✓	
FCC-2	✓		

3.4.2.1.2 Forward error correction encoder and interleaver

The forward error correction (FEC) encoder, as specified in Recommendation ITU-T G.9902, is shown in Figure 3.4-3. It consists of an inner convolutional encoder and the outer Reed Solomon (RS) encoder. The parameters of the FEC encoder are:

- the number of incoming RS information blocks, $m \geq 1$;
- the number of bytes, K, in the incoming RS information blocks;
- the number of RS parity-check bytes, R;
- the number of bits incoming the inner encoder, k_I;
- the inner code rate, r_I.
- the number of output bits, N_{FEC}, (the FEC code word size depends on the overall code rate).

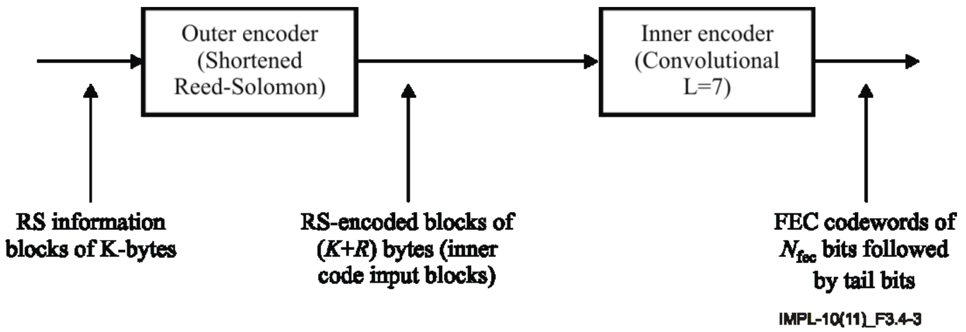


Figure 3.4-3 – FEC encoder

The incoming MPDU shall be first divided into RS information blocks. The number of RS information blocks, *m*, depends on the size of the MPDU. The information block size, *K*, shall be an integer number of bytes. The *m* output FEC code words followed by tail bits shall be concatenated into an FEC code word block. The order of the FEC code words in the FEC code word block (at the output of the FEC encoder) shall be the same as the order of the corresponding RS information blocks at the input of the FEC encoder.

3.4.2.1.3 The preamble

The preamble shall be pre-pended to every PHY frame. It is intended to assist the receiver in detecting the presence of the frame, synchronizing to the frame boundaries, and acquiring the physical layer parameters such as channel estimation and OFDM symbol alignment. The preamble shall meet the same transmit signal limits as the PHY Frame Header (PFH) and the payload symbols of the PHY frame.

The preamble comprises of two sections. Each section I (I = 1, 2) comprises N_I repetitions of an OFDM symbol (S_I) employing all subcarriers of the supported sub-carriers (SSC) set (with subcarrier spacing F_{SC}). Each preamble section shall be windowed in order to comply with the transmit signal limits using the specified. The general preamble structure is illustrated in Figure 3.4-4 which shows the ITU-T G.9902 preamble waveform. In the figure, the number of windowed samples is indicated as β.

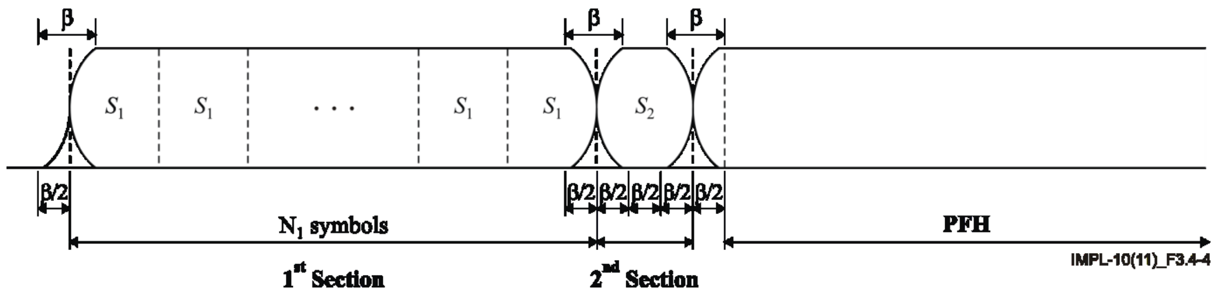


Figure 3.4-4 − Preamble structure

The range of valid values of N_1, depends on the AC mains frequency, and the frequency band used, as defined in Annex A of Recommendation ITU-T G.9901 for CENELEC and FCC bands.

3.4.2.1.4 Channel estimation symbols

The channel estimation symbols (CES) shall be transmitted using the bit allocation table (BAT) Type 0. The modulation parameters of the CES shall be the same as for PFH symbols. The windowing shall be as used for PFH symbols. The CES shall be transmitted after N_{OCES} PFH symbols, using the same signal levels as symbols of the preamble, and meet specified transmit signal limits. The number of the Offset CES symbols N_{OCES} depends on the bandplan. The bits loaded onto CES shall be generated using the pseudo random binary signal (PRBS) generator. The PRBS generator shall be initialized at the beginning of each CES with the same seed as the preamble symbols S1 and S2. The first CES shall be equal S2, while the second CES shall be an inverted copy of the first CES, i.e., -S2 = S1.

3.4.2.1.5 PHY frame format

The format of the PHY frame is presented in Figure 3.4-5. The PHY frame includes preamble, PFH, CES and payload. Preamble and CES are added to the PHY frame in the PMD. The PFH and the payload are generated and formatted in the PCS. Preamble and CES do not carry any data and are intended for synchronization and initial channel estimation only.

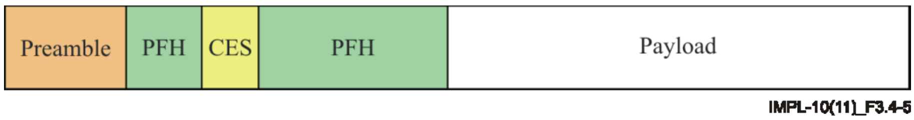


Figure 3.4-5 – Format of the PHY frame

All components of the PHY frame (preamble, PFH, CES, and the payload) consist of an integer number of OFDM symbols. The number of symbols of the PFH depends on the applied bandplan. All symbols in the PFH for a particular bandplan are transmitted using a predefined set of coding and modulation parameters.

The length of the payload may vary from frame to frame; payload may also be of zero length. For payload, different coding and modulation parameters can be used in different PHY frames, depending on channel and noise characteristics of the medium. The coding and modulation parameters of the payload are defined in the PFH. PHY frames are divided into several types, depending on their purpose. The type of the PHY frame is indicated in the PFH.

3.4.3 Data link layer specification

(For further information see Recommendations ITU-T G.9902, ITU-T G.9903, and ITU-T G.9904.)

The functional model of the data link layer (DLL), as specified in Recommendation ITU-T G.9902, is presented in Figure 3.4-6. The A-interface and PMI are, respectively, two demarcation reference points between the application entity (AE), or more specifically the application data primitive (ADP), and DLL (more specifically APC) and between DLL (more specifically MAC) and PHY (more specifically MPDU). Internal reference points x1 and x2, respectively, show logical separation between the APC and LLC and between the LLC and MAC.

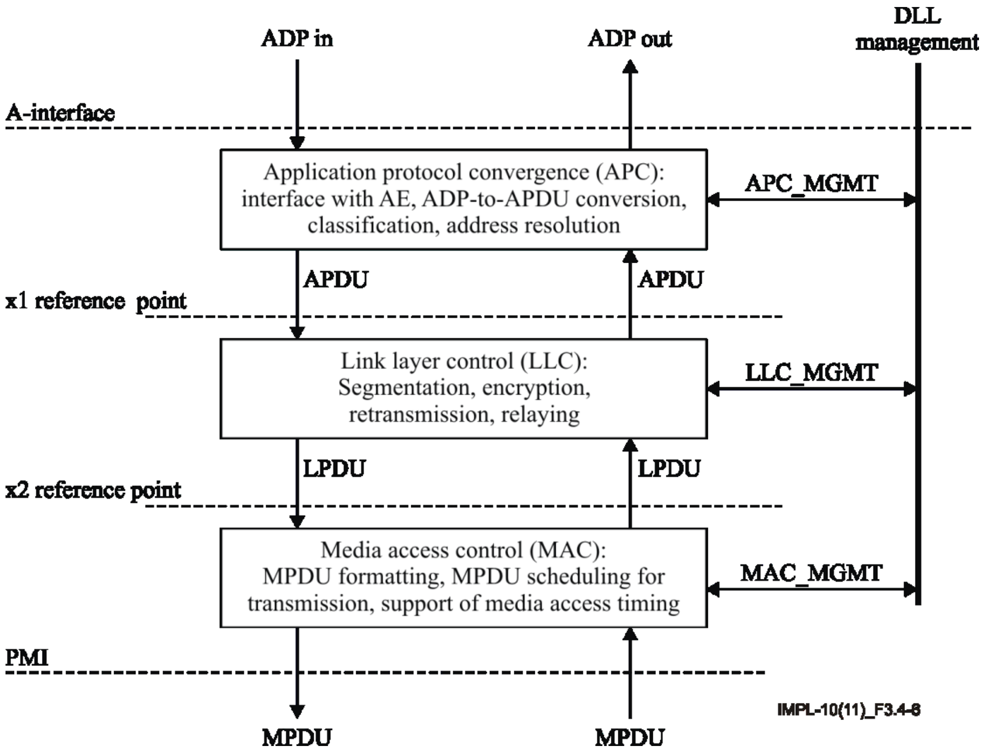


Figure 3.4-6 – Functional model of DLL

In the transmit direction, ADPs enter the DLL from the AE via the A-interface. Every incoming ADP set meets the format defined by the particular application protocol. Each incoming ADP set is converted by the APC into an application protocol data unit (APDU), which includes all parts of ADP intended for communication to the destination node(s). The APC is responsible for forwarding APDUs to peer APCs.

The APC also identifies ADP classification primitives (e.g., class of service, priority tags, etc.) to support QoS requirements assigned for the service delivered by the ADP and shall maintain one or more priority queues associated with APDUs it transmits; it assigns each APDU to the corresponding queue. The number of queues may depend on the application protocol and the profile of the device.

NOTE – The bridging function between the clients associated with the ITU-T G.9902 node (if more than one) is considered to be a part of the AE and is beyond the scope of this Technical paper.

The APC transfers APDUs to the LLC via the x1 reference point, which is application independent. The LLC also receives from the DLL management entity sets of management data primitives for LLC control frames, which are mapped into link control data units (LCDUs). The LLC is responsible to establish exchange of LCDUs (management frames) between peer LLCs.

In the LLC, the incoming APDU and LCDU are mapped into LLC frames and may be encrypted using assigned encryption keys. Long LLC frames are segmented. Segments are transformed into LLC protocol data units (LPDUs) and then passed to the MAC via the x2 reference point. The LLC is also responsible for relay operation (if enabled) and for retransmission of improperly received segments (if required).

The MAC is responsible to concatenate LPDUs into MAC protocol data units (MPDUs) and then convey these MPDUs to the PHY via the PMI, in the order determined by their media access (MA) priorities, and according to the medium access rules established in the domain.

In the receive direction, MPDUs from the PHY enter via the PMI. The MAC disassembles the received MPDUs into LPDUs, which are passed over the x2 reference point to the LLC. The LLC recovers the original APDUs and LCDUs from the received LPDUs, decrypts them if required, and conveys them to the APC and the LLC management entity, respectively. In the APC, the ADPs are recovered from the received APDUs and conveyed to the AE.

The LLC is responsible for detection of erroneous LPDUs and generation of acknowledgement. It discards the erroneous LPDUs and, if the source node requested retransmission of erroneous LPDUs, LLC generates an ACK response to trigger retransmission.

NOTE – No assumptions should be made on partitioning of APC, LLC, and MAC in particular implementations; x1 and x2 are reference points and serve exclusively for convenience of system definition.

The functional model of the application protocol convergence sublayer (APC) is shown in Figure 3.4-7. It is intended to describe in more detail the APC functional block presented in Figure 3.4-6.

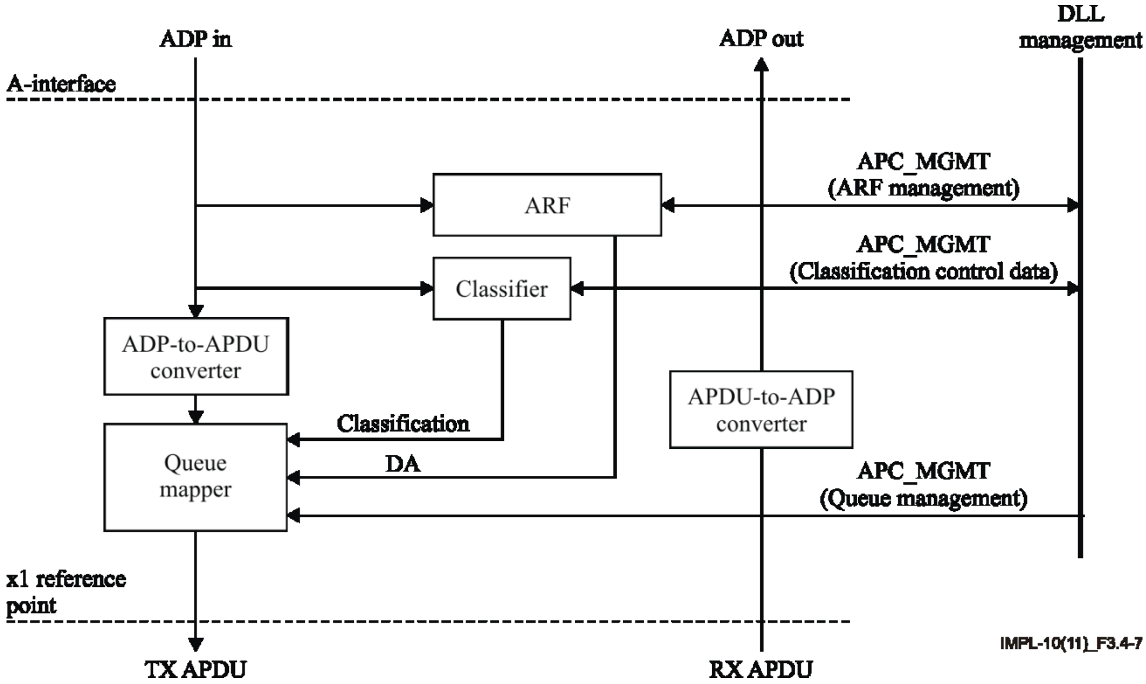


Figure 3.4-7 – Functional model of APC

In the transmit direction, the incoming ADP data unit is converted into an APDU. The queue mapper maps APDUs into queues, depending on their destination address (DA), class of service (priority), and control parameters provided by DLL management entity. After mapping, each APDU, tagged with its priority, is sent to LLC via the x1 reference point. The size of the ADP (in both transmit and receive directions) can be up to 1522 bytes. In the receive direction, the APDUs incoming via the x1 reference point are converted back into the ADP set of the corresponding application protocol. The classification information embedded in the ADP is extracted from the incoming data units and may be used to map the APDU into an appropriate priority queue. Relevant classification parameters depend on the application protocol.

The address resolution function (ARF) associates the destination address of the incoming ADP with the physical address of the node this ADP has to be sent. The ARF may store addresses of the clients associated with the node collected from the incoming ADP, and addresses of the clients associated with other nodes in the network (advertised by these nodes). The address resolution procedure performed by ARF depends on the application protocol.

The APC sublayer allows serving of one or more application protocols. The functional model in Figure 3.4-7 shows an APC serving a particular AE protocol. In case more than one application protocol is needed, multiple APC shall be used, as shown in Figure 3.4-8.

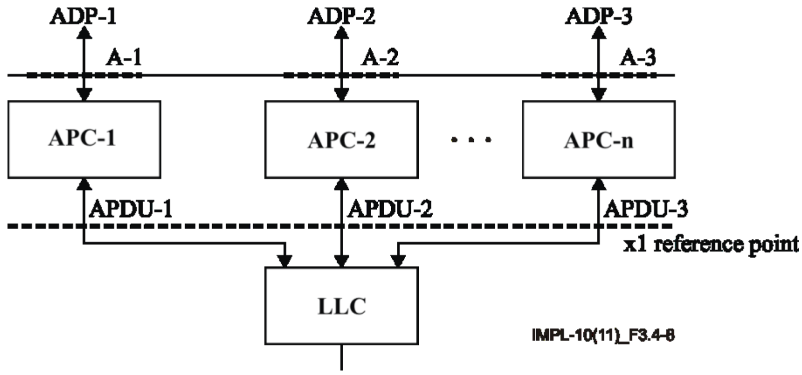


Figure 3.4-8 – Block diagram of APC sublayer serving multiple application protocols

Each APC in Figure 3.4-8, same as in Figure 3.4-7, serves a particular AE protocol. All ADPUs from all APCs are passed to the LLC via the x1 reference point, each with a tag indicating its application protocol. The tag is further communicated to the receiving node in the LLC frame type (LLCFT) field of the LLC frame header (LFH); based on this tag, the received APDU is passed to the corresponding APC. The format of each APDU is per its application protocol. Simultaneous support of multiple application protocols is optional. The maximum number of APCs (not more than 8) and arbitration of the order in which APDUs of different APCs are passed to LLC (internal priority of APC) are for further study.

The functional model of the logical link control sublayer (LLC) is presented in Figure 3.4-9. It is intended to describe in more detail the LLC functional block presented in Figure 3.4-6.

In the transmit direction, an LLC frame is formed from each APDU entering via the x1 reference point and from each LCDU entering via the LLC_MGMT reference point. The APDU has a format depending on the application protocol, as defined in the annex of Recommendation ITU-T G.9956 describing the application protocol convergence sub-layer. The LCDU carry management data. The LLC frame may be encrypted.

Further, LLC frame is divided into segments of equal size; the size of the segment is controlled by the LLC. Each segment is pre-pended by a header and appended with a CRC, thus forming an LPDU. LPDUs are passed to the MAC via the x2 reference point and also stored in the automatic repeat request (ARQ) buffer, if the transmitted LLC frame has to be acknowledged.

LPDUs that need to be retransmitted are extracted from the ARQ buffer and passed to the MAC to be assembled into the outgoing MPDU. To assist retransmission, the receive part of the LLC generates ACKs, which are passed to the MAC to be transmitted using immediate acknowledgement (Imm-ACK) frames.

In the receive direction, the LPDUs disassembled from the incoming MPDU in the MAC enter the LLC via the x2 reference point. The LLC verifies all received LPDUs, generates an acknowledgement, if so instructed by the source of the received frame, and discards erroneous LPDUs. Further, after all the LPDUs associated with the sent LLC frame are cleared, the LLC recovers the LLC frames from the received LPDUs. The recovered LLC frames are decrypted (if encryption is enabled) and their payloads are passed to APC via x1-reference point, if they carried an APDU or to the DLL management via the LLC_MGMT reference point, if they carried an LCDU.

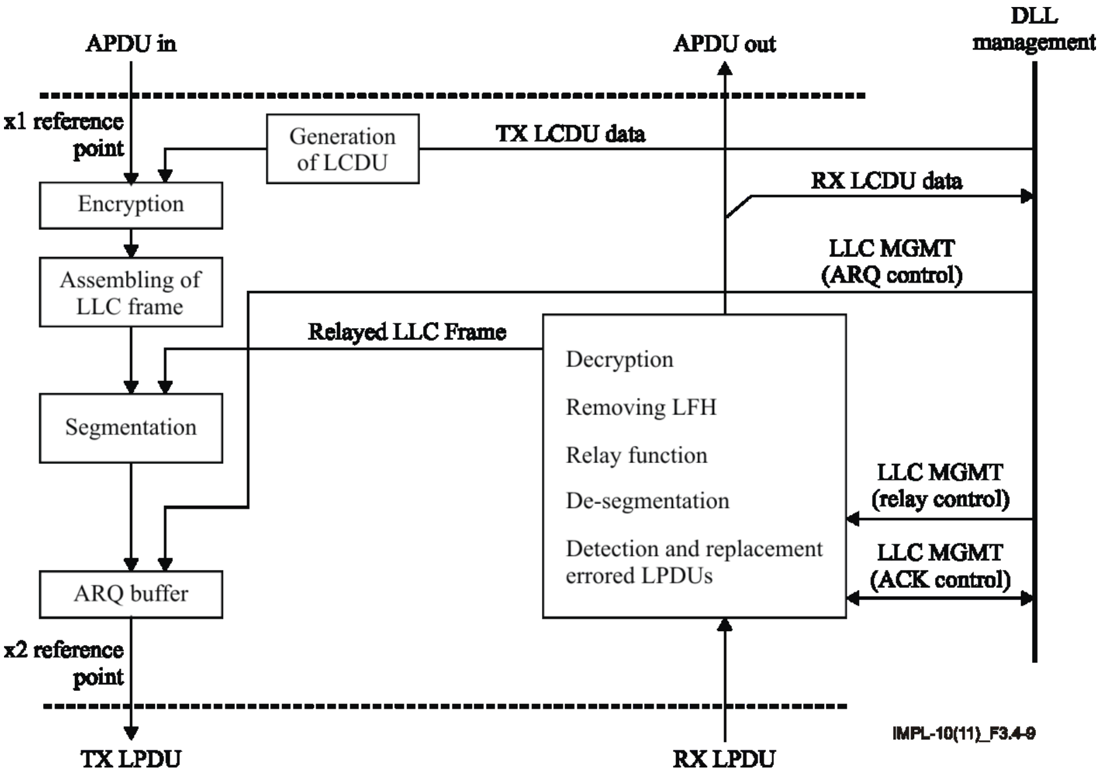


Figure 3.4-9 – Functional model of LLC

The relay function, if enabled, extracts LLC frames that are subject to relaying using information in the LFH and passes them back to the MAC for transmission to the next destination. The relayed LLC frames are processed as regular LLC frames (Figure 3.4-9). The DLL management entity controls priority settings for the relayed LLC frames. Relayed LLC frames shall not be decrypted.

