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

**Guide on the use of the ITU-T
Recommendations related to optical fibres
and systems technology**

ITU-T G-series Recommendations – Supplement 42



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Supplement 42 to ITU-T G-series Recommendations

Guide on the use of the ITU-T Recommendations related to optical fibres and systems technology

Summary

Supplement 42 to ITU-T G-series Recommendations contains a functional grouping of the ITU-T Recommendations on optical fibres and systems technology (e.g., optical fibres and cables, physical optical interfaces, optical fibre submarine cable systems).

An introduction to each category with more than one Recommendation outlines the subjects which are common to the category.

For each Recommendation, there is a short description of the purpose, content and, in many cases, the evolution of the content in the subsequent versions. There are also cross-references to the other Recommendations dealing with related issues.

The main purpose of this guide is to give to developing countries an improved capability in the application of standards, while the telecommunication industry, particularly manufacturers and operators, could benefit from the greater involvement of developing countries in the making and application of standards.

The guide could also have a wider use among manufacturers and operators who are not directly involved in the preparation of this group of Recommendations and they could find the guide to be a useful tool both for rapidly focusing on the Recommendation(s) of specific interest and for better understanding the meaning and the objectives of each Recommendation.

History

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FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications, information and communication technologies (ICTs). The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this publication, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

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Supplement 42 to ITU-T G-series Recommendations

Guide on the use of the ITU-T Recommendations related to optical fibres and systems technology

1 Scope

WTSA-04 Resolution 44 (*Bridging the standardization gap between developing and developed countries*) requires the preparation of guiding documents to assist in the implementation of ITU-T Recommendations that could be used by developing countries in preparing national specific requirements for deploying new networks and services.

In this way, developing countries could benefit from an improved capability in the application of standards, while the telecommunication industry, particularly manufacturers and operators, could benefit from the greater involvement of developing countries in the making and application of standards.

The main objective of this "Guide on the use of the ITU-T Recommendations related to optical fibres and systems technology" is to fulfil these requirements from the WTSA.

However, the guide could also have a wider use among manufacturers and operators who are not directly involved in the preparation of this group of Recommendations and they could find the guide to be a useful tool both for rapidly focusing on the Recommendation(s) of specific interest and for better understanding the meaning and the objectives of each Recommendation.

Recommendations related to the construction of optical cables, to the installation techniques (duct, tunnel, aerial, buried, mini-trench, micro-trench, etc.) and the associated hardware (closures, connectors, cabinets, poles, etc.) are outside the scope of this Guide because they are dealt with in [ITU-T L-Guide].

2 References

- [ITU-T G.707] Recommendation ITU-T G.707/Y.1322 (2007), *Network node interface for the synchronous digital hierarchy (SDH)*.
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- [Agrawal] Agrawal, G.P. (2002), *Fiber-optic Communication Systems*, 3rd Edition, John Wiley & Sons Inc.

3 Definitions

3.1 Terms defined elsewhere

All the terms used in this supplement are defined in the described Recommendations.

3.2 Terms defined in this Supplement

There are no new terms defined in this Supplement.

4 Abbreviations and acronyms

This Supplement uses the following abbreviations and acronyms:

AON	All Optical Network
APD	Avalanche Photodiode
ASE	Amplified Spontaneous Emission
ATM	Alternative Test Method
BER	Bit Error Ratio
CWDM	Coarse Wavelength Division Multiplexing
DC	Dispersion Compensation
DGD	Differential Group Delay
DWDM	Dense Wavelength Division Multiplexing
FEC	Forward Error Correction
FSO	Free Space Optical
IaDI	Intra-Domain Interface
IrDI	Inter-Domain Interface
MFD	Mode Field Diameter
NRZ	Non-Return to Zero
OA	Optical Amplifier

OADM	Optical Add-Drop Multiplexer
OEO	Optical-to-Electrical-to-Optical
ONE	Optical Network Element
OSNR	Optical Signal-to-Noise Ratio
OTN	Optical Transport Network
OTUk	Completely standardized optical channel transport unit – k
PDH	Plesiochronous Digital Hierarchy
PDL	Polarization Dependent Loss
PMD	Polarization Mode Dispersion
PXC	Photonic Cross-Connect
RTM	Reference Test Method
SDH	Synchronous Digital Hierarchy
SLM	Single-Longitudinal Mode
STM	Synchronous Transport Module
TTE	Terminal Transmission Equipment
WDM	Wavelength Division Multiplexing