The functional model of the Medium access control sublayer (MAC) is presented in Figure 3.4-10. It is intended to describe in more detail the MAC functional block presented in Figure 3.4-6.

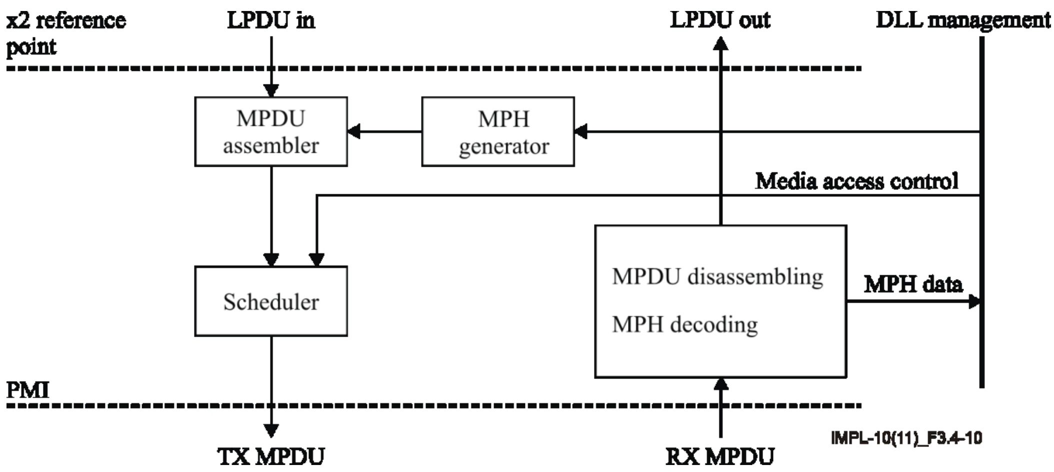


Figure 3.4-10 – Functional model of MAC

In the transmit direction, MPDUs are assembled from LPDUs that are passed over the x2 reference point and the MPDU header (MPH) that is generated by the MAC. The MPDU assembler also adds the pad to meet the closest valid size of MPDU.

The assembled MPDUs are scheduled for transmission according to the medium access procedure, using one or more established priorities queues. The medium access control primitives include the carrier sense (CRS) that indicates whether medium is busy or not. After being scheduled for transmission, the MPDU is passed to the PHY via PMI.

In the receive direction, the incoming MPH is decoded, the MPDU is disassembled, the relevant MPDU parameters communicated in the MPH are passed to the DLL management via MAC_MGMT reference point, and the recovered LPDUs are passed to the LLC via the x2 reference point. The received acknowledgement data is passed via PMI interface.

3.4.3.1 DLL characteristics overview

Recommendation ITU-T G.9902 defines contention-based prioritized carrier sense multiple access with collision avoidance (CSMA/CA) with 4 priority levels. The three lower priorities are intended for user data frames and the fourth priority is for frames carrying emergency signalling. All management frames are granted the third priority, to make network management more dynamic.

An ITU-T G.9902 node of a standard profile shall supports prioritized contention-based medium access with four medium access (MA) priorities denoted from 0 (lowest priority) to 3 (highest priority); nodes of low-complexity profile shall support two MA priorities, 0 and 2.

3.4.3.1.1 Assignment of MA priorities

The classifier, in APC (Figure 3.4-7), assigns a certain priority to each APDU based on the QoS-related information carried by the primitives of the corresponding ADP or based on the relevant management primitives. This assigned APDU priority determines the priority of the LLC frame carrying the APDU and can be 0, 1 and 2. The priority value of 3 is assigned for pre-defined emergency data transfers only. All LLC frames carrying LCDUs (internal management communications) shall be assigned to priority 2.

The assignment of APDU priority depends on the application protocol but shall not exceed the number of MA priority queues supported by the node, which is 4 for standard profile and may be less for other profiles.

Nodes of standard profile shall support:

- three MA priority queues for application data (priority 0, 1, and 2) and management data (priority 2);
- a MA priority queue for emergency signals (priority 3), that shall also be used for asynchronous beacons.

Nodes of other profiles shall support at least priority 0 for application data and priority 2 for management data; other supported priorities are for further study.

3.4.3.1.2 Prioritized contention-based medium access

The prioritized contention-based medium access is defined in terms of contention periods (CP). The contention process starts at the beginning of the CP. The CP ends T_{IFG_MIN} (minimum inter-frame gap) after a node that won the contention completes transmission of the frame sequence, which includes the transmitted frame and the ACK frame, if required. A new CP starts immediately after the end of the previous CP.

The CP shall consist of 4 priority resolution periods that may overlap. Each such period is associated with a contention window (CW). The CW consists of a variable number of fixed duration time slots (TS). The number of slots assigned to each CW shall vary; the minimum number of TS is 1. The CP shall start with the CW associated with the highest priority. A CW associated with a certain priority shall not start prior to a CW associated with a higher priority. An MPDU assigned with a specific MA priority is allowed to be transmitted during the CW associated with the same or lower priority according to the specified back-off procedure. The size of the CW for each priority is dynamically updated based on the expected number of nodes contending at the next CP. This update is provided by a combination of autonomous and centralized mechanisms. By forcing particular values of these parameters, domain master or its proxies can control the update process and even insist a particular set of nodes to use fixed CW parameters (fully-centralized setup).

The medium access process includes the following steps:

1. Nodes shall contend for transmission of an MPDU based on the MA priority of the MPDU assigned by the scheduler.
2. Nodes shall contend for transmission of an MPDU during the CW that is associated with the MA priority assigned to this MPDU or during a CW associated with a lower MA priority.
3. Nodes that won the contention may transmit their MPDU.
4. Nodes that lost the contention shall use the specified back-off rules.
5. The next CP shall start T_{IFG_MIN} period after the transmission of the frame sequence is complete, i.e., after the ACK frame is sent (in case ACK was requested by the transmitter) or after the frame was transmitted (in case no ACK was requested by the transmitter).

The procedure of transmission during the CP is illustrated with an example in Figure 3.4-11. The figure presents the positions and sizes of CWs for a particular CP in which a node that won the contention for CW_0 sends a low priority MPDU. After T_{AIFG} seconds, the MPDU is followed by an immediate acknowledgement (Imm-ACK) frame.

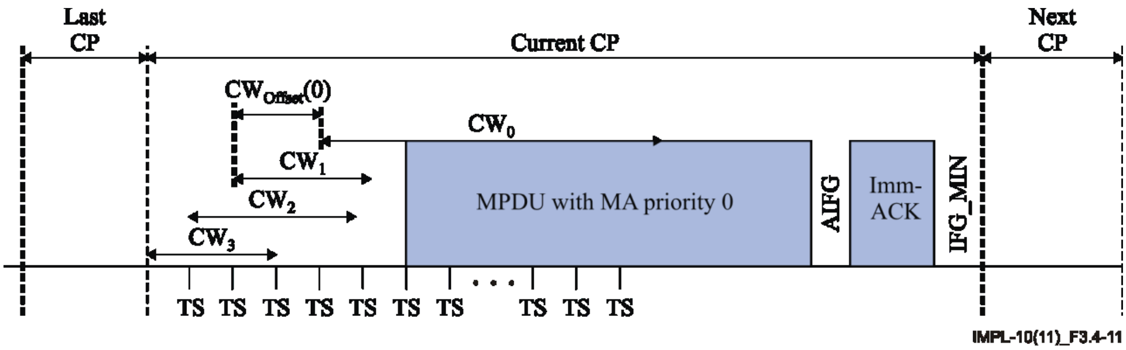


Figure 3.4-11 – Illustration of a typical transmission during the CP

3.4.3.1.3 CP back-off procedure

To support the back-off procedure described in this section, each node shall maintain at least the following back-off parameters:

- A back-off counter (BC) per transmission attempt;
- A CW size for each MA priority.

The BC determines the number of TS the node shall wait before it may begin the transmission if medium is idle. The duration of the TS is denoted as T_{TS}.

The CW size determines the range from which the back-off value shall be picked before transmission, which is the function of MA priority and further denoted CW(x), where x stands for the MA priority. The size of CW(x) is expressed in the number of TS.

Node that survives the priority resolution period preceding the start of the CW associated with the MA priority of the MPDU it intends to transmit, shall compete in the CW using its back-off parameters for that MA priority, and shall act according to the following procedure before starting a transmission in a CP:

1. Pick a random value of the BC in the range 0 to CW(x).

2. If the picked value of BC is zero, the node shall start transmitting its frame within a time window of T_{TX_ON} after the start of the first TS of the CW(*x*).
3. If the picked value of BC is not zero, the node shall decrement its BC upon completion of each TS in which it detects no PHY preamble (the medium is idle).
4. If upon completion of certain TS, the value of BC is zero, the node shall start transmitting its frame within a time window of T_{TX_ON} after the end of this TS. The BC shall be disabled till the next CP. The value of T_{TX_ON} is 10 µs and is independent of the bandplan (see Tables 9-8 and 9-9 of Recommendation ITU-T G.9902).
5. If a node detects a PHY preamble during a TS and its BC at this TS is not zero, it shall not transmit in this CP and shall defer transmission to the next CP.
6. In case a node gets an MPDU to transmit and no previous transmission was detected for more than $T_{CP\ MAX}$ from the start of the CP, the node may transmit the MPDU immediately.
7. In the next CP, nodes shall repeat steps 1-6 above.

If a node that contends in a CP gets an MPDU to transmit after the start of a particular CW, it may still contend for this MPDU in this CW using the back-off procedure defined in this section, but only if the MA priority of the MPDU is equal to or higher than the priority associated with the CW. The node shall pick a random value of the BC in the CW in the same way as nodes that had the MPDU ready to transmit prior to the start of the CW. Alternatively, the node may defer transmission to the next CP.

3.4.3.1.4 Retransmission and acknowledgement

The retransmission and acknowledgment protocol comprises the following steps:

- The transmitter sends a frame with a request to acknowledge the MPDU and indicates the type of the acknowledgement in ACK_REQ field of the PFH (PHY Frame Header) and ACK_TYPE field of the MPH (MPDU header);
- The receiver acknowledges the MPDU by transmitting an Imm-ACK frame, using the type of acknowledgement requested by the transmitter. No Imm-ACK frame shall be sent if acknowledgement is not requested by the transmitter;
- The transmitter retransmits the MPDU or its tributary LPDUs indicated in the received Imm-ACK frame.

3.4.3.1.5 Intra-domain multi-hop transmission

Recommendation ITU-T G.9902 allows performing mesh networking by using either L2 routing (by relaying the LLC frames) or L3 routing (by relaying the protocol data units above the A-interface). Prior to initialization, each domain shall be set into a particular routing mode that either allows intra-domain L2 routing (L2 relaying mode) or that disallows it (no L2 relaying is allowed for any node of the domain).

The domain master shall inform all nodes registering into the domain whether L2 relaying is enabled or not. If L2 relaying is enabled, all relayed communications in the domain shall be performed as defined in this section. If L2 relaying is disabled, only single-hop communications in the domain are allowed, and nodes shall not relay any of the received frames, except beacon frames, if assigned by the domain master.

NOTE – A beacon frame is a management frame which is transmitted periodically by the domain master. Beacon frames carry information to be distributed to all nodes of the domain, describing for all nodes of the domain the specifics of the domain operation, such as bandplan, domain name, domain ID, the security mode to be used, spectral compatibility requirements (frequency band and maximum transmit power, if applicable), mode of operation, and others.

For a node, L2-relaying capability is optional. Nodes shall indicate to the domain master their L2-relaying capabilities as they register into the domain. If L2-relaying within the domain is enabled, nodes that are relay-capable may be assigned as domain relays for unicast, multicast, or broadcast.

The L2 relaying functionality of nodes shall be as follows:

- All nodes (including not relay-capable) shall be capable to source the relayed transmission (create a mesh header) and to receive LLC frames that were relayed to it as a final destination (process a frame that includes a mesh header).
- When L2 relaying is enabled, all relay-capable nodes assigned as domain relays shall perform full relaying functionality (i.e., as an LLC frame originator, a relaying node, and a receiver of relayed LLC frames) for unicast, multicast, or broadcast.
- All relay-capable nodes that are not assigned as domain relays shall discard all frames for which this node is not a final destination.
- When L2 relaying is disabled, all nodes in the domain shall not generate LLC frames to be relayed and discard all received LLC frames for which that node is not the final destination.

3.4.3.1.6 Security

Security is provided by encryption and authentication of the relevant data and management frames communicated between the nodes of the domain. The specified encryption method is based on AES-128.

Node authentication, generation and distribution of encryption keys between nodes, encryption key updates, and node authentication updates are provided by a set of authentication and key management (AKM) procedures. The AKM procedure can establish both group keys (i.e., a unique set of keys for a particular group of nodes) and pair-wise keys (i.e., a unique set of keys per every pair of communicating nodes).

3.5 Broadband home networking transceivers over powerline, phone line and coaxial cable

Editors: John Egan and Les Brown

This section describes the system architecture, physical layer (PHY), data link layer (DLL), power spectral density (PSD) management tools and coexistence for wireline-based home networking (HN) transceivers capable of operating over premises wiring including powerline, inside telephone wiring and coaxial cable. The content of this section is based on that of Recommendations ITU-T G.9960, ITU-T G.9961, ITU-T G.9964 and ITU-T G.9972.

3.5.1 Overview

(For further information, see Recommendation ITU-T G.9960.)

This section describes the system architecture and physical layer for wireline based home networking transceivers capable of operating over premises wiring including inside telephone wiring, coaxial cable, and power line wiring.

Specifically, this section describes:

- the home networking architecture and reference models;
- the physical layer specification (physical coding sublayer (PCS), physical; medium attachment (PMA) and physical medium dependent (PMD) sublayers);
- the data link layer specification (application protocol convergence (APC), logical link layer (LLC), and medium access control (MAC) sublayers);

- the PSD tools available to manage the PSD of the transceivers;
- the coexistence mechanism for the transceivers and those defined within IEEE 1901.

An ITU-T G.9960 home network offers:

- Quality of service (QoS) support for services with explicit traffic and rate specifications;
- QoS guarantees for traffic class, bandwidth, jitter, latency and block error ratio;
- Security including Advanced Encryption Standard 128 (AES-128), end-to-end encryption, and authentication.
- Support for protocol-specific convergence layers (Ethernet convergence layer defined currently);
- Spectrum notching over power line and phone line for compatibility with amateur radio services;
- Compatibility with very high speed digital subscriber line (VDSL2) over the same or nearby lines;
- Compatibility with other coaxial services such as cable-TV channels;
- Local and remote management of ITU-T G.9960 nodes.

An ITU-T G.9960 home network consists of one or more domains. A domain contains nodes connected to the same medium, where one node is acting as a domain master. The function of the domain master is to assign and coordinate resources (bandwidth and priorities) of all nodes in its domain. Nodes are not required to be domain master capable. That is, some nodes may not support the functionality necessary to become a domain master.

The following rules apply for any domain:

- More than one domain may be established over the same medium, for example, by using orthogonal signals over different frequency bands;
- The home network shall have a unique name. All domains of the same home network shall use this name;
- The domain ID shall be used to identify a specific domain. Each domain in a home network shall have a unique domain ID;
- All nodes within the same domain shall use the same domain ID;
- All nodes in a domain shall be managed by a single domain master;
- There shall be one and only one active domain master per domain. In case an active domain master is not assigned, fails, or is switched off, a domain master selection procedure is initiated to assign a new active domain master;
- The domain master shall assign a DEVICE_ID to a node in its domain during the node's registration process;
- All nodes within a domain shall support point-to-point (P2P) and relaying (REL) (REL is considered a subset of P2P, where the first destination address for the node is a relay node);
- A node shall keep track of the domain where it associates and shall discard frames received in MSG type PHY frames from domains other than its own. These frames can be distinguished by examination of the DOD field in the PHY frame headers that are transmitted for these types of frames.

- A node is required to report the existence of neighbouring domains to its domain master when it receives one or more PHY-frame headers containing a DOD value other than the one used in its domain.

The following features characterize an ITU-T G.9960 transceiver:

NOTE – The term "ITU-T G.9960 transceiver" means a home networking transceiver based on Recommendations ITU-T G.9960, ITU-T G.9961, and ITU-T G.9964.

- PHY-layer transmission rates of up to 1 Gbit/s;
- Operation over powerline, phone line and/or coaxial cable;
- Nodes of the same home network operating over the same medium (that is, nodes that can communicate with each other directly at the physical layer) shall be assigned to the same domain;

  NOTE – "Direct communication at the physical layer" does not include crosstalk between closely routed wires.
- A node shall keep track of the domain where it associates and shall discard frames received in MSG type PHY frames from domains other than its own;
- A node reports the existence of neighbouring domains to its domain master when it receives one or more PHY-frame headers containing a domain ID value other than the one used in its domain;
- Nodes are not required to be domain master capable. That is, some nodes may not support the functionality necessary to become a domain master;
- Support for constant and variable bit-rate data services.

The following sections describe in further detail some of the above features. For others, see Recommendation ITU-T G.9960.

3.5.2 System architecture of the ITU-T G.9960 home network

3.5.2.1 Home network architecture and topology

An architectural model of the home network is presented in Figure 3.5-1. The model includes one or more domains, inter-domain bridges (IDB), and bridges to alien domains (such as a WiFi or Ethernet home network), or a digital subscriber line (DSL) or passive optical network (PON) access network. The logical global master function coordinates resources such as bandwidth reservations, flow priorities, and operational characteristics between domains, and may convey the relevant functions initiated by a remote management system (e.g., Broadband Forum TR-069 and Recommendation ITU-T G.9980). The specification of bridges to alien domains and to the access network is beyond the scope of Recommendation ITU-T G.9960 and, therefore, of this Technical paper.

NOTE 1 – It is not necessary that all inter-domain bridges presented in Figure 3.5-1 be used. Depending on the application, domains could be daisy-chained, or star-connected, or could use another connection topology.

NOTE 2 – It is possible to install multiple ITU-T G.9960 home networks (i.e., not connected by inter-domain bridges) per dwelling.

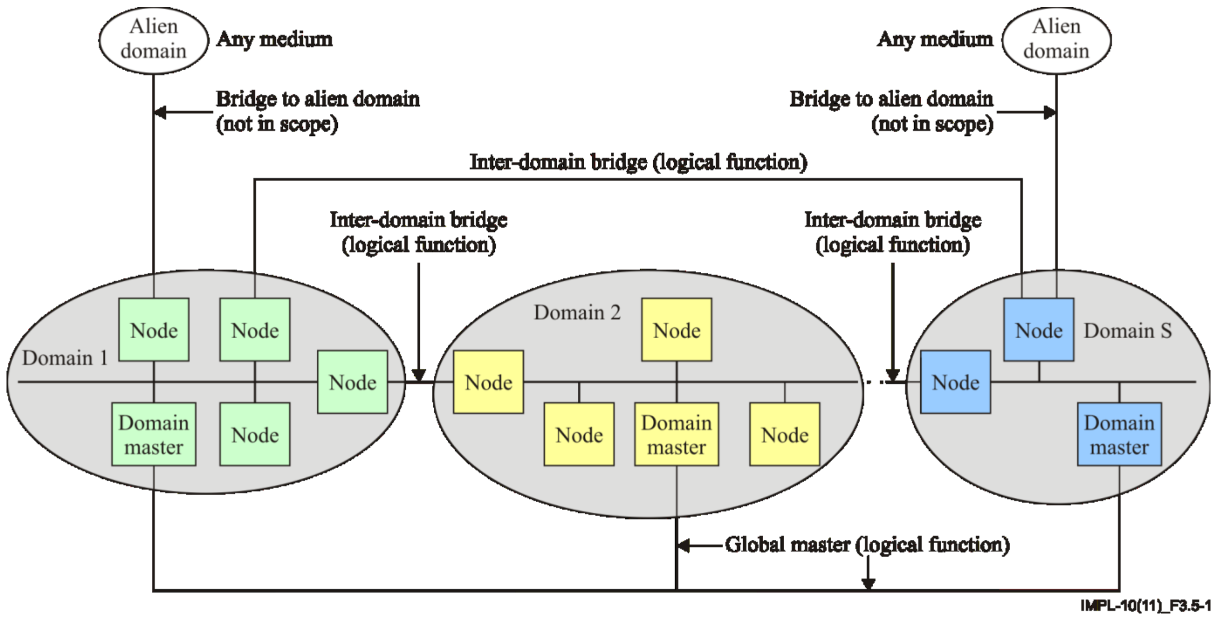


Figure 3.5-1 – Home network architecture reference model

A node is any network device that contains an ITU-T G.9960 transceiver. A domain contains nodes connected to the same medium, where one node is acting as a domain master. Nodes of the same domain communicate via the medium over which the domain is established. Nodes connected to different domains communicate via inter-domain bridges (e.g., L2 or L3 bridging, see Recommendation ITU-T G.9960 clause 5.1.6).

A domain shall be capable of supporting at least 32 registered nodes and may optionally support up to 250 registered nodes. Each node shall be capable of supporting simultaneous communication sessions with at least eight other nodes.

The domain master considers bridges to alien domains as application entities (AEs) of a node with certain requirements, while it considers inter-domain bridges as AEs of nodes whose interfaces (see Recommendation ITU-T G.9960 clause 5.1.6) comply with Recommendation ITU-T G.9960.

3.5.2.2 Modes of operation

A domain can operate in one of three modes: peer-to-peer mode (PM), centralized mode (CM), or unified mode (UM).

In PM, only P2P is used in the domain. Thus, direct signal traffic is established between two communicating nodes.

In CM, only REL shall be used, with only one node to act as a relaying node. Thus, any node of the domain can communicate with another node only through the domain access point (DAP). The DAP receives signals from all nodes of the domain and further forwards them to the corresponding addressee nodes. In case of DAP failure, no communication between nodes in the domain is allowed.

In UM, there is support for nodes that cannot communicate between themselves directly; these nodes are considered "hidden" nodes in relation to one another. A hidden node in a domain can communicate with another node through a relay node. Security of an encrypted data flow is maintained through a relay node.

Different domains within the home network can use different modes of operation, i.e., PM, CM, or UM. Examples of domains in different operational modes are presented in Recommendation ITU-T

G.9960 Appendix I. Broadcast and multicast are supported in any domain, independent of its operational mode (PM, CM or UM).

3.5.2.3 Quality of service

Quality of service (QoS) is a measure of the quality of services delivery in the home network, placing requirements on the transmission and queuing of traffic. Two QoS methods are supported, in accordance with Recommendation ITU-T G.9960: priority-based QoS and parameter-based QoS.

QoS requirements are supported between nodes inside the same domain and between nodes connected to different domains, if services communicated between nodes belong to different domains. In the latter case, inter-domain bridges are expected to not compromise the QoS requirements (such as latency). Inter-domain bridges are also expected to facilitate provisioning of QoS between nodes connected to different domains.

The ITU-T G.9960 QoS mechanism operates per flow. A flow is a unidirectional stream of data between two nodes related to a specific application and/or characterized by a set of QoS requirements. Flows are set up, modified and terminated on a service basis. The characteristics of the service are used to select the QoS method used to deliver the traffic associated with the flow and to determine any relevant QoS parameters. Frames belonging to a specific flow are scheduled to be sent onto the medium in accordance with the defined QoS method. The ITU-T G.9960 QoS method shall handle both constant and variable data rate traffic.

"Priority-based QoS" refers to a mechanism that provides different priorities for medium access to different flows. All ITU-T G.9960 transceivers shall support priority-based QoS. The number of supported priority levels associated with the incoming application data primitives (ADPs) (at the A-interface of Figure 3.5-2) shall be eight (denoted from 0 to 7).

With priority-based QoS, the ITU-T G.9960 transceiver associates each flow with a certain priority queue, based on priority or other priority-related parameters of incoming frames. The ITU-T G.9960 priority-based QoS method defines the order in which frames from each queue will be sent to the medium and the order in which frames will be processed (and possibly dropped), based solely on the priority assigned to the queue. The number of supported priority queues may be less than eight. The mapping between the priority of the flow and the associated priority queue shall be as recommended by IEEE 802.1D for user priority to traffic class mappings (Recommendation ITU-T G.9960 Appendix III). Other methods of classification are for further study.

"Parameter-based QoS" refers to a mechanism that provides specific performance metrics (QoS parameters) for a given flow associated with the application (service), and resource allocation for medium access to meet these performance metrics. A set of these parameters may include, but is not limited to, data throughput, latency or jitter.

With parameter-based QoS, the ITU-T G.9960 transceiver associates each flow with a set of QoS parameters related to the particular service and with a certain queue. The ITU-T G.9960 parameter-based QoS method provides appropriate resources (e.g., bandwidth) necessary to communicate each flow through the medium so that QoS parameters associated with this flow are met. It also determines the order in which frames from each queue will be sent to the medium and the order in which frames will be processed (and possibly dropped) based on the knowledge of traffic parameters. The minimum number of supported flows (queues) depends on the profile.

3.5.2.4 Security

Security in Recommendation ITU-T G.9960 is designed to address operation over shared media, such as power line and coaxial cable. Besides admission procedures, which ensure that only permitted nodes can join a home network via one of its domains, Recommendation ITU-T G.9960 defines point-to-point security, allowing authentication of each pair of nodes prior to communication and unique encryption keys for each pair of communicating nodes or per multicast group.

NOTE – Point-to-point security generally improves security by building another layer of protection against an intruder that has broken through the admission control, and maintains full confidentiality for all communications within the home network. This makes Recommendation ITU-T G.9960 suitable for installation in public places (hotels, small businesses, home offices) requiring at least the same grade of security and confidentiality as defined in the most recent IEEE 802.11 specification for wireless LAN. See Recommendation ITU-T G.9960 Appendix IV for a description of the threat model.

Security provides the following main features, according to Recommendation ITU-T G.9960:

- Encryption based on AES-128 in FIPS Pub 197 and on CCM mode in NIST-SP800-38C, both available from the US National Institute of Standards and Technology;
- Advanced authentication and secure admission of nodes into a domain, based on Recommendation ITU-T X.1035;
- Key management, including generation, secure communication, update, and termination of encryption keys;
- High confidentiality and integrity of all transactions, including point-to-point authentication and unique encryption keys;
- Support of secure operation in the presence of relay nodes;
- Allows simultaneous operation of distinct, separately secured domains on the same medium per the rules specified in Recommendation ITU-T G.9960 clause 5.1.1.1;
- Provides user-friendly procedures for setting up a secure network.

Security procedures that are user-friendly may require the user to set a password for each node prior to installation. The rest of the procedures necessary to establish and maintain security are facilitated automatically by the security controller (SC) function, without involvement of the user.

Nodes that do not include an appropriate user interface may use a unique manufacturer-set password.

Security and mutual confidentiality between applications associated with the same node are supposed to be resolved at the higher layers of the protocol stack and are beyond the scope of Recommendation ITU-T G.9960.

3.5.2.5 Inter-domain bridging

The inter-domain bridge (IDB) function connects nodes of two domains.

3.5.2.5.1 End-to-end QoS for multi-domain connections

The end-to-end QoS requirements are defined by priority level (in case of priority-based QoS), or by traffic parameters such as data rate and latency (for parameterized QoS). In both cases, to meet end-to-end requirements, requirements are imposed on in-domain flows forming the connection and on the IDB.

3.5.2.5.2 Security in multi-domain connections

For a multi-domain home network, secure operation is achieved by setting all its domains to secure mode. Communications between secure and non-secure domains shall not be allowed, unless special security measures are provided by the IDB (on higher protocol levels). These measures are beyond the scope of Recommendation ITU-T G.9960, as are security measures protecting the IDB from outside intrusion (i.e., when the intruder is one of the AEs connected to the IDB).

3.5.2.6 Power-saving modes

Four modes of operation are defined with the intention of reducing the total power consumption in home networks. When switched on, an Recommendation ITU-T G.9960 transceiver shall operate in one of the following modes:

- Full-power mode (L0): This is the mode in which transmission up to the maximum data rate is possible. In this mode, power consumption is limited only by the defined power spectral density (PSD), see Recommendation ITU-T G.9964 for PSD tools.
- Efficient-power mode (L1): In this mode, power consumption is reduced by limiting medium access only to a portion of a MAC cycle. The maximum data rate is supported in aggregate over all nodes in the domain.
- Low-power mode (L2): In this mode, power consumption is reduced by suppressing medium access over multiple MAC cycles. Only a limited data rate is supported.
- Idle mode (L3): In this mode, power consumption is minimized by suppressing medium access over a longer period of MAC cycles. The ITU-T G.9960 transceiver is switched on and connected physically to the home network, but no data except for control messages is transmitted or received.

During all power modes and transitions between them, the node shall maintain its original DEVICE_ID.

3.5.2.7 Reference models

3.5.2.7.1 Protocol reference model of an ITU-T G.9960 transceiver

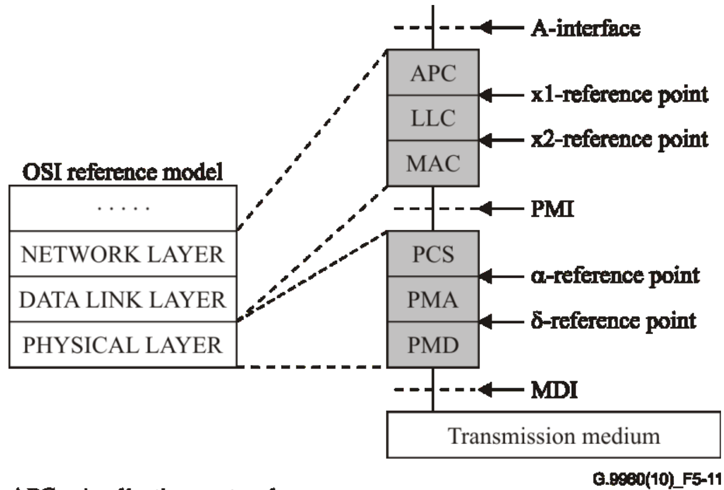
The protocol reference model of an ITU-T G.9960 transceiver is shown in Figure 3.5-2. It includes three main reference points: application interface (A-interface), physical medium-independent interface (PMI), and medium-dependent interface (MDI). Two intermediate reference points, x1 and x2 are defined in the data link layer (DLL), and two other intermediate reference points, α and δ are defined in the PHY layer (Figure 3.5-2).

The A-interface is user application-protocol specific (e.g., Ethernet, IP). The functional description of the A-interface is given in Recommendation ITU-T G.9960 clause 5.2.2.1.

The PMI interface is both medium independent and application independent. It is defined in Recommendation ITU-T G.9960 clause 5.2.2.2 as a functional interface, in terms of functional flows and logical signals.

The MDI is a physical interface defined in terms of the physical signals transmitted over a specific medium (see Recommendation ITU-T G.9960 clause 7.2) and mechanical connection to the medium.

All intermediate reference points are independent of the type of medium the node is communicating over and are defined as functional (logical) interfaces in terms of functional flows and logical signals.



APC Application protocol convergence
LLC Logical link control
PCS Physical coding sub-layer
PMA Physical medium attachment
PMD Physical medium dependent
PMI Physical medium-independent interface
MDI Medium-dependent interface

Figure 3.5-2 – Protocol reference model of a home networking transceiver

The application protocol convergence (APC) sublayer provides an interface with the application entity (AE), and operates with an application-specific protocol, such as Ethernet. The APC also provides data rate adaptation between the AE and the home networking transceiver.

The logical link control (LLC) sublayer coordinates transmission of nodes in accordance with requests from the domain master. In particular, it is responsible for establishing, managing, resetting and terminating all connections of the node inside the domain. The LLC also facilitates quality of service (QoS) constraints of the flow, defined for its various connections.

The medium access control (MAC) sublayer controls access of the node to the medium using various medium access protocols.

The physical coding sublayer (PCS) provides data rate adaptation (data flow control) between the MAC and PHY and encapsulates transmit MAC protocol data units (MPDUs) into a PHY frame and adds PHY-related control and management overhead.

The physical medium attachment (PMA) sublayer provides encoding of PHY frame content for transmission over the medium.

The physical medium dependent (PMD) sublayer modulates and demodulates PHY frames for transmission over the medium using orthogonal frequency division modulation (OFDM). By implementation, the PMD may include medium-dependent adaptors for different media, including frequency shifting for passband transmission.

The layers above the data link layer (above the A-interface) are beyond the scope of Recommendation ITU-T G.9960 and this Technical paper. Management functions are not shown in Figure 3.5-2.

3.5.2.7.2 Interfaces – functional description

This section contains the functional description of the ITU-T G.9960 transceiver interfaces (A, PMI, and MDI) in terms of signal flows exchanged between corresponding entities.

3.5.2.7.2.1 A-interface

The A-interface is described in terms of primitives exchanged between the AE and the DLL. There are six general types of A-interface primitives.

3.5.2.7.2.2 Physical medium-independent interface (PMI)

The PMI is described in terms of primitives exchanged between the DLL and PHY layer. The direction of each primitive flow indicates the entity originating the primitive. Both transmit and receive data primitives are exchanged in MAC protocol data units (MPDUs).

3.5.2.7.2.3 Medium-dependent interface (MDI)

Functional characteristics of the MDI are described by two signal flows:

- transmit signal (TX DATA) which is the flow of frames transmitted onto the medium;
- receive signal (RX DATA) which is the flow of frames received from the medium.

3.5.2.7.3 Functional model of a home networking transceiver

The functional model of a home networking transceiver is presented in Figure 3.5.-3. It addresses nodes without extended capabilities as well as nodes with extended capabilities such as domain master and relaying (including DAP), which differ by their MAC, LLC and upper layer functionalities. The PMD function depends on the medium on which the transceiver operates. It can be configured for baseband or passband operation. The PCS provides data rate adaptation (data flow control) between the MAC and the PHY and encapsulates transmit MAC protocol data units (MPDUs) into PHY frames. The transmit PHY frame is further encoded in the PMA to meet the corresponding PMD. The functionality of the PCS, and the PMA is the same for any medium, but their parameters are medium-specific. By appropriate parameter settings, any node can be configured to operate on any type of wiring in both baseband and passband modes.

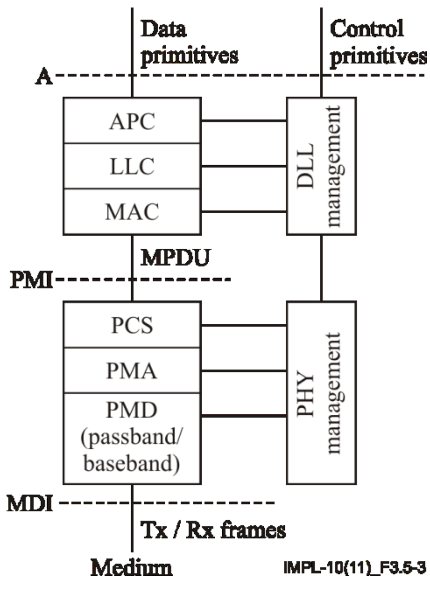


Figure 3.5-3 – Functional model of a home networking transceiver

3.5.2.8 Profiles

Profiles are intended to specify nodes with significantly different levels of complexity and functionality. For every domain type, a more complex profile is a superset of less complex profile and shall interoperate with that profile. A node shall be classified into particular profiles according to its degree of complexity and functionality. For compliance with Recommendation ITU-T

G.9960, a node is required to support one profile, at a minimum. Profiles of the nodes are summarized in Table 3.5-1.

Table 3.5-1 Profiles

Profile name	Domain type	Valid bandplans (Note)
Low-complexity profile	Power-line baseband	25 MHz-PB
Standard profile	Power-line baseband	50 MHz-PB, 100 MHz-PB
	Telephone-line baseband	50 MHz-TB, 100 MHz-TB
	Coax baseband	50 MHz-CB, 100 MHz-CB
	Coax RF	50 MHz-CRF, 100 MHz-CRF, 200 MHz-CRF
NOTE – In order to be compliant with a given profile, at least one bandplan shall be implemented.		

PB – Power-line Bandplan
TB – Phone-line Bandplan
CB – Coaxial Bandplan
CRF – Coaxial Radio Frequency Bandplan

ITU-T G.9960 transceivers are defined to operate at any time over one of the medium-specific bandplans as defined in the Table 3.5-2. ITU-T G.9960 transceivers may only operate over some or one medium and in some or one bandplan for that medium. The vendor implementations of ITU-T G.9960 transceivers may vary regarding what mediums and bandplans they operate over; however, the specifications for specific bandplans per medium do not.

Table 3.5-2 – Mediums and bandplans for Recommendation ITU-T G.9960

Medium	Bandplan Designation	Baseband or RF	Start MHz	End MHz	Notes
Powerline	25MHz-PB	Baseband	2	25	Low-complexity profile (LCP)
Powerline	50MHz-PB	Baseband	2	50	
Powerline	100MHz-PB	Baseband	2	100	
Phone line	50MHz-TB	Baseband	2	50	
Phone line	100MHz-TB	Baseband	2	100	
Coax	50MHz-CB	Baseband	2	50	
Coax	100MHz-CB	Baseband	2	100	
Coax	50MHz-CRF	RF	350	2850	50 MHz wide band within these bounding frequencies
Coax	100MHz-CRF	RF	350	2850	100 MHz wide band within these bounding frequencies
Coax	200MHz-CRF	RF	350	2850	200 MHz wide band within these bounding frequencies
The 100MHz-PB (powerline 100 MHz Bandplan) by default definition is notched starting at 80 MHz to avoid FM interference. Coax Baseband configuration is for when the coaxial cable has no services operating below 100 MHz. Coax RF is for use when other services are resident on the coaxial cable in the lower frequencies (below 100 MHz).					

3.5.3 Physical layer specification

3.5.3.1 Medium independent specification

3.5.3.1.1 Functional model of the PHY

The functional model of the PHY is presented in Figure 3.5-3. The PMI and MDI are, respectively, two demarcation reference points between the PHY and MAC and between the PHY and the transmission medium. Internal reference points δ and α show separation between the PMD and PMA, and between the PCS and PMA, respectively.

For a description of each of the functions shown in Figure 3.5-4 see Recommendation ITU-T G.9960, clause 7.

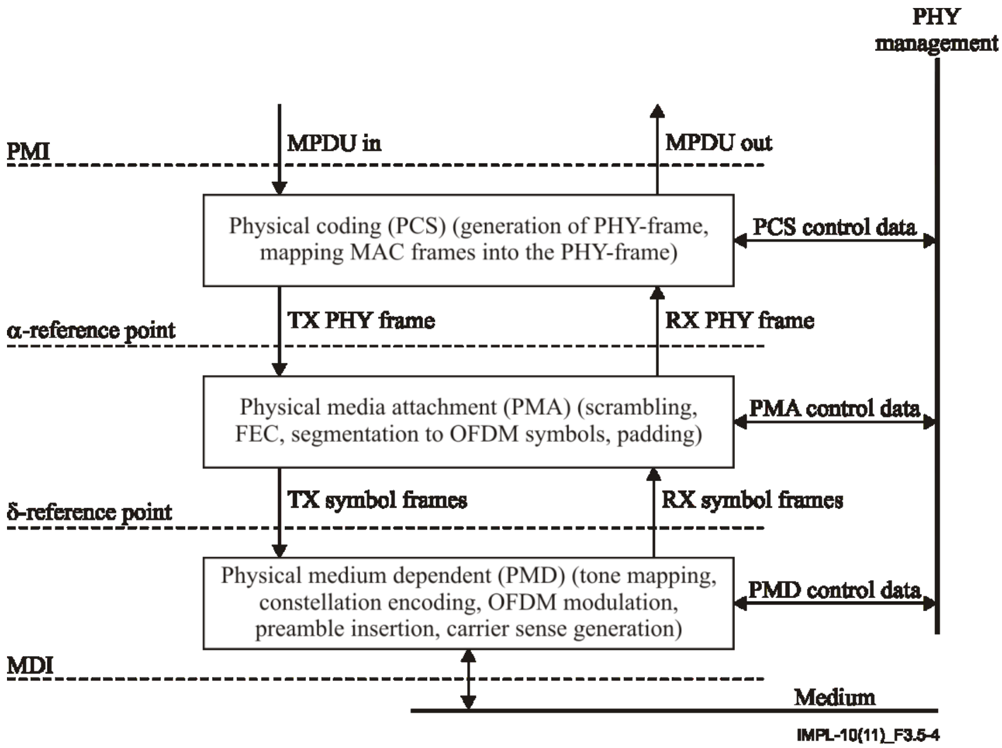


Figure 3.5-4 – Functional model of the PHY layer

3.5.4 Data link layer specifications

(For further information see Recommendation ITU-T G.9961.)

3.5.4.1 Overview

This section describes the data link layer (DLL) for wire-line based home networking transceivers capable of operating over premises wiring including inside telephone wiring, coaxial cable, and power line wiring. Its content is based on that of Recommendation ITU-T G.9961. It complements the system architecture and physical layer (PHY) descriptions provided in section 3.5.2 and 3.5.3.

3.5.4.2 Data link layer specification

3.5.4.2.1 Functional model and frame formats

3.5.4.2.1.1 Functional model of the data link layer

The functional model of the DLL is presented in Figure 3.5-5. The A-interface is the demarcation point between the application entity (AE) and the DLL; the physical medium independent (PMI) interface is the demarcation point between the DLL and the PHY. Internal reference points x1 and x2 show logical separation between the APC and LLC and between the LLC and MAC, respectively.

Application data primitives (ADPs), e.g. Ethernet primitives, are passed across the A-interface while MAC protocol data units (MPDUs) are exchanged over the PMI.

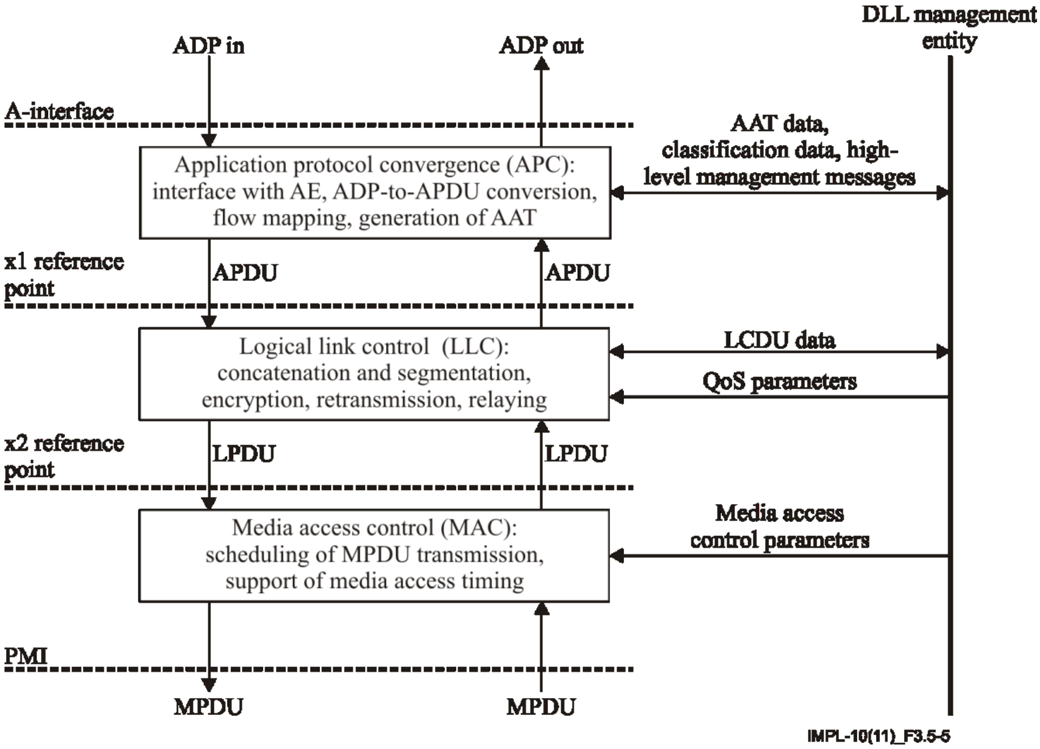


Figure 3.5-5 – Functional model of the DLL

In the transmit direction, application data primitive (ADP) sets enter the DLL from the AE across the A-interface. Every incoming ADP set meets the format defined by the particular application protocol; for an Ethernet type AE, the ADP set has one of the standard Ethernet formats, as presented in Recommendation ITU-T G.9961 Annex A (Ethernet APC). Each incoming ADP set is converted by the APC into APC protocol data units (APDUs), which include all parts of the ADP set intended for communication to the destination node(s). The APC also identifies ADP classification primitives (e.g., priority tags), which can be used by the LLC to support QoS requirements assigned to the service delivered by the ADP. Further, the APC is responsible for establishing flows of APDUs between peer APCs and assigning one or more queues for these flows according to the classification information associated with each APDU. The number of queues may depend on the profile of the device; for the Ethernet APC, mapping of user priorities to the same destination into priority queues (traffic classes) shall follow Table III.1 of Recommendation ITU-T G.9960.

The APDUs are transferred to the LLC across the x1 reference point, which is both application independent and medium independent. In addition, LLC receives management data primitives from the DLL management entity intended for LLC control frames, which are mapped into link control data units (LCDUs). The LLC is responsible for establishing flows of LCDU (control frames) between peer LLCs.

In the LLC, the incoming APDU and LCDU are converted into LLC frames and may be encrypted using assigned encryption keys (see Recommendation ITU-T G.9961 clause 9.2). LLC frames are subject to concatenation and segmentation, as described in Recommendation ITU-T G.9961 clause 8.1.3.2. Segments are transformed into LLC protocol data units (LPDUs) by adding an LPDU header (LPH) and CRC. LPDUs are then passed to the MAC across the x2 reference point. The LLC is also responsible for retransmission and relay operations.

The MAC is responsible for concatenating LPDUs into MAC protocol data units (MPDUs) and then conveying these MPDUs to the PHY in the order determined by the LLC (scheduling, using number of transmission queues) and applying medium access rules established in the domain.

In the receive direction, MPDUs from the PHY enter the MAC across the PMI together with associated PHY frame error information. The MAC disassembles the received MPDU into LPDUs, which are passed over the x2 reference point to the LLC. The LLC recovers the original APDUs and LCDUs from the LPDUs, performs decryption if required, and conveys them to the APC and LLC management entity, respectively. In the APC, ADPs are generated from the received APDUs and conveyed to the AE.

The LLC is responsible for the decision regarding errored LPDUs. It decides whether to request retransmission of errored LPDUs (and generates the ACK response to assist retransmission), or to discard the errored LPDUs.

The functionality of the APC, LLC, and MAC is the same for all types of medium, although some of their functions and control parameters may be adjusted for efficient operation of the transceiver over particular medium. Specific control parameters for APC, LLC, and MAC are described in Recommendation ITU-T G.9961 clause 8.4.

The detailed description of the APC, LLC and MAC can be found in Recommendation ITU-T G.9961.

3.5.4.3 Node functions and addressing

3.5.4.3.1 Functions of the endpoint node

The following are the functions of an endpoint node.

NOTE – The term "endpoint node" is used, according to the context, to differentiate between the domain master node functionalities and non-domain master node functionalities.

- MAC cycle synchronization and synchronized transmissions;
- Bandwidth reservation;
- Routing of ADPs;
- Broadcast of LLC frames;
- Reporting of detected neighbouring domains;
- MAP relaying;
- Relaying messages;
- Retransmissions and acknowledgement;
- Bidirectional flows.

3.5.4.3.2 Domain master node functional capabilities

A domain master-capable node is a node that, in addition to supporting all of the required capabilities of an endpoint node, is also able to assume the role of a domain master.

At any given time, only one node is allowed to act as a domain master for a domain. All other nodes within the domain are managed (coordinated) by this domain master. If a domain master fails, another node of the same domain, capable of operating as a domain master, should pick up the function of the domain master.

The domain master shall perform medium access using the same medium access rules as for endpoint (non-domain master) nodes and using the same medium access plan (MAP) distributed to the endpoint nodes.

NOTE – It is not a requirement that every node be domain master capable.

A list of the domain master functions follows:

- Network admission including:
  - Registration into the domain;
  - Periodic re-registrations;
  - Resignation from the domain (self and forced resignation);
  - Admission via Proxy.
- Bandwidth management including:
  - Flow establishment;
  - Flow establishment via relay nodes;
  - Flow maintenance;
  - Flow termination;
- Synchronization to an external source, such as AC line cycle synchronization.
- Routing and topology management:
  - Domain master operation for routing and topology management.
- Backup domain master:
  - Backup domain master assignment and release;
  - Recovery of the domain master failure by backup;
  - Domain master selection;
- Selection of PHY-frame header segmentation.
- Selection of the domain name identifier (DNI) and the domain ID (DOD).

3.5.4.3.3 Addressing scheme

3.5.4.3.3.1 Node identifier

The following three node identification parameters are used:

- DEVICE_ID;
- MULTICAST_ID;
- BROADCAST_ID.

The same node can be identified by its unique DEVICE_ID, by several MULTICAST_IDs and by the BROADCAST_ID, which is the same for all nodes.

The node identifier shall be used to identify the assignment of transmission opportunity (TXOP) and time slot (TS) within shared transmission opportunity (STXOP) to the nodes in the MAP and to identify the source and destination of a PHY frame (SID, source identification, and destination identification (DID) (see Recommendation ITU-T G.9960, clause 7.1.2.3).

3.5.4.4 Medium access and frame acknowledgements

3.5.4.4.1 Medium access plan frame

The medium access plan (MAP) frame describes when a subsequent MAC cycle shall start and describes the TXOPs it shall include, and includes information and parameters of the domain operation. Each MAC cycle is identified by a sequence number (see Recommendation ITU-T G.9961 clause 8.8.3) contained in the MAP frame describing it. By default, the medium access plan described by a MAP frame is for a single MAC cycle, but it may carry persistency information related to one or more subsequent MAC cycles.

3.5.4.4.2 Retransmission and acknowledgement protocol

The retransmission and acknowledgment protocol specifies acknowledgment (either immediate or delayed) by the receiver of the reception of a frame.

3.5.4.5 Security

Security inside a domain is provided by encryption of the relevant LLC frames communicated between the nodes of the domain. The encryption method used is based on AES-128 and described in Recommendation ITU-T G.9961 clause 9.1. Every pair of nodes in unicast and nodes of every multicast group communicating in a secure mode may use a unique encryption key.

Authentication, generation, distribution of encryption keys between nodes, and periodical key and authentication updates are provided by a set of authentication and key management (AKM) procedures, described in Recommendation ITU-T G.9961 clause 9.2.

Security of a network containing more than one domain is provided by setting all the domains of the network in secure mode. Inter-domain bridges are considered to be secure, while security measures protecting inter-domain bridges against outside intrusion are beyond the scope of Recommendation ITU-T G.9961 and therefore of this Technical paper.

Confidentiality between clients associated with the same node is considered to be resolved at the higher layers of the client protocol stack and is beyond the scope of Recommendation ITU-T G.9961.

3.5.5 Power spectral density (PSD) specification

(For further information, see Recommendation ITU-T G.9964.)

3.5.5.1 Overview

This section descries the control parameters that determine spectral content, power spectral density (PSD) mask requirements, a set of tools to support reduction of the transmit PSD, means to measure this PSD for transmission over telephone wiring, power line wiring and coaxial cable, as well as the allowable total transmit power into a specified termination impedance. The content of this section is based on that of Recommendation ITU-T G.9964. It complements the system architecture and physical layer (PHY) specified in Recommendation ITU-T G.9960, and the data link layer (DLL) specified in Recommendation ITU-T G.9961.

3.5.5.2 Transmit PSD Mask

Transmit PSD mask (TxPSD) is determined by a sub-carrier mask (SM), a PSD shaping mask (PSM), a notching of international amateur radio bands defined in Recommendation ITU-T G.9964, the limit PSD mask (LPM) defined for each particular medium, and a regional PSD mask (RPM) if specified in a regional annex of Recommendation ITU-T G.9960. The same TxPSD shall be applied to all nodes in the domain.

The PSD of the transmit signal at any frequency shall never exceed the transmit PSD mask. The PSD of the transmit signal may be further limited by a PSD ceiling (PSDC) that is applied to nodes involved in a particular connection (Recommendation ITU-T G.9964 clause 5.4).

The LPM (see Recommendation ITU-T G.9964 clauses 6.1.2, 6.2.2 and 6.3.2) specifies the absolute limit of the transmit PSD. However, if an RPM is specified for a particular region, the absolute limit shall be the minimum level between the LPM and RPM at any given frequency. The SM, PSDC, and PSM provide further reduction and shaping of the transmit PSD using three mechanisms: sub-carrier masking (notching), PSD ceiling (limit on PSD level), and PSD shaping.

ITU-T G.9960 transceivers shall support sub-carrier masking, notching of international amateur radio bands, and PSD ceiling. Support of PSD shaping is optional.

The transmit PSD mask shall comply with national and regional regulatory requirements.

NOTE – In addition to the mechanisms described in this section that provide absolute limits to the transmit PSD (both in-band and out-of-band), Recommendation ITU-T G.9964 defines a mechanism of PSD ceiling that allows dynamic reduction of the transmit power for each particular connection to the minimum value that is sufficient to achieve the given QoS targets.

3.5.5.2.1 Sub-carrier masking

Sub-carrier masking shall be used to eliminate transmission on one or more sub-carriers. Sub-carrier masking is defined by a sub-carrier mask (SM). Transmit power of sub-carriers specified in SM shall be set to zero (linear scale). SM shall override all other instructions related to the transmit power of the sub-carrier.

3.5.5.2.2 PSD shaping

PSD shaping allows transmit reduction of PSD in some parts of the spectrum, mainly for spectrum compatibility and coexistence with alien home networking technologies. PSD shaping is specified by a PSM.

PSM is defined on the frequency range between the lowest sub-carrier x_1 and the highest sub-carrier x_H, and consists of one or more frequency segments.

3.5.5.2.3 Notching of international amateur radio bands

If an amateur radio band is masked, the sub-carriers with frequencies $(F_{AL} - F_{SC}) \leq f \leq (F_{HL} + F_{SC})$, where F_{AL} and F_{HL} are the low and the high frequency of the amateur radio band shall be turned off (zero power transmitted). In addition, for any node operating over phone line or power line, the PSD of the transmitted signal in all international amateur radio bands that are masked in the particular domain shall be at −85 dBm/Hz or lower. See Annex D of Recommendation ITU-T G.9964 for start and stop frequencies for each amateur radio band.

3.5.5.2.4 PSD ceiling

PSD ceiling specifies the PSD level that is used to impose a limit (i.e., a ceiling function) on the transmit signal. PSDC is independent of frequency and indicated by a single value in dBm/Hz. The valid range of PSDC values is from −50 dBm/Hz to −100 dBm/Hz in steps of 2 dB.

PSDC shall be supported by all ITU-T G.9960 transceivers.

3.5.5.2.5 Notching of VDSL2 bands

Any node operating over phone line, coaxial cable, or power line, shall be able to reduce the PSD of the transmitted signal in one or more VDSL2 frequency bands to the levels appropriate for reliable transmission of VDSL2 signals.

3.5.5.3 Medium dependent specification of spectral content

3.5.5.3.1 Specification of spectral content for phone lines

The specification covers:

- Control parameters;
- PSD mask specifications over phone lines;
- Permanently masked sub-carriers.

3.5.5.3.2 Specification of spectral content for power lines

The specification covers:

- Control parameters;
- PSD mask specifications over power lines;
- Permanently masked sub-carriers.

3.5.5.3.3 Specification of spectral content for coaxial cable

The specification covers:

- Control parameters;
- PSD mask specifications over coaxial cable;
- Permanently masked sub-carriers;
- Coexistence on coaxial cable.

3.5.5.3.4 Termination impedance

The nominal values of termination (load) impedance for different types of media are defined in Recommendation ITU-T G.9964 Table 6-11. The standard termination impedance shall be used for PSD and total transmit power measurement.

3.5.5.3.5 Total transmit power

The total transmit power of the transceiver terminated with a standard termination impedance (see Recommendation ITU-T G.9964 clause 6.4) shall not exceed the values presented in Recommendation ITU-T G.9964 Table 6-12.

3.5.5.3.6 Receiver input impedance

When operating on power line medium and not transmitting, a device implementation shall present a minimum impedance of 40 Ohm in the band from 1.8 MHz to 50 MHz measured between line (phase) and neutral terminals. It shall present a minimum impedance of 20 Ohm in the ranges from 100 kHz to 1.8 MHz and from 50 MHz to 100 MHz.

3.5.6 Coexistence mechanism for wireline home networking transceivers

This section describes a coexistence mechanism for home networking transceivers capable of operating over power line wiring. The coexistence mechanism allows ITU-T G.9960 transceivers to coexist with other coexisting systems, as defined in Recommendation ITU-T G.9972, operating on the same power line wiring. The content of this section is based on that of Recommendation ITU-T G.9972.

(For further information, see Recommendation ITU-T G.9972.)

3.5.6.1 Overview

Inter-system protocol (ISP) allows for the power line medium to be shared between coexisting systems in the time domain, called time domain multiplexing (TDM), the frequency domain, called frequency domain multiplexing (FDM), or both. ISP supports coexistence between up to four non-interoperable coexisting systems. Recommendation ITU-T G.9972 assumes that there is only one access system operating over the distribution lines that provides power to a given customer premise.

NOTE – Coexistence means that power line communications (PLC) will not stop working.

The frequency range used by ISP signalling ranges from 2 MHz to 50 MHz.

Sharing of the power line medium between coexisting systems is determined by the following:

- Number of coexisting systems on the powerline;
- The type of coexisting system;
- Access system capacity request.

An overview of ISP is provided in the following sections.

3.5.6.2 Inter-system protocol

3.5.6.2.1 Coexistence signalling

Coexistence signalling is carried out by the use of periodically repeating ISP windows that are used to convey information on the presences of coexisting systems, resource requirements and resynchronization requests. Each type of coexisting system is allocated a particular ISP window in a round robin fashion.

3.5.6.2.2 Network status

By monitoring the signals transmitted within the ISP windows (allocated to other coexisting systems), a coexisting system is able to detect the number and type of other coexisting systems present on the line and the resource requirements of the access system (i.e. partial / full bandwidth).

By monitoring the signals within its own ISP window a coexisting system is able to detect a resynchronization request from one of the other coexisting systems.

This set of instantaneous information is termed the network status. Network status is used to determine the allocation of resources to each coexisting system.

3.5.6.3 Resource allocation

3.5.6.3.1 Frequency domain multiplexing

Within ISP, FDM may only be invoked by an access system. The overall FDM scheme consists of two frequency bands. The upper band is shared using TDM by in-home systems, the lower band reserved for access systems. One of two FDM band separation frequencies (10 MHz or 14 MHz) is chosen by the access system.

3.5.6.3.2 Time domain multiplexing

ISP allows TDM to be implemented between coexisting in-home systems or between coexisting in-home systems and an access system. The allocation of resources in the time domain is described in Recommendation ITU-T G.9972 section 9.

3.5.6.4 Start-up and re-synchronization procedures

In order to allow coexisting systems to synchronize to the appropriate ISP sequence and hence to effectively coexist, the ISP defines:

- procedures for system start-up;
- triggers and procedures for re-synchronizing to a different ISP sequence.

Chapter 4
Copper wires, optical fibres, optical cables and infrastructure

Editor: Gastone Bonaventura

Introduction

This chapter deals with two main subjects. The first one is the description of the main characteristics of the copper wires deployed in the local access networks, which are the physical support for the realization of the xDSL systems described in Chapter 1. The second is the description of the optical fibres, the optical cables and the related infrastructures, which are the physical support for the realization of the xPON networks described in Chapter 2 of this Technical paper. These two subjects are dealt with in separate series of ITU-T Recommendations.

Copper wires

Twisted copper pairs able to realize a physical point-to-point connection between public/private telephones and central offices (also known as "exchanges") started to be deployed and used more than 130 years ago. Since then, they have progressively penetrated into both urban and rural telephone networks, as a consequence of the continuous expansion of the telephone service.

This means that by the time the standardization of the xDSL systems started (about 20 years ago) copper-pair cable networks were already extremely widespread around the world. As a consequence, the objective of xDSL systems standardization was to exploit existing networks, re-using their physical and electrical characteristics.

The ITU-T standards related to these copper wire networks mainly specify the overall quality of the telephone service on the links between the local exchange and the customer premises (ITU-T G.1xx series for transmission levels, noise, crosstalk, group delay distortion, etc.), but giving network operators the freedom to choose their preferred copper wire characteristics [wired gauge, twisted structure (pairs/quads), winding pitch] with the only condition that the overall quality of service be satisfied.

A short description of the limited ITU-T material related to the specific characteristics of the copper pairs laid in the local networks is given in the following Section 4.1.

Optical fibres, optical cables and related infrastructures

In contrast, there is a completely different situation for optical fibres, which are the physical support for xPON networks. In this case, ITU-T started intensive standards development from 1975, i.e., immediately after the research phase of fibre-optic communication systems. The first two Recommendations were approved in 1980: ITU-T G.651, describing characteristics of a multimode optical fibre operating at 850 nm; and ITU-T G.955, describing characteristics of the optical systems operating at 850 nm and suitable for the bit rates of the plesiochronous digital hierarchy.

At present, the ITU-T G.65x series of Recommendations is dedicated to the specification of various types of optical fibres specifically designed for different types of applications. As for access networks, in addition to ITU-T G.652, which has a wide range of applications, including access, a new type of fibre (ITU-T G.657) has been specified since 2006 for local network applications only.

Moreover, the ITU-T L-series of Recommendations specifies different optical cable structures and different laying methods for various types of installation (duct, underground, aerial, sewer, etc.). More recently, ITU-T has specified optical cable structures for access networks in Recommendations ITU-T L.10, ITU-T L.26, ITU-T L.43 and ITU-T L.58, while the specification of the installation of such cables in the access network is at present in progress. Given the great amount of work carried out in the field of optical fibre and fibre-optic cable, ITU-T published the manual "Optical fibres, cables and systems" in 2009, which is devoted to the subject and available for download at: http://www.itu.int/pub/T-HDB-OUT.10-2009-1.

Section 4.2 provides general information on optical fibres, cables and infrastructures mainly related to access networks, with reference to the specific sections of the earlier manual and to specific Recommendations that provide further information.

4.1 Copper lines for xDSL systems

(For further information see Recommendation ITU-T G.991.1.)

4.1.1 Minimum requirements for digital local lines

The transmission medium over which the xDSL digital transmission systems, specified in the ITU-T G.99x series, are expected to operate is the local line distribution network. A local line distribution network usually employs cables with copper twisted pairs / quads to provide services to customers. In a local line distribution network, customers are connected to the local exchange via local lines.

A metallic local line is able to simultaneously carry bidirectional digital information in the appropriate xDSL format. To simplify the provision of xDSL, a digital transmission system must be capable of satisfactory operation over the majority of copper local lines without requiring special adaptation. In order to permit the use of xDSL transmission systems on the maximum possible number of local lines, the restrictions imposed by xDSL requirements are kept to the minimum necessary to guarantee acceptable operation. These minimum requirements for the digital local lines to be used for xDSL applications are the following:

– no loading coils
– only twisted pair or quad cable
– no additional shielding necessary.

Some words could be useful on bridged taps, which are branching connections spliced onto a cable (Figure 4.1-1). This connection is realized by a length of wire pair that is connected to a loop at one end and is not terminated at the other end. More than one bridged tap can be present on a loop. Bridged taps can be located near the exchange, near the customer or at an intermediate point. The aim of a bridged tap is to allow all the pairs in a cable to be used or reused to serve any customer along the cable route.

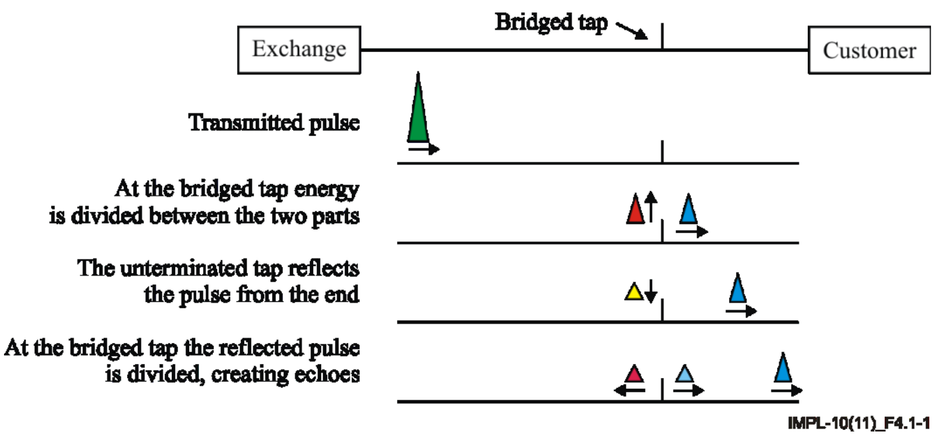


Figure 4.1-1 – Pulse propagation in presence of a bridged tap

There are two basic impairments related to the presence of the bridged taps: signal loss and reflections.

The energy traversing the wire line from the exchange is divided at the point where the bridged tap is located. Half the energy remains on the main line and half goes into bridged-tap connection. If the bridged tap is terminated on the characteristic impedance of the line (usually about 100 Ohm), half the energy is lost each time a tap occurs. This means that terminated taps before an xDSL modem result in a signal loss: for instance, three terminated taps before the modem can give a 8-9 dB of signal loss. The longer the bridged tap, the closer the loss will be to the 3 dB value that characterizes the termination on the characteristic impedance.

When taps are not terminated, as it is the usual case, they are an open circuit at higher frequencies with a reflection of the signal energy. The reflected energy has a delay at any frequency with respect to the energy at the same frequency on the main line. This means that the coming back energy on the main line in the same direction of the main signal may add destructively at some frequencies and constructively at other frequencies, creating a “rippled” frequency characteristic. The recovery of the reflected signal coming from the bridged taps requires an integrating mechanism in the receiver to recover both first and delayed energy.

In conclusion, bridged taps reduce performance even in the best of situations and so fewer taps mean higher data rates and reliability of the DSL connections. xDSL systems can operate with some bridged taps inserted in the loop. Their maximum number is related to the power budget of the specific systems.

Operators may decide to cut or remove these bridged taps when they can find them, but this a costly operation.

4.1.2 Digital local line physical characteristics

A general description of the digital local line physical model is shown in Figure 4.1-2 and typical examples of cable characteristics are given in Table 4-1.

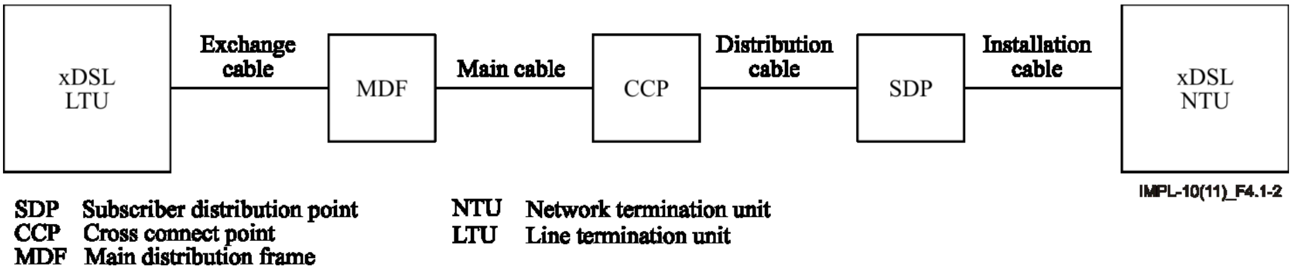


Figure 4.1-2 – Digital local lines physical model

The correspondence between the values of the wire diameter expressed in millimetres in Table 4-1 and the corresponding values expressed as American wire gauge (AWG) are shown in Table 4-2.

4.1.3 Digital local lines electrical characteristics

The transmitted signal will suffer from impairments due to crosstalk, impulsive noise and the non-linear variation with frequency of the characteristics of the digital local lines. These impairments are described in more detail in the following.

4.1.3.1 Principal characteristics

The principal electrical characteristics varying non-linearly with frequency are:

- Insertion loss: The copper wires have an insertion loss, which increases with the link length and with the square root of the frequency. The insertion loss reduces the signal level at the receiving side. The decrease of this level can cause errors in bit recognition. An upper limit to the number of bit errors is specified as the maximum tolerable bit error ratio (BER).

- Group delay: In essence, group delay measures the spread in delay between the fastest and slowest moving frequencies. The greater the group delay, the greater the dispersion in the transmission line.
- Characteristic impedance, comprising real and imaginary parts: The characteristic impedance of a uniform transmission line, usually written Z_0, is the ratio of the amplitudes of a single pair of voltage and current waves propagating along the line in the absence of reflections. Maximum power is transferred from the power supply to the load when the source impedance is the conjugate of the load impedance. Generally, the parameters involved in the calculation of the characteristic impedance are frequency dependent and are determined by measurements (for further information, see Appendix II of ITU-T G.991.1).

Table 4-1 – Cable characteristics

	Exchange cable	Main cable	Distribution cable	Installation cable
Wire diameter (mm)	0.5; 0.6; 0.32; 0.4	0.3-1.4	0.3-1.4	0.4; 0.5; 0.6; 0.8; 0.9; 0.63
Structure	SQ (B) or TP (L)	SQ (B) or TP (L)	SQ (B) or TP (L)	SQ or TP or UP
Maximum number of pairs	1200	2400 (0.4 mm) 4800 (0.32 mm)	600 (0.4 mm)	2 (aerial) 600 (in house)
Installation		underground in ducts	underground or aerial	aerial (drop) in ducts (in house)
Capacitance (nF/km at 800 Hz)	55 ... 120	25 ... 60	25 ... 60	35 ... 120
Wire insulation	PVC, FRPE	PE, paper pulp	paper, PE, Cell PE	PE, PVC

TP Twisted pairs
SQ Star quads
UP Untwisted pairs
L Layer
B Bundles (units)
PE Polyethylene
PVC Polyvinylchloride
Pulp Pulp of paper
Cell PE Cellular foam polyethylene
FRPE Fire-resistant PE

NOTE – This table is intended to describe the cables presently installed in the local loop. Not all of the above cable types are suitable for xDSL systems.

Table 4-2 – Wire diameters

Wire diameter (mm)	American wire gauge (AWG)
0.32	28
0.4	26
0.5	24
0.63	22

4.1.3.2 Differences in physical transmission characteristics between pairs in the DLL

Between the line termination unit (LTU) and network termination unit (NTU), the characteristics of the pairs may differ (Figure 4.1-1). This difference may be in wire diameter, insulation type, length, number and length of bridged taps, and exposure to impairments. These differences in transmission characteristics may change with time.

NOTE - LTU and NTU are usually called LT and NT.

The common circuitry of the xDSL systems compensate for any differences in the transmission time due to these pair differences.

4.1.3.3 Crosstalk characteristics

The telephone cables of the access networks can contain up to several thousand separate wire pairs packed closely together. The electrical signals in a wire pair generate a small electromagnetic field, which surrounds the wire pair and induces electrical signals in nearby wire pairs. The twisting of the wire pairs reduces this inductive coupling (crosstalk), but some signal leakage remains. Crosstalk is most pronounced at the segment of cable near the interfering transmitters. The crosstalk resulting from other transmission systems in the same cable (and especially the same binder group within the cable) is a primary factor limiting the bit rates and loop reach achievable by xDSL systems. Management of pair-to-pair crosstalk requires care in the bandwidth and signal power of the transmitters and out-of-band signal rejection by receivers.

In other words, crosstalk noise in general results due to finite coupling loss between pairs sharing the same cable, especially those pairs that are physically adjacent. Finite coupling loss between pairs causes a vestige of the signal flowing on one digital local line (the disturber digital local line) to be coupled into an adjacent digital local line (the disturbed digital local line). This vestige is known as crosstalk noise.

Near-end crosstalk (NEXT) is a major impairment for systems that share the same frequency band for upstream and downstream transmission (e.g. echo-cancelled hybrid transmission). NEXT noise is seen by the receiver located at the same end of the cable as the transmitter that is the noise source (Figure 4.1-3).

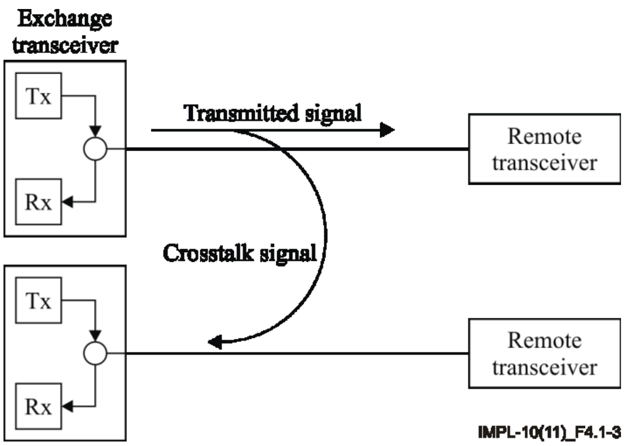


Figure 4.1-3 – Near-end crosstalk (NEXT)

NEXT can in principle be eliminated by not transmitting in both directions in the same frequency band at the same time, separating the two directions of transmission into either non-overlapping intervals in time or in non-overlapping frequency bands. This is how xDSL systems attempt to avoid NEXT, by using frequency- or time-division duplexing. However, FDM systems still must cope with NEXT from other types of systems that transmit in the same frequency band. Values for 1% worst case NEXT loss vary from 40 dB to 70 dB at 150 kHz depending upon the cable type, number of disturbers, and the environment.

Far-end crosstalk (FEXT) is the noise detected by the receiver located at the far end of the cable from the transmitter that is the noise source (Figure 4.1-4). FEXT is less severe than NEXT because the FEXT noise is attenuated by traversing the full length of the cable. Vectoring, as defined in ITU-T G.993.5, largely cancels the effects of FEXT for VDSL2.

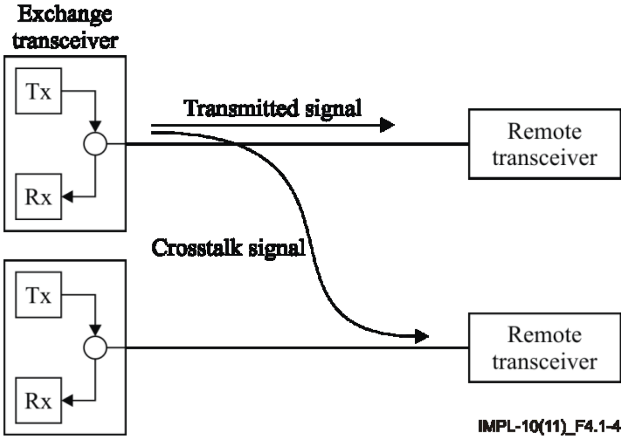


Figure 4.1-4 – Far-end crosstalk (FEXT)

Crosstalk noise usually changes slowly over time; therefore, the noise levels are often predictable and relatively easy to take into account when operators create deployment-planning rules.

4.1.3.4 Impulse noise

The digital local lines will have impulse noise resulting from other systems sharing the same cables, as well as from other sources. Impulsive noise, such as that due to impulses and radio-frequency interference (RFI), is intermittent in nature. It is geographically variable and unpredictable, and therefore it is usually accounted for in planning rules by assuming a safety margin. xDSL systems seek to implement some additional signal processing, such as error correction with interleaving and adaptive line codes, to mitigate such sources of noise.

4.1.3.5 Micro-interruptions

A micro-interruption is a temporary line interruption due to external mechanical action on the copper wires constituting the transmission path, for example, at a cable splice. Splices can be hand-made wire-to-wire junctions, and during cable life oxidation phenomena and mechanical vibrations can induce micro-interruptions at these critical points.

The effect of a micro-interruption on the transmission system can be a failure of the digital transmission link, together with a failure of the power feeding (if provided) for the duration of the micro-interruption.

The objective is that, in the presence of a micro-interruption of specified maximum length, the system should not reset, and the system should automatically reactivate with a complete start-up procedure if a reset occurs due to an interruption.

4.1.3.6 Electromagnetic compatibility

xDSL transmission systems are required to operate on access wire pairs that exist in a harsh physical and electromagnetic environment. Since they cannot be screened and are often hung from poles, they have the capacity to act as antennas. This means that they can pick up radiated emissions that can become sources of interference to xDSL systems; equally, there is the potential for xDSL line signals to leak out of the cables and cause interference to radio systems. Obviously, it is vital that both of these possibilities are understood and their impact controlled.

Emissions

Most xDSL line signals up to and including ADSL, use frequencies and signal levels so low that emissions are unlikely to radiate significantly. Access network cables transmit xDSL signals in a balanced mode (equal and opposite voltages on each wire), which tends to cancel out potential emissions. Any signal that does not find its way into the radiative, unbalanced mode is likely to be poorly radiated because the wavelength is so long that the antenna efficiency of the cables is very low.

At VDSL frequencies, the picture changes somewhat. Although the signal levels are still very low, the frequencies are much higher to the extent that the degrading balance of the cables allows more of it to enter the radiative mode. Once there, the shorter wavelength raises the antenna efficiency, so significant emission becomes a more real prospect. By making some careful design choices, the problems can be reduced to manageable proportions.

Susceptibility

Antennas work reciprocally, of course, so cables that can radiate emissions can also receive them from external sources. Normal radio signals do not pose much of a threat to xDSL signals, though, because the sophisticated receivers used have intrinsic abilities to eliminate or ignore them. RFI pickup only really becomes an issue when there are strong nearby transmitters. Again, VDSL systems are most likely to be affected because of the increased antenna efficiency of network cables at these frequencies. Some special methods can be used to mitigate these effects, such as RFI cancellation. In very severe RFI environments, such as close proximity to a strong AM broadcast transmitter, xDSL systems may not be workable, so substitute technology, such as direct fibre, may be the only alternative.

4.2 Optical fibres, cables and infrastructures for PONs

(For further information see ITU-T Manual on Optical fibres, cables and systems.)

In contrast to conventional networks, a passive optical network (PON) has no active components between the central office and the customer's premises. As a matter of fact, only completely passive optical components are placed in the network transmission path to guide the traffic signals contained within specific optical wavelengths. Replacing active devices with passive components provides a significant cost savings in maintenance by eliminating the need to power and manage active components in the outside cable plant. In addition, since the passive devices have no electrical power or signal-processing requirements, they have extremely high mean time between failures (MTBFs).

PONs are thus generally characterized by the absence of active components, with the exception of the sites where the optical line termination (OLT) and the optical network unit/optical network termination (ONU/ONT) are placed. However, a PON can also include a reach extender (RE), which contains active components, when a long distance between the OLT and the ONU is required. PONs are generally based on tree network topologies that use passive optical splitters. The general structure of a PON network is shown in Figure 4.2-1.

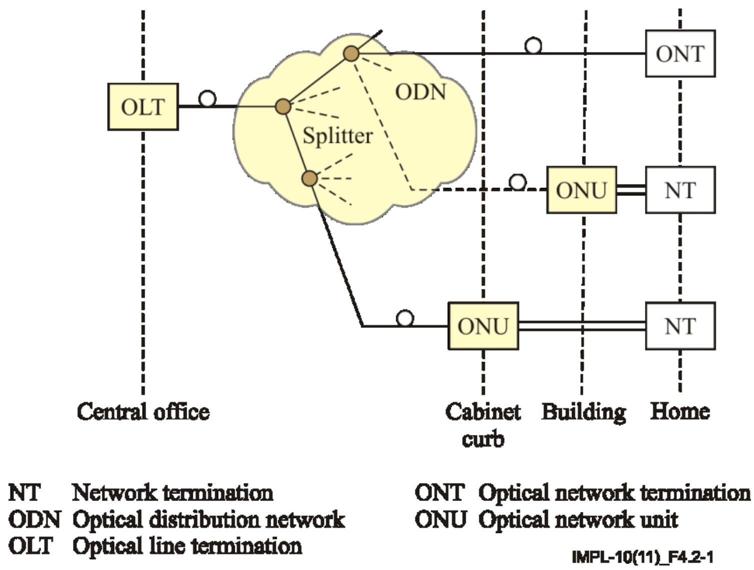


Figure 4.2-1 – General structure of a PON

At the network side, there is an OLT, which is usually installed at the local central office (CO). The OLT is the interface between all the users connected to the given PON and the metro network. Such users have access to the services offered by the network, through the network terminal (NT), and to the optical network through the ONU/ONTs. The OLT and the ONUs are connected via an optical distribution network (ODN), which in many cases has a point-to-multipoint configuration with one or more splitters.

In order to reduce the need for dual-fibre ODNs, the aforementioned PON systems can take advantage of the WDM signal multiplexing technique, where downstream and upstream channels are transmitted at different wavelengths (e.g., 1260-1360 nm for the upstream, and 1480-1500 nm for the downstream). It is also possible to add another optical signal, e.g., to carry radio-frequency-video signals in the 1550-1560 nm band, called the enhancement band.

Active PON modules (OLT, ONT, ONU) are described in Chapter 2, while this chapter only deals with the passive components of the ODN.

4.2.1 PON architectures

A generic physical configuration of an optical distribution network is shown in Figure 4.2-2.

The ODN is defined between reference points S and R, which are defined as follows:

- S: Point on the optical fibre just after the OLT[a]/ONU[b] optical connection point (i.e., optical connector or optical splice).
- R: Point on the optical fibre just before the ONU[a]/OLT[b] optical connection point (i.e., optical connector or optical splice).

Definition [a] holds when considering optical signals travelling from the OLT to the ONU; definition [b] holds when considering optical signals travelling from the ONU to the OLT.

Depending on the physical realization of the ODN, points S and R at each end of the ODN may be located either on the same fibre (i.e., they coincide) or on separate fibres.

At the physical layer, interfaces O_r and O_l may require more than one fibre, e.g., for separation of transmission directions or different types of signals (services).

If additional connectors or other passive devices are needed for ODN rearrangement, they shall be located between points S and R, and their losses shall be taken into account in any optical loss calculation.

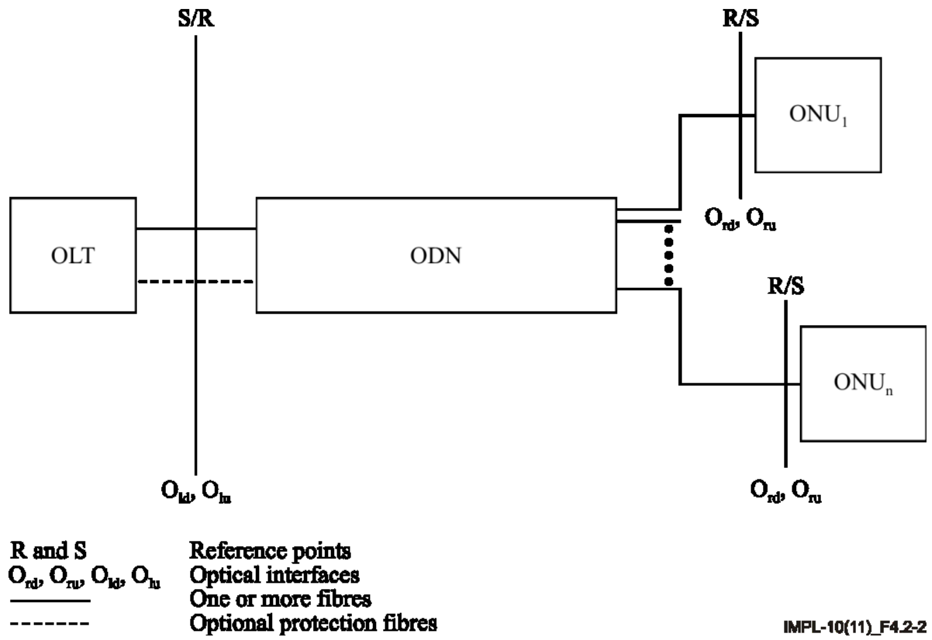


Figure 4.2-2 – Generic physical configuration of an ODN

The location of optical branching components (in central offices, outside plant or customer premises) is the most important item in terms of this network design and construction (see Chapter 2).

4.2.2 Passive optical components used in an ODN

The main passive optical components that constitute an Optical Distribution Network (ODN) are: optical fibres, optical cables, optical splices, optical connectors, optical branching components, etc.

4.2.2.1 Optical fibres

The general characteristics of the single-mode optical fibres, specified in the ITU-T G.65x series, are described in Chapter 1 of the *ITU-T Manual on Optical fibres, cables and systems*. Moreover Chapter 8 and 9 of that manual describe their possible applications.

From the above-quoted texts it clearly appears that the most frequently deployed optical fibres in ODNs are those specified in Recommendations ITU-T G.652 and ITU-T G.657.

The single-mode optical fibres specified in Recommendation ITU-T G.652 were the first single-mode fibres specified by ITU-T. These fibres were also the first to be widely deployed in the public network, and they represent the large majority of fibres that have been installed. Recommendation ITU-T G.652 can be considered the foundation of modern optical networks that are the basis of all modern telecommunications.

In contrast, Recommendation ITU-T G.657, which is the most recent ITU-T Recommendation for a specific type of optical fibres, has the purpose of providing specifications for a bending loss-insensitive, single-mode fibre for use only in access networks.

Experience with the installation and operation of single-mode fibre and cable based networks is extensive, and ITU-T G.652 fibre characteristics have been adapted to reflect this experience. Nevertheless, the specific use in an optical access network puts different demands on the fibre and cable. Due to the density of cables in the distribution and drop-cable network, to the limited space in this work area, and to the frequent activity in this part of the network, fibre and cable requirements have to be optimized for lower bending sensitivity compared to that of cabled fibre used in the transport network.

It is the aim of Recommendation ITU-T G.657 to support this bending optimization by recommending different attribute values and by recommending other classes of single-mode fibre. Recommendation ITU-T G.657 describes two categories (A and B) of single-mode optical fibre cable that are suitable for use in the access networks, including inside buildings at the end of these networks.

Category A fibres are suitable to be used in the O-, E-, S-, C- and L-band (i.e., throughout the 1260 to 1625 nm range). Fibres and requirements in this category are a subset of ITU-T G.652.D fibres and have the same transmission and interconnection properties. The main improvements are lower bending loss and tighter dimensional specifications, both for improved connectivity.

Category B fibres are suitable for transmission at 1310, 1550 and 1625 nm for restricted distances that are associated with in-building transport of signals. These fibres may have different splicing and connection properties than ITU-T G.652 fibres, but can be used at very low bend radii because of further improved bending loss.

The different suffix numbers of these categories have been chosen to refer more easily to the minimum specified bending radius of 10 mm, 7.5 mm or 5 mm, as shown in Figure 4.2-3.

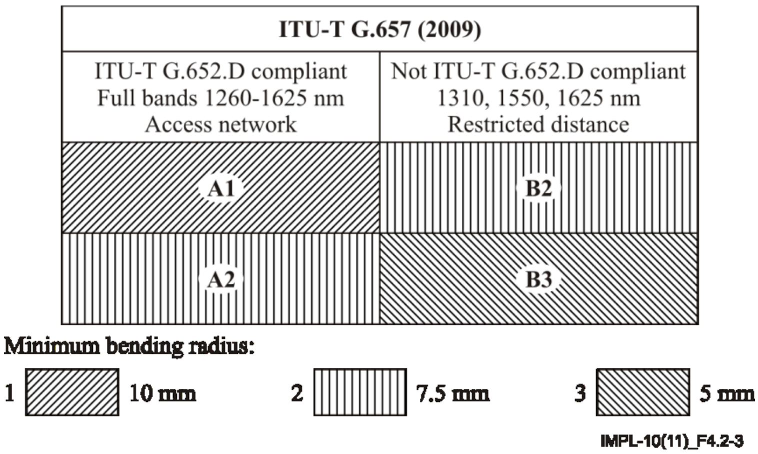


Figure 4.2-3 – Relationship between fibre sub-categories and bending radii

The improved macro-bending behaviour of ITU-T G.657 fibres for use in broadband optical access networks supports small volume fibre management systems and low-radius mounting in telecom offices and customer premises, including apartment buildings and single dwelling houses.

4.2.2.2 Optical fibre cables

Structure of the optical fibre cables

The optical fibre cables suitable for use in ODNs are described in Chapter 2 of the *ITU-T Manual on Optical fibres, cables and systems* and in greater detail in Recommendations ITU-T L.10, ITU-T L.26, ITU-T L.43 and ITU-T L.58.

In particular, an optical cable for specific multi-dwelling fibre-to-the-home (FTTH) indoor applications (riser cable) has been specified. With the on-going demand for FTTH, it is necessary to provide fibre(s) to the customer premises within different scenarios (residential, aerial, multi-dwelling units, etc.). Indoor cables can be used from the building entry and may be used for short runs within a house or long runs through a building. Since products are used in customer premises, they all offer some form of flame retardancy. This includes the use of a low-smoke, zero-halogen sheath, while the cable is constructed, so as to afford some degree of protection from flame propagation and smoke emission. The materials are characterized for halogen content and for susceptibility to corrosion.

Several riser cable designs have been developed and installed worldwide. Strength members, such as fibre-glass reinforced plastic material in the sheath, or peripheral strength-element aramid yarns, can be used to provide sufficient tensile strength to the cable, since the cable will be installed inside buildings, sometimes within fully-occupied ducts.

Some of the available designs are described as follows:

i. micro-module riser cable design, based on micro-modules containing optical fibres (Figure 4.2-4);

ii. individual fibre protected by buffer, stranded to form the optical core (Figure 4.2-5).

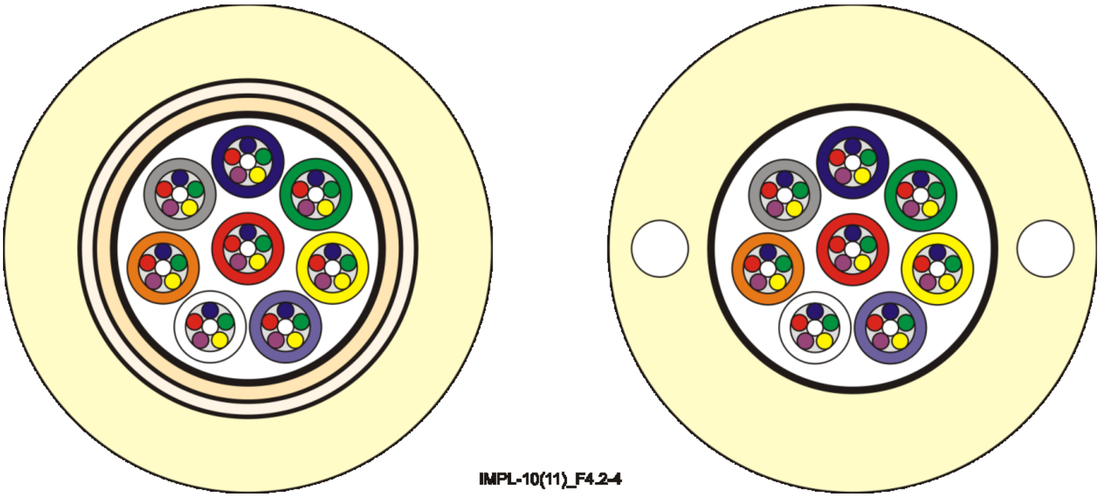


Figure 4.2-4 – Example of micro-module riser cable

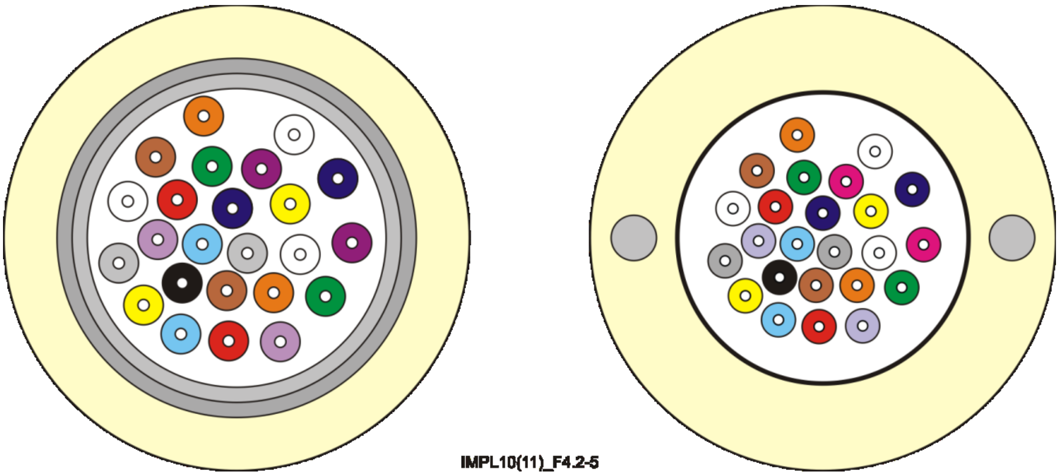


Figure 4.2-5 – Example of individual fibre buffer riser cable

Still remaining in a multi-dwelling environment, vertical access to buildings with several floors is required. In this vertical cabling, mid-span access allows one to extract a fibre or bundle of fibres on each floor, depending on the building configuration or on the number of customers to be connected. There are two types of mid-span access:

i. Full mid-span access: All fibres, or bundles of fibre, are extracted at each distribution point, by removing the entire riser sheath over a few tens of centimetres.

ii. Tapping access, or easy mid-span access: Extraction of necessary fibre(s) or bundle(s) of fibre is made at the distribution point, creating windows into the cable sheath with a dedicated tool, in order to access the cable core content. The other fibre(s) or fibre bundle(s) remain in the cable core, without the need for dedicated management at the distribution point.

Installation of optical cables

Each type of optical fibre cable has a specific strain limit and special care and arrangements may be needed to ensure successful installation without exceeding it. Damage caused by overloading during installation may not be immediately apparent, but can lead to failure later in its service life. Also, aspects related to bending during the installation may require special consideration. Chapter 3 of the *ITU-T Manual on Optical fibres, cables and systems* describes many types of cable installation (underground duct, trenchless, mini-trench, aerial, submarine, indoor, etc.).

As for the installation of indoor cables (within buildings) it is important to point out that various types of optical fibre cable construction can be used and it is important to ensure that the most appropriate type for each part of the indoor network is employed.

Moreover, it is to be outlined that where cables are routed along the floor, a short straight route is preferable, with cable passing through, rather than around, walls to avoid sharp bends. For under-floor installation, computer-type flooring is normally satisfactory. Non-ruggedized cable is best run in conduit, racks or trays, but care must be taken to ensure that turning points are properly constructed so that cable bending criteria can be satisfied. Where cable is fitted directly to walls, care must be taken to ensure proper cleats and straps are used and that they are not over-tightened. Much internal optical fibre cable installation is done by hand; therefore, the possibility of fibre overstrain during this handling should be borne in mind.

4.2.2.3 Optical fibre splices

(For further information, see Chapter 4 of the *ITU-T Manual on Optical fibres, cables and systems* and Recommendations ITU-T L.12 and ITU-T G.671).

Splices are critical points in the optical fibre network, as they strongly affect not only the quality of the links, but also their lifetime. In fact, the splice shall ensure high quality and stability of performance with time. High quality in splicing is usually defined as low splice loss and tensile strength near that of the fibre proof test level. Splices shall be stable over the design life of the system under its expected environmental conditions.

At present, two technologies, fusion and mechanical, can be used for splicing glass optical fibres and the choice between them depends upon the expected functional performance and considerations of installation and maintenance. These splices are designed to provide permanent connections.

A suitable procedure for splicing should be carefully followed in order to obtain reliable splices between optical fibres. This procedure applies both to single fibres or ribbons (mass splicing).

All optical fibre splices mentioned in Chapter 4 of the *ITU-T Manual on Optical fibres, cables and systems* should be suitable for indoor applications as well as for outdoor environments, when suitably protected in appropriate accessories.

4.2.2.4 Optical connectors

(For further information, see Chapter 4 of the *ITU-T Manual on Optical fibres, cables and systems* and Recommendations ITU-T L.36 and ITU-T G.671).

Fibre-optic connectors provide a method for jointing the ends of two optical fibres. Such a joint is not a permanent one, but it can be opened and closed several times. The optical connectors are required in the points of the network in which it is necessary to have flexibility in terms of network configuration and test access.

Fibre-optic connectors have applications in all types of network, at the input and output ports of the transmission systems, and are also used to connect test equipment and instrumentation.

The main effects of the introduction of a connector in an optical line are attenuation of the transmitted signal and reflection of part of the signal.

4.2.2.5 Optical branching components

(For further information, see Chapter 5 of the *ITU-T Manual on Optical fibres, cables and systems* and Recommendations ITU-T L.37 and ITU-T G.671).

An optical branching component (wavelength non-selective) is a passive component possessing three or more ports, which shares optical power among its ports in a predetermined fashion, without any amplification, switching or other active modulation. It is also called an "optical splitter" or an "optical coupler".

Optical branching components provide a method for splitting optical signals between M input and N output ports (Figure 4.2-6). Optical branching components are required when an optical signal has to be split into two or more fibre lines or when several signals coming from different fibre lines have to be mixed in a single fibre line; in general, optical branching components are dividers/combiners of transit signals. The insertion loss increases as the number of branches is increased.

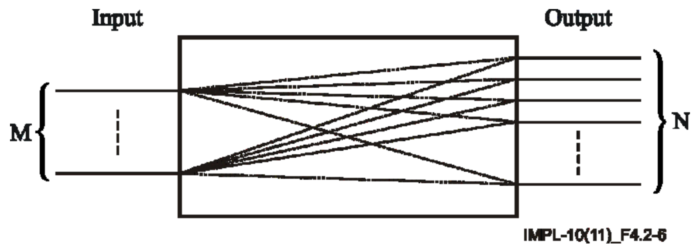


Figure 4.2-6 – Schematic of an M × N branching component

In passive optical networks (PON) with a point-to-multipoint distribution architecture (see Chapter 2), optical branching components are used to connect an OLT located at a central office to several ONUs located in outside plant or customer premises. The typical configuration of a branching component is “1” input port and “X” output ports, where X = 4, 8, 16, 32. Optical branching components for PONs are designed to be wavelength independent (i.e., insensitive to wavelength variations within both the second (1260-1360 nm) and third (1450-1600 nm) windows).

Optical branching components for PONs are characterized by several parameters, the most important of which are: insertion loss, reflectance, optical wavelength range, polarization-dependent loss, directivity and uniformity. Those characteristics are described in Chapter 5 of the *ITU-T Manual on Optical fibres, cables and systems* and in ITU-T G.671.

For the application of PON splitters in the optical access networks see Chapter 2 of this Technical paper.

The number of branches of the optical branching component should be selected once the following factors are properly taken into consideration: number of potential customers (including future demand), the maximum transmission distance, and the total optical loss. It is possible to respond to user demand in a flexible manner by increasing the number of branches. Such flexibility is, however, limited by the optical loss budget of the PON system used. Namely, the total loss of ODN (the loss of the fibre plus the loss of the optical branching component) must be no more than the optical loss budget supported between OLT and ONU.

Environmental conditions, namely, temperature, humidity and mechanical conditions, may affect performance. Such environmental conditions differ from region to region, especially when using an optical branching component in the ODN. The optical branching components should be designed and protected from the environmental conditions, such as temperature, vibrations, water, etc., to enable it to operate under such conditions, taking into account Recommendation ITU-T L.37.

Moreover, the optical branching component should be protected from adverse biological factors. For further information on this specific issue, see Recommendation ITU-T L.46.

4.2.2.6 Other passive optical components

Optical attenuators

An optical attenuator with either fixed or variable attenuation may be necessary to adjust optical power budgets to the required ranges. The characteristics of the optical attenuators are described in Chapter 5 of the *ITU-T Manual on Optical fibres, cables and systems* and in Recommendations ITU-T G.671 and ITU-T L.31.

Optical filters

An optical filter may be necessary to filter out the required wavelengths used for a particular service and to reject other services' wavelength bands or optical test wavelengths transported in the ODN. Such filters have properly formed spectral responses, in such a way that they can select very narrow or very broad wavelength regions depending on the target application. The optical filter performance should follow the specifications of Recommendation ITU-T G.671.

Passive optical nodes

Passive optical nodes properly store and protect all compatible passive devices, such as splices, branching devices and connectors, without altering their performance. Moreover, they contain, protect and manage the extra fibre length.

The general characteristics of the passive optical nodes are described in Chapter 5 of the *ITU-T Manual on Optical fibres, cables and systems* and in Recommendation ITU-T L.51.

Depending on the environment, they can be classified as:

- for indoor applications (optical distribution frame, ODF), as described in Chapter 5 of the *ITU-T Manual on Optical fibres, cables and systems* and in Recommendation ITU-T L.50.
- for outside plant (joint closures) in aerial and underground applications (described in Chapter 5 of the *ITU-T Manual on Optical fibres, cables and systems* and in Recommendation ITU-T L.13) or in street cabinets.

4.2.3 Passive node elements for fibre optical networks

(For further information, see Recommendation ITU-T L.51.)

The quality of an optical network is determined by the performance of each of its individual components. Nodes are key components of the physical network.

A “node” is defined as a point of intervention in the network; e.g., it occurs at each opening or end of a cable jacket. "Passive" applies to nodes that do not contain active electronics, or other devices that are exothermic. Examples of passive nodes are optical distribution frames, joint closures for underground and aerial applications, street cabinets, etc. Each node shall be capable of performing its expected function in the network, while exposed to the environment in which it is intended to reside.

4.2.3.1 Optical distribution frames

(For further information, see Recommendation ITU-T L.50.)

A passive optical node that resides in a central office environment, is generally contained in a rack or frame. This is commonly referred to as an optical distribution frame (ODF) or optical termination frame (OTF).

The term ODF refers to a frame including the fibre organizer and the means to store and guide pigtails and cables inside the frame. An ODF does not include the means for routing cables or pigtails outside the frame (also known as pigtail ducts or "raceway" systems).

The term frame refers to the mechanical structure to which cables are attached and that holds all other elements of the ODF. It may be a rack and shelf type of structure, similar to what is used to contain the electronics, as well as any other types of structure. Its main functions are mechanical support and a basic level of protection of its content.

4.2.3.2 Fibre closures and fibre organizers

(For further information, see Recommendation ITU-T L.13.)

Optical closures

As said above, a node occurs at each opening or end of a cable sheath. When an optical node resides in an outdoor environment, it is generally contained in a sealed enclosure. This is also commonly referred to as an optical closure, optical cable joint or optical sheath joint. Here the term "optical closure" will be used.

An optical closure comprises a mechanical structure (closure housing) that is attached to the ends of the sheaths joined, and a means (organizer) for containing and protecting the fibres and passive optical devices.

The term closure housing only refers to the sealed container or box, not including the organizer system. Its main functions are: sealing of the cables, mechanical attachment of the cable and protection of its content.

The optical closure will:

i) restore the integrity of the sheath, including mechanical continuity of strength members when required;

ii) protect the fibres, fibre joints and optical devices from the environment in all types of outdoor plant (aerial, direct buried, in ducts and under water);

iii) provide for the organization of the fibre joints, passive devices and the storage of fibre overlength;

iv) provide electrical bonding and grounding of the metal parts of the sheath and strength members where required.

Fibre organizers

Fibre organizers are an integral part of an optical closure. The organizers are comprised of one or more sheets or trays that have means for routing and holding fibre joints and fibre over-length in an orderly manner, and should minimize fibre strain.

Glossary

1:1 protection	a system of 1:1 protection configuration carries traffic in the working equipment while the protection equipment stands by without serving any traffic. The 1:1 protection configuration is a special case of the more general 1:N protection where the protection equipment is shared among N sets of working equipment.
1+1 protection	a system of 1+1 protection configuration carries identical traffic in both working and protection equipment.
10-Gigabit-capable passive optical network (XG-PON)	a PON system supporting nominal transmission rates on the order of 10 Gbit/s in at least one direction and implementing the suite of protocols specified in the ITU-T G.987.x-series of Recommendations.
Activation	a set of distributed procedures executed by the OLT and the ONUs that allows an inactive ONU to join or resume operations on the PON. The activation process includes three phases: parameter learning, serial number acquisition and ranging.
Adaptation function (AF)	additional equipment and/or function to change an ONT/ONU subscriber-side interface into the UNI. Functions of AF depend on the ONT/ONU subscriber-side interface and UNI interface. AF is also used to change an OLT network interface into the SNI interface that is required by an operator.
Adaptation unit (AU)	provides adaptation functions between the optical network unit (ONU) and the user side.
ADSL system overhead	all overhead needed for system control, including CRC, EOC, AOC synchronization bytes, fixed indicator bits for OAM, and FEC; that is, the difference between total data rate and net data rate.
Anomalies	a discrepancy between the actual and desired characteristics of an item. The desired characteristics may be expressed in the form of a specification. An anomaly may or may not affect the ability of an item to perform a required function.
AS0	data channel from the ATU-C to the ATU-R.
Assured bandwidth	bandwidth that is always available to the ONU/ONT if the T-CONT buffer is expected to have cells to transmit. If the T-CONT buffer does not have cells to transmit, this bandwidth may be used by other T-CONTs. Assured Bandwidth is therefore able to participate in DBA.
Attenuation	the total relative optical power loss of an optical signal propagating through the ODN. Attenuation is caused by absorption and scattering of light in the fibre (caused by fibre impurities and imperfections, fluctuations of the refractive index, material dispersion), as well as connectors, splices, splitters, wavelength couplers, attenuators, and other passive optical components.
Backchannel	the channel through which the VTU-R sends clipped error samples to the VCE. The backchannel may be implemented as part of the EOC or as part of the Ethernet data stream from the VTU-R to the VTU-O.
Backoff signal	a symbol sequence that active transmitters can transmit during the three Signal Slots which follow a collision.
Back-off time	the time a node waits before attempting a new transmission in a medium used by more than one transmitter.

Bandplan	a specific range of the frequency spectrum that is defined by a lower frequency and upper frequency.
Bandwidth allocation	an upstream transmission opportunity granted by the OLT for a specified time interval to a specified traffic-bearing entity within an ONU.
Beacon frame	a management frame which is transmitted periodically by the domain master. Beacon frames carry information to be distributed to all nodes of the domain, describing for all nodes of the domain the specifics of the domain operation, such as bandplan, domain name, domain ID, the security mode to be used, spectral compatibility requirements (frequency band and maximum transmit power, if applicable), mode of operation, and others.
Bearer channel	a user data stream of a specified data rate that is transported transparently by an ADSL system.
Best effort bandwidth	bandwidth that a T-CONT may be able to use if no higher-priority traffic consumes the bandwidth; there is no assurance or guarantee that the bandwidth will be available. Best effort bandwidth is able to participate in DBA.
Bidirectional protection	Upon detecting a failure of its working equipment, a system of bidirectional protection configuration requires acknowledgement from the far-end protection equipment before switching to the protection equipment.
Broadband passive optical network (BPON)	one-to-n broadband optical transmission systems. BPONs can transparently transport any type of data, for example voice, video, IP data, etc. BPON is able to carry data regardless of the type of data link frame (i.e. not only native ATM, but also HDL Ethernet frame, etc.).
Bridged taps	sections of un-terminated twisted-pair cables connected in parallel across the cable under consideration.
CENELEC band	frequency band between 3 kHz and 148.5 KHz allowed to be used for power line communications by Annex E. Four CENELEC bands are defined: A 3-95 kHz B 95-125 kHz C 125-140 kHz D 140-148.5 kHz
Centralized mode (CM)	a mode of domain operation in which all nodes use relayed communication (REL) with a single relay node. In centralized mode, only one relay node is allowed and it is known as the domain access point (DAP);
Channel	a connection conveying signals between two nodes. Channels may be unidirectional or bidirectional.
Churning	a function which can be applied to the downstream user data from an OLT to its ONUs. Churning provides the necessary function of data scrambling and offers a low level of protection for data confidentiality. It is installed at the TC layer of the ATM-PON system and can be activated for point-to-point downstream connections.
Coexistence	the capability that allows two or more non-interoperable systems to share the same medium, while minimizing mutual interference to each other.

Coexisting system	a power line communications system that belongs to one of the Coexisting System Categories and is using ISP to coexist with other non-interoperable systems.
Connection	an association of transmission channels or circuits, switching and other functional units set up to provide a means for a transfer of user, control and management information between two or more end points (blocks) in a telecommunication network.
Contention-free period	a media access period, allocated to a single network device, in which media access collisions should not (normally) occur.
Convergence layer	a protocol-specific sublayer that maps transport layer protocols into the native primitives of the link layer.
Data rate	the average number of data elements (bits, bytes, or frames) communicated (transmitted) in a unit of time. Depending on the data element, data bit rate, data byte rate, and symbol frame rate may be used. The usual unit of time for data rate is 1 second.
Data symbol rate	the net average rate (after allowing for the overhead of the synchronization symbol) at which symbols carrying user data are transmitted .
Data	all bits or bytes transported over the channel that individually convey information. Data includes both user data and overhead bits. Data does not include bits or bytes that, by themselves, do not convey any information, such as bits in a sync frame. See also "data frame" and "data symbol".
Defect	a limited interruption in the ability of an item to perform a required function. It may or may not lead to maintenance action depending on the results of additional analysis. Successive anomalies causing a decrease in the ability of an item to perform a required function are considered as a defect (see Figure 9-4).
Device ID	a unique identifier allocated to a device by the master after registration.
Differential fibre distance	the absolute difference between the fibre distances of two particular ONUs connected to the same OLT PON interface.
Diplex working	bidirectional communication using a different wavelength for each direction of transmission over a single fibre.
Dispersion	a physical phenomenon comprising the dependence of the phase or group velocity of a light wave in the medium on its propagation characteristics such as optical frequency (wavelength) or polarization mode.
Domain ID	a unique identifier of a domain.
Domain master (DM)	a node that manages (coordinates) all other nodes of the same domain. Domain master is a node with extended management capabilities that enables to form, control, and maintain the nodes associated with its domain.
Downstream	a traffic flow from OLT to ONT.
Dual latency	simultaneous transport of multiple data bearer channels in any one direction, in which user data is allocated to both the fast and interleaved paths.
Duplex working	bidirectional communication using the same wavelength for both directions of transmission over a single fibre.

Dynamic bandwidth assignment (DBA)	a process by which the OLT distributes upstream PON capacity between the traffic-bearing entities within ONUs, based on dynamic indication of their traffic activity and their configured traffic contracts.
Dynamic range	an optical receiver characteristic that represents the difference between the worst-case sensitivity (i.e., maximum over the operating conditions) and the worst-case overload (i.e., minimum over the operating conditions), and is usually expressed as a ratio of the former to the latter.
Electrical length	an estimate of the loop attenuation, assuming that all the sections of cable obey a √f attenuation characteristic. Specifically, the electrical length is the attenuation, in dB at 1 MHz, of an equivalent hypothetical loop with a perfect √f attenuation characteristic.
Embedded OAM	an operation and management channel between the OLT and the ONUs that utilizes the structured overhead fields of the downstream GTC frame and upstream GTC burst, and supports the time sensitive functions, including bandwidth allocation, key synchronization and DBA reporting.
Embedded operations channel	a component of ADSL system overhead which provides communications between management entities in the ATU-C and ATU-R. It includes both clear channel and stateful messaging modes.
Enhancement band	wavelength region allocated for new additional service capabilities, which include at least video services and DWDM (dense wavelength division multiplexing) services.
Equalization delay (EqD)	the requisite delay assigned by the OLT to an individual ONU in order to ensure that the ONU's transmissions are precisely aligned on a common OLT-based upstream frame reference. The ONU's equalization delay is assigned as a result of ranging and is subject to in-service updates in the course of burst arrival phase monitoring.
FCC band	frequency band between 9 kHz and 490 KHz allowed to be used for power line communications.
FEC output frame	a frame of data presented to the constellation encoder after Reed-Solomon encoding
Gigabit-capable passive optical network (G-PON)	a variant of the passive optical network (PON) access technology supporting transmission rates in excess of 1 Gbit/s and based on the ITU-T G.984-series of Recommendations.
Global master (GM)	a function that provides coordination between different domains of the same network (such as communication resources, priority setting, policies of domain masters, and interference mitigation). A GM may also convey management functions initiated by the remote management system. Detailed specification and use of this function is for further study.
G-PON encapsulation method (GEM)	a data frame transport scheme used in G-PON systems that is connection-oriented and that supports fragmentation of the user data frames into variable-sized transmission fragments.
G-PON transmission convergence (GTC) layer	a protocol layer of the G-PON protocol suite that is positioned between the physical media-dependent (PMD) layer and the G-PON clients. The GTC layer is composed of GTC framing sublayer and GTC adaptation sublayer.
Grant (data grant)	OLT controls each upstream transmission from ONUs by sending a permission. Grant is a permission to transmit an upstream cell of each ONU when an ONU receives own grant.

GTC adaptation sublayer	a sublayer of the G-PON transmission convergence layer that supports the functions of user data fragmentation and de-fragmentation, GEM encapsulation, GEM frame delineation and GEM Port-ID filtering.
GTC framing sublayer	a sublayer of the G-PON transmission convergence layer that supports the functions of GTC frame/burst encapsulation and delineation, embedded OAM processing and Alloc-ID filtering.
Home area network (HAN)	a network at customer premises that interconnects customer-owned devices for energy management and communications with the utility.
Impulse noise protection (INP)	the number of consecutive DMT symbols as seen at the δ-reference point, for which errors can be completely corrected by the Retransmission function, regardless of the number of errors within the errored DMT symbols.
Impulse protection against repetitive electrical impulse noise (INP_REIN)	the number of consecutive DMT symbols that are corrupted by REIN, as seen at the δ-reference point, for which errors can be completely corrected by the retransmission function, regardless of the number of errors within the errored DMT symbols.
Inter-domain bridge (IDB)	a bridging function to interconnect nodes of two different domains.
Interface	a point of demarcation between two blocks through which information flows from one block to the other. An interface may be a physical interface or a logical interface. See logical and physical-interface definitions for further details.
Inter-network bridge (INB)	a bridging function to interconnect nodes of two different networks.
Isolation function	a device which provides spectral isolation between the in-premises wiring and the access network, such as a filter, gateway etc.
Layer/sublayer	a collection of objects of the same hierarchical rank.
Logical (functional) interface	an interface in which the semantic, syntactic, and symbolic attributes of information flows are defined. Logical interfaces do not define the physical properties of signals used to represent the information. It is defined by a set of primitives.
Logical information flow path	a sequence of information transfers from an initial information source object to a terminal information destination object, either directly or through intermediate objects. Different physical information flow paths may be associated with a logical information flow path segment or with the entire path, in different implementations.
Logical reach	the logical reach is defined as the maximum length that can be achieved for a particular transmission system independent of optical budget.
LS0	data channel from the ATU-R to the ATU-C.
MAC cycle	the media access period between two consecutive transmissions of the MAP control frame.
MAP	a control frame describing the media access plan for the following MAC cycle.
Master	an HNT device that has master-capabilities and was selected as the current active master. The master is responsible for planning media access timing on the network and periodically advertising the media access plan to all devices on the network.
Master-controlled network	a network that contains a HNT device that is acting in the role of master.

Medium	a wire-line facility allowing physical connection between nodes. Nodes connected to the same medium may communicate on the physical layer, and may interfere with each other unless they use orthogonal signals (e.g., different frequency bands, different time periods).
Network termination (NT)	the element of the access network performing the connection between the infrastructures owned by the access network operator and the Service-Consumer System (ownership decoupling). The NT can be passive or active, transparent or not.
Network timing reference	an 8 kHz timing marker used to support the distribution of a timing reference over the network.
Next generation-access (NGA)	a possible new optical access system that coexists with G-PON on the same ODN.
Next generation-PON (NG-PON)	in the context of ITU-T standards development activity, a generic term referencing the PON system evolution beyond G-PON. The concept of NG-PON currently includes NG-PON1, where the ODN is maintained from B-PON and G-PON, and NG-PON2, where a redefinition of the ODN is allowed from that defined in B-PON and G-PON.
Node ID	a unique identifier allocated to a node within the domain.
Node	any network device that contains a transceiver.
ODN	an ODN provides the optical transmission means from the OLT towards the users, and vice versa. It utilizes passive optical components.
OLT	an OLT provides the network-side interface of the OAN, and is connected to one or more ODNs.
ONT management and control channel (OMCC)	the communications circuit connecting the control function of the OLT to that of the ONT. The protocol used for this is defined in ITU-T G.983.2.
ONT management and control interface (OMCI)	the interface between the OLT and an ONU defined in ITU-T G.983.2 that provides a uniform method for managing faults, configuration, performance, and security on ONTs.
Optical access network (OAN)	the set of access links sharing the same network-side interfaces and supported by optical access transmission systems. The OAN may include a number of ODNs connected to the same OLT.
Optical distribution network (ODN)	a point-to-multipoint optical fibre infrastructure. A *simple* ODN is entirely passive and is represented by a single-rooted point-to-multipoint tree of optical fibres with splitters, combiners, filters, and possibly other passive optical components. A *composite* ODN consists of two or more passive *segments* interconnected by active devices, each of the segments being either an optical trunk line segment or an optical distribution segment.
Optical distribution segment (ODS)	a simple ODN, that is, a point-to-multipoint optical fibre infrastructure that is entirely passive and is represented by a single-rooted tree of optical fibres with splitters, combiners, filters, and possibly other passive optical components.
Optical network termination (ONT)	an ONU used for FTTH and includes the user port function. The term "ONU" refers to both ONTs and ONUs. Any reference to ONUs includes ONTs.
Optical network unit (ONU)	an ONU provides (directly or remotely) the user-side interface of the OAN, and is connected to the ODN. The term "ONU" refers to both ONTs and ONUs. Any reference to ONUs includes ONTs.

Optical path penalty (OPP)	the apparent reduction of receiver sensitivity due to distortion of the signal waveform during its transmission over the optical path. The optical path penalty accounts for total degradations including the effects of reflections, intersymbol interference, mode partition noise, and laser chirp.
Optical return loss (ORL)	the total reflection at the source reference point of the optical signal propagation path associated with both discrete reflections at the refractive index discontinuities and distributed backscattering, such as Rayleigh scattering, along the path. Optical return loss is measured as a ratio of the transmitted power to the reflected power.
Optical trunk line (OTL)	a passive point-to-point segment of a composite ODN.
Passive optical network (PON)	a combination of network elements in an ODN-based optical access network that includes an OLT and multiple ONUs and implements a particular coordinated suite of physical medium dependent layer, transmission convergence layer, and management protocols.
Payload encoding	the baud and the constellation encoding (bits-per-symbol) of the payload bits.
Peer-to-peer communication	a type of communication within a domain in which direct signal traffic is established between nodes with no relay nodes.
Physical interface	an interface defined in terms of physical properties of the signals used to represent the information transfer. A physical interface is defined by signal parameters like power (power spectrum density), timing, and connector type.
Physical layer OAM (PLOAM)	an operation and management channel between the OLT and the ONUs that is close to real time and is based on a fixed set of messages.
Physical reach	the maximum physical distance that can be achieved for a particular transmission system.
Plesiochronous	a clocking scheme in which the SHDSL frame is based on the input transmit clock but the symbol clock is based on another independent clock source.
PNT frequencies	in this Technical paper, considered as being 4 MHz to 30 MHz.
Power cutback (PCB)	scalar-valued parameter controlling the difference (expressed in dB), between the nominal transmit PSD level and the reference transmit PSD level (REFPSD), in any one direction.
Primitives	basic measures of performance, usually obtained from digital signal line codes and frame formats, or as reported in overhead indicators from the far-end. Performance primitives are categorized as events, anomalies and defects. Primitives may also be basic measures of other quantities (e.g. ac or battery power), usually obtained from equipment indicators.
QoS class	in the context of ATM services, QoS refers to a set of performance parameters that constitute the traffic contract between the subscriber equipment and the network. Examples of these performance parameters include, cell loss ratio, cell transfer delay, and cell delay variation tolerance. The parameters are used to define distinct QoS classes.

QoS contract	a contract defining a set of negotiated QoS flow parameters between devices involved in a flow. A QoS contract is negotiated between devices at the endpoints of a flow in order to establish buffering and channel (BER/PER) constraints. A QoS contract is negotiated between flow source device and master in order to constrain bandwidth, latency and jitter requirements.
Quiet window	a time interval during which the OLT suppresses all bandwidth allocations to in-service ONUs in order to avoid collisions between their upstream transmissions and the transmissions from ONUs whose burst arrival time is uncertain. The OLT opens a quiet window to allow new ONUs to join the PON and to perform ranging of specific ONUs.
R/S	reference points at the interface of the ONU to the ODN.
R'/S'	reference points at the interface of the reach extender to the OTL.
Ranging grant	an allocation structure that is addressed to the default alloc-ID of the ONU and has the PLOAMu flag set.
Ranging	a procedure of measuring the logical distance between the OLT and any of its subtending ONUs with the objective to determine and assign the appropriate equalization delay, which is necessary to align the ONU's upstream transmissions on a common OLT-based upstream frame reference. Ranging is performed during ONU activation and may be performed while the ONU is in service.
Reference point	a set of interfaces between any two related blocks through which information flows from one block to the other. A reference point comprises one or more logical (non-physical) information-transfer interfaces, *and* one or more physical signal-transfer interfaces.
Reference transmit power spectral density level (REFPSD)	the nominal transmit PSD level, lowered by the power cutback (PCB), in any one direction.
Relay node	a node supporting relay functionality that acts as an intermediary node, through which other nodes of the same domain can pass their signal traffic (data, control, or management).
Relayed communication	a type of communication within a domain in which a node can communicate with other nodes through a relay node. The relay node receives a signal from a node and forwards it to the addressee nodes.
Repetitive electrical impulse noise (REIN)	a type of electrical noise encountered on digital subscriber lines. It is evident as a continuous and periodic stream of short impulse noise events. Individual REIN impulses commonly have duration less than 1 millisecond. REIN is commonly coupled from electrical power cables appliances drawing power from the AC electrical power network, having a repetition rate of twice the AC power frequency (100 or 120 Hz).
Quiet window	a time interval during which the OLT suppresses all bandwidth allocations to in-service ONUs in order to avoid collisions between their upstream transmissions and the transmissions from ONUs whose burst arrival time is uncertain. The OLT opens a quiet window to allow new ONUs to join the PON and to perform ranging of specific ONUs.
S/R	reference points at the interface of the OLT to the ODN.
S'/R'	reference points at the interface of a reach extender to ODN.
Scrambler	a device to randomize a data stream.
Self-NEXT	NEXT from other systems of the same type.

Service node (SN)	a network element that provides access to various switched and/or permanent telecommunication services.
Service node interface (SNI)	an interface which provides customer access to a service node.
Showtime	the state of either ATU-C or ATU-R – reached after all initialization and training is completed – in which user data is transmitted.
Simplex working	communication which uses a different fibre for each direction of transmission.
Single high impulse noise event (SHINE)	a type of electrical noise encountered on digital subscriber lines. SHINE generally arises as an aperiodic stream of impulses with effectively random inter-arrival time and impulse length both inversely related to intensity. Generally the term SHINE is associated with large impulses with duration in the range milliseconds to seconds.
Single latency	simultaneous transport of one or more bearer channels in any one direction, in which all user data is allocated to either the fast or the interleaved path.
Space division multiplexing	bidirectional multiplexing using different fibres for upstream and downstream signals.
Splitter	filter that separates the high frequency signals (ADSL) from the voiceband signals; (frequently called POTS splitter even though the voiceband signals may comprise more than POTS).
Synchronous	a clocking scheme in which the SHDSL frame and symbol clocks are based on the STU-C input transmit clock or a related network timing source.
Time division multiple access (TDMA)	transmission technique involving the multiplexing of many time slots onto the same time payload.
Time division multiplexing	multiplexing information onto fixed time ranges.
Total data rate	aggregate data rate plus FEC overhead.
Transmission container (T-CONT)	a traffic-bearing object within an ONU that represents a group of logical connections, is managed via the ONU management and control channel (OMCC), and, through its TC layer Alloc-ID, is treated as a single entity for the purpose of upstream bandwidth assignment on the PON.
Transmission opportunity (TXOP)	an interval of media time, with distinct start-time and length relative to the start of the MAP that can be used by an HNT device for the transmission of frames.
Transmit power back-off (PBO)	reduction of the transmitted PSD for spectral compatibility purposes, via PSD shaping using a predefined method that is dependent only on loop conditions and is independent of the service (bearer) requirements such as net data rates, INP, and delay.
Transmit power cut-back (PCB)	reduction of the transmitted PSD using the PSD ceiling mechanism. The PCB is dependent on the service (bearer) requirements, such as net data rates, INP, and delay, and on the desired SNR margin. The PCB also accommodates the dynamic range of the far-end receiver.
Unidirectional protection	a system of unidirectional protection configuration can switch to protection equipment once it detects failure in its working equipment.

Unified mode (UM)	a mode of domain operation in which all nodes within a domain communicate using P2P or REL, as necessary, while some of the relay nodes may have additional functionalities. Unified mode can be used to support hidden nodes. In unified mode, more than one relay node is allowed.
Upstream	the upstream is a traffic flow from ONT to OLT.
User-network interface (UNI)	the interface between the terminal equipment and a network termination at which interface the access protocols apply.
Vectored group	the set of lines over which transmission from the AN is eligible to be coordinated by pre-compensation (downstream vectoring), or over which reception at the AN is eligible to be coordinated by post-compensation (upstream vectoring), or both. Depending on the configuration of the vectored group, downstream vectoring, upstream vectoring, both or none may be enabled.
Vectoring	the coordinated transmission and/or coordinated reception of signals of multiple DSL transceivers using techniques to mitigate the adverse effects of crosstalk to improve performance.
Voiceband services	POTS and all data services that use the voiceband or some part of it.
Voiceband	0 to 4 kHz; expanded from the traditional 0.3 to 3.4 kHz to deal with voiceband data services wider than POTS.
Wavelength blocking filter (WBF)	an optical filter to prevent an optical receiver from receiving unwanted optical signals with different wavelengths.
Wavelength division multiplexing	bidirectional multiplexing using different optical wavelength for upstream and downstream signals.
WF1 filter	WDM and/or optical combining/splitting functions, which separate/combine wavelength and/or split/combine optical power for ATM-PON transport service and additional services. It is located between ODN and the OLT.
WF2 filter	WDM and/or optical combining/splitting functions, which separate/combine wavelength and/or split/combine optical power for ATM-PON transport service and additional services. It is located between ODN and the ONU.
X:N protection architecture	a system of X:N protection architecture offers X protection PONs for N working PONs, where some or all of the protected ONUs on the working PONs can be connected to any of the X protection PONs.
XG-PON encapsulation method (XGEM)	a data frame transport scheme used in XG-PON systems that is connection-oriented and that supports fragmentation of user data frames into variable sized transmission fragments.
XG-PON transmission convergence (XGTC) layer	a protocol layer of the XG-PON protocol suite that is positioned between the physical media-dependent (PMD) layer and the XG-PON clients. The XGTC layer is composed of the XGTC service adaptation sublayer, the XGTC framing sublayer, and the XGTC PHY adaptation sublayer.
XG-PON1	a variant of XG-PON system that operates at a nominal line rate of 10 Gbit/s downstream and 2.5 Gbit/s upstream.
XG-PON2	a variant of XG-PON system that operates at a nominal line rate of 10 Gbit/s downstream and upstream.
XGTC framing sublayer	a sublayer of the XG-PON transmission convergence layer that supports the functions of XGTC frame/burst encapsulation and delineation, embedded OAM processing, and Alloc-ID filtering.

XGTC PHY adaptation sublayer	a sublayer of the XG-PON transmission convergence layer that supports the functions of physical synchronization and delineation, forward error correction (FEC), and scrambling.
XGTC service adaptation sublayer	a sublayer of the XG-PON transmission convergence layer that supports the functions of SDU (user data and OMCI traffic) fragmentation and reassembly, XGEM encapsulation, XGEM frame delineation, and XGEM port-ID filtering.

List of the acronyms

AAL	ATM Adaptation Layer
ACS	Auto-Configuration Server
ADP	Application Data Primitive
ADSL	Asymmetric Digital Subscriber Line
AE	Application Entity
AES	Advanced Encryption Standard
AGAF	Access Gateway Application layer Function
AGC	Automatic Gain Control
AGTF	Access Gateway Transport layer Function
AGW	Access Gateway
AK	Acknowledgement
AKM	Authentication and Key Management
ALDF	Application Layer Device Function
AN	Access Node
AN	Access Network
ANI	Access Node Interface
ANT	Access Network Transport
AOC	ADSL Overhead Control channel
AP	Access Point
APC	Application Protocol Convergence
APD	Avalanche Photo Diode
A-PON	ATM over PON
APS	Automatic Protection Switching
AR	Acknowledge Request
ARF	Address Resolution Function
ARIB	Association of Radio Industries and Businesses
ARQ	Automatic Repeat reQuest
ASG	Application Service Gateway
ATC	ATM Transfer Capability
ATM	Asynchronous Transfer Mode
ATM-TC	Asynchronous Transfer Mode – Transmission Conversion
ATU-C	ADSL Transceiver Unit - Central office
ATU-R	ADSL Transceiver Unit - Remote terminal end
AVCs	Attribute Value Changes
BBCoC	BroadBand Communication equipment Code of Conduct on energy consumption
BC	Back-off Counter
BER	Bit Error Ratio
BIP	Bit-Interleaved Parity
BM	Burst Mode

BT	Bridged Tap
BWmap	BandWidth map
CA	Collision Avoidance
CAP	Carrierless Amplitude/Phase Modulation
CATV	Community Antenna TeleVision
CB	Coaxial Bandplan
CBS	Committed Burst Size
CCM	Counter with CBC-MAC
CCP	Cross Connect Point
CE	Cyclic Extension
CES	Channel Estimation Symbols
CFTXOP	Contention-Free TXOP
CIR	Committed Information Rate
CIR/PIR	Committed Information Rate / Peak Information Rate
CM	Continuous Mode
CM	Centralized Mode
CMAC	Cipher-based Message Authentication Code
CO	Central Office
CO-MIB	Central Office - Management Information Base
CP	Cyclic Prefix
CP	Customer Premises
CPCS-PDU	Common Part Convergence Sublayer - Protocol Data Unit
CPCS-UU	Common Part Convergence Sublayer – User-to-User
CPE	Customer Premises Equipment
CPI	Common Part Indicator
CRC	Cyclic Redundancy Check
CRF	Coaxial Radio Frequency bandplan
CRS	Carrier Sense
CS	Cyclic Suffix
CSA	Capabilities and Status Announcements
CSACF	CSA Control Frame
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CTRL	ConTRoL
CTXOP	Contention TXOP
CW	Contention Window
CWMP	CPE WAN Management Protocol
DA	Ethernet Destination Address
DAC	Digital-to-Analogue Convertor
DAP	Domain Access Point
DBA	Dynamic Bandwidth Assignment

DBRu	Dynamic Bandwidth Report
DELT	Dual-Ended Line Testing
DFB	Distributed FeedBack
DHCP	Dynamic Host Configuration Protocol
DID	Destination IDentification
Diffserv	Differentiated services
DLL	Data-Link Layer
DMT	Discrete Multitone
DOCSIS	Data Over Cable Service Interface Specification
DPBO	Downstream transmit Power Back-Off
DRR	Deficit Round Robin
DS1	DownStream band 1
DSL	Digital Subscriber Line
DSLAM	DSL Access Multiplexer
DTU	Data Transfer Unit
DWDM	Dense Wavelength Division Multiplexing
EC	Echo Canceller
ECH	Echo Cancellation Hybrid
EDR	Extended Differential Reach
EIA	OAM interface adapter
EMC	ElectroMagnetic Compatibility
EOC	Embedded Operations Channel
EOF	End-Of-Frame
EUT	End User Terminal
FCS	Frame Check Sequence
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FER	Frame Error Rates
FEXT	Far-End Crosstalk
FMC	Fixed Mobile Convergence
FPD	Functional Processing Device
FT	Frame Type
FTTB	Fibre-To-The-Building
FTTC	Fibre-To-The-Curb
FTTCab	Fibre-To-The-Cabinet
FTTCell	Fibre-To-The-Cell site base stations
FTTEx	Fibre-To-The-Exchange
FTTH	Fibre-To-The-Home
FTTN	Fibre-To-The-Node
FTTO	Fibre-To-The-Office

GEM	G-PON Encapsulation Method
GE-PON	Gigabit Ethernet Passive Optical Network
GM	Global Master
GPON	Gigabit-capable Passive Optical Networks
GTC	G-PON Transmission Convergence
HC	Home Client
HD	Home Decoder
HDSL	High bit rate Digital Subscriber Line
HDTV	High Definition Television
HEC	Header Error Control
HN	Home Network
HNT	Home Network Transceiver
IAT	Inter-Arrival Time
IB	Indicator Bit
ICMP	Internet Control Message Protocol
ICT	Information and Communications Technologies
IDB	Inter-Domain Bridges
IDFT	Inverse Discrete Fourier Transform
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IF	Isolation Function
IFG	Inter-Frame Gap
IMA	Inverse Multiplexing over ATM
INB	Inter-Network Bridges
INCL	Impulse Noise Cluster Length
INM	Impulse Noise Monitoring
INP	Impulse Noise Protection
INS	Impulse Noise Sensor
IP	Internet Protocol
IPCP	Internet Protocol Control Protocol
IPTV	Internet Protocol TeleVision
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
ISDN	Integrated Services Digital Network
ISDN-BA	ISDN - Basic Access
ISI	Inter-Symbol Interference
ISP	Inter-System Protocol
L2TP	Layer Two Tunnelling Protocol
LAN	Local Area Network
LANT	Local Area Network - side Termination
LARQ	Limited Automatic Repeat reQuest

LCDU	Link Control Data Unit
LICF	Link Integrity Control Frame
LLC	Link Layer Control
LLCFT	LLC Frame Type
LLDP	Link Layer Discovery Protocol
LOS	Loss-Of-Signal
LPDU	LLC Protocol Data Unit
LPH	LPDU Header
LPM	Limit PSD Mask
LPR	Loss-of-PoweR
LT	Line Termination
LTE	Long Term Evolution
LTU	Line Termination Unit
MA	Medium Access
MAC	Media Access Control
MAP	Media Access Plan
MDF	Main Distribution Frame
MDI	Medium-Dependent Interface
MDU	Multi Dwelling Unit
ME	Management Entity
MELT	MEtallic Line Testing
MIB	Management Information Base
MIC	Message Integrity Check
MII	Media-Independent Interface
MPDU	MAC Protocol Data Unit
MPLS	MultiProtocol Label Switching
MPS-TC	Management Protocol Specific TC
MSK	Master Session Key
MSO	Multi-Service Operator
MT	Message Type
MTBF	Mean Time Between Failures
MTU	Multi-Tenant Unit
NACK	Negative ACKnowledgment
NAT/NAPT	Network Address Translation / Network Address/Port Translation
NB-PLC	Narrowband Power Line Communications
NDR	Net Data Rate
NEXT	Near-end Crosstalk
NGA	Next generation-Access
NG-PON	Next Generation-PON
NID	Network Interface Device
NIST	National Institute of Standards and Technology

NMS	Network Management System
NRZ	Non-Return to Zero
NRZI	NRZ Inverted
NSP	Network Service Provider
NT	Network Termination
NTR	Network Timing Reference
NTU	Network Termination Unit
OAM	Operation, Administration and Maintenance
OAN	Optical Access Network
OCES	Offset CES symbols
ODN	Optical Distribution Network
ODS	Optical Distribution Segment
OEO	Optical / Electrical / Optical
OFDM	Orthogonal Frequency Division Multiplexing
OLR	On-Line Reconfiguration
OMCC	ONU Management Control Channel
OMCI	ONU management and control interface
ONT	Optical Network Terminal (equivalent to ONU)
ONU	Optical Network Unit (equivalent to ONT)
OTDR	Optical Time Domain Reflectometer
OTL	Optical Trunk Line
PAD	PADding bits
PB	Power-line Bandplan
PCB	Physical Control Block
PCS	Physical Coding Sub-layer
PDU	Protocol Data Unit
PE	Payload Encoding
PFH	PHY Frame Header
PHY	PHYsical layer
PIN	“P” type “I” intrinsic “N” type photo diode
PLC	Power Line Communication
PLOAM	Physical Layer Operations, Administration and Maintenance
PM	Peer-to-peer Mode
PMA	Physical Medium Attachment
PMD	Physical Medium Dependent
PMS-TC	Physical Media Specific - Transmission Convergence
PNT	Phoneline Networking Transceivers
PON	Passive Optical Network
Port-ID	Port IDentifier
POTS	Plain Old Telephone Service
PPP	Point-to-Point Protocol

PRBS	Pseudo-Random Binary Sequence
PRIME	PoweRline Intelligent Metering Evolution
PS	POTS Splitter
PSB	Physical Synchronization Block
PSD	Power Spectral Density
PSDC	PSD Ceiling
PSM	PSD Shaping Mask
PST	PON Section Trace
PSTN	Public Switched Telephone Network
PSync	Physical Synchronization sequence
PTM	Packet Transfer Mode
PtP or P2P	Point-to-Point
QAM	Quadrature Amplitude Modulation
QLN	Quiet Line Noise
QoS	Quality of Service
R/S	Receive / Send (interfaces)
RE	Reach Extender
REG	REGenerator
REIN	Repetitive Electrical Impulse Noise
RF	Radio Frequency
RFI	Radio-Frequency Interference
RG	Residential Gateway
RMS	Remote Management Server
ROC	Robust Overhead Channel
RPM	Regional PSD Mask
RRC	Retransmission Request Channel
RRCF	Rate Request Control Frames
RS	Reconciliation Sub-layer
R-S	Reed-Solomon
RSVP	Resource reSerVation Protocol
RT	Remote Terminal
S/R	Send / Receive (interfaces)
SA	Ethernet Source Address
SBU	Small Business Unit
SC	Security Controller
SDH	Synchronous Digital Hierarchy
SDO	Standards Development Organization
SDP	Subscriber Distribution Point
SDSL	Symmetric DSL
SDU	Service Data Unit
SELT	Single-Ended Line Testing

SFC	Superframe Counter
SFD	Start Frame Delimiter
SFU	Single Family Unit
SHDSL	Symmetric High Bit Rate Digital Subscriber Line
SHINE	Single High Impulse Noise Event
SID	Sequence Identifier
SID	Source Identification
SLAAC	Stateless Address Auto-Configuration
SM	Sub-carrier Mask
SN	Serial Number
SNI	Service Node Interface
SNMP	Simple Network Management Protocol
SNR	Signal-to-Noise Ratio
SOC	Special Operations Channel
SP	Strict Priority
SRA	Seamless Rate Adaptation
SSC	Supported Sub-Carriers
STB	Set Top Box
STM	Synchronous Transport Modules
STU	SHDSL Transceiver Unit
STU-C	STU at the Central office, or exchange end
STU-R	STU at the Remote end
STXOP	Shared Transmission Opportunity
TB	Telephone-line Bandplan
TC	Transmission Convergence
TCA	Threshold Crossing Alert
TCI	Transaction Correlation Identifier
TCM-ISDN	Time Compression Multiplexing – ISDN
T-CONT	Transmission CONTainer
TCP	Transmission Control Protocol
TC-PAM	Trellis Coded Pulse Amplitude Modulation
TDIM	Time-Division Inverse Multiplexing
TDM	Time Domain Multiplexing
TDMA	Time Division Multiple Access
TEQ	Time-domain EQualizer
TOS	Type Of Service
TPS-TC	Transport Protocol Specific Transmission Convergence
TS	TimeStamp
TS	Time Slot
TTR	TCM-ISDN Timing Reference
TWP	Twisted Wire Pair

TXOP	Transmission OPportunity
TXOP	Transmission OPportunities
TxPSD	Transmit PSD mask
UM	Unified Mode
UNI	User Network Interface
UPBO	Upstream Power Back-off
UPnP	Universal Plug and Play
US1	UpStream band 1
UTP	Unshielded Twisted Pair
UTXOP	Unallocated TXOP
VBR	Variable Bit-Rate
VC	Virtual Channel
VCE	Vectoring Control Entity
VDSL	Very high speed DSL
VLAN	Virtual Local Area Network
VME	VDSL2 Management Entity
VoIP	Voice over Internet Protocol
VP	Virtual Path
VTU-O	VDSL Terminal Unit at the ONU
VTU-R	VDSL Terminal Unit at the Remote site
WAN	Wide Area Network
WANT	Wide Area Network - side Termination
WBF	Wavelength Blocking Filter
WC	Wavelength Conversion
WDM	Wavelength Division Multiplexing
WFQ	Weighted Fair Queuing
WRR	Weighted Round Robin
X/S	Interference signal(s) / Optical power of the basic band signal
XGEM	XG-PON Encapsulation Method
XG-PON	XG-Gigabit-capable Passive Optical Network
XGTC	XG-PON Transmission Convergence

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