5 Evolution of optical technology and of the related ITU-T Recommendations

The invention of the laser and its demonstration is dated 1960. It was suggested in 1966 that optical fibres might be the best choice for using laser light for optical communications, as they are capable of guiding the light in a manner similar to the guiding of electrons in copper wires. The main problem was the high losses of optical fibres: fibres available during the 1960s had losses in excess of 1,000 dB/km. A breakthrough occurred in 1970 when the losses could be reduced to below 20 dB/km in the wavelength region near 1,000 nm. At about the same time, GaAs semiconductor lasers, operating continuously at room temperature, were demonstrated. The simultaneous availability of compact sources and of low-loss optical fibres led to a worldwide effort for developing optical fibre communication systems.

The real research phase of fibre-optic communication systems started around 1975. The enormous progress realized over the 35-year period extending from 1975 can be grouped in several distinct phases. Over this time period the BL product (B is the bit rate and L is the repeater spacing, where the repeaters perform optical-to-electrical-to-optical conversion) doubled every year. In every phase, BL increased initially but began to saturate as the technology matured. Each new phase brought a fundamental change.

5.1 The first phase

The first phase of lightwave systems operated near 850 nm and used GaAs semiconductor lasers with multimode fibres. After several field trials during the period 1977-79, such systems became available commercially in 1980. They operated at a bit rate of 34-45 Mbit/s and allowed repeater spacings of up to 10 km. The larger repeater spacing compared with 1-km spacing of coaxial systems was an important motivation for system designers because it decreased the installation and maintenance costs associated with each repeater.

This phase of lightwave systems was specified in two ITU-T Recommendations. The first one is Recommendation ITU-T G.651, where the characteristics of a multimode optical fibre operating at 850 nm are specified. The second one is Recommendation ITU-T G.956 (now

Recommendation ITU-T G.955) where are specified the characteristics of the optical systems operating at 850 nm and suitable for the bit rates of the plesiochronous digital hierarchy (PDH).

5.2 The second phase

It was clear during the 1970s that the repeater spacing could be increased considerably by operating the lightwave systems in the wavelength region near 1300 nm, where fibre loss is below 1 dB/km. Furthermore, optical fibres exhibit minimum dispersion in this wavelength region. This realization led to a worldwide effort for the development of InGaAsP semiconductor lasers and detectors operating near 1300 nm.

The second phase of fibre-optic communication systems, based on InGaAsP semiconductor lasers and detectors operating near 1300 nm became available in the early 1980s, but the bit rate of early systems was limited to below 100 Mbit/s because of dispersion in multimode fibres. This limitation was overcome by the use of single-mode fibres. A laboratory experiment in 1981 demonstrated transmission of 2 Gbit/s over 44 km of single-mode fibre. The introduction of commercial systems followed. By 1988, second-generation lightwave systems, operating at bit rates of up to 1.7 Gbit/s with a repeater spacing of about 50 km, were commercially available.

This second phase of lightwave systems was also specified in some ITU-T Recommendations. In particular, Recommendation ITU-T G.652 specifies the characteristics of a single-mode optical fibre operating at 1300 nm. Recommendation ITU-T G.957 specifies the characteristics of optical systems operating at 1300 nm and suitable for transmitting the bit rates of the synchronous digital hierarchy (SDH) up to STM-16 (2.5 Gbit/s). Moreover, the text of Recommendation ITU-T G.956 (now Recommendation ITU-T G.955) was extended to include also PDH systems operating at 1300 nm.

5.3 The third phase

The repeater spacing of the second phase lightwave systems was limited by the fibre losses at the operating wavelength of 1300 nm (typically 0.5 dB/km). Losses of silica fibres become minimal near 1550 nm. Indeed, a 0.2 dB/km loss was realized in 1979 in this spectral region.

However, the introduction of third phase lightwave systems operating at 1550 nm over single-mode fibres was considerably delayed by the large fibre dispersion near 1550 nm. Conventional InGaAsP semiconductor lasers could not be used because of pulse spreading occurring as a result of simultaneous oscillation of several longitudinal modes. The dispersion problem can be overcome either by using dispersion-shifted fibres designed to have minimum dispersion near 1550 nm or by limiting the laser spectrum to a single longitudinal mode. Both approaches were followed during the 1980s. By 1985, laboratory experiments indicated the possibility of transmitting information at bit rates of up to 4 Gbit/s over distances in excess of 100 km. Third generation lightwave systems operating at 2.5 Gbit/s became available commercially in 1992. Such systems were capable of operating at a bit rate of up to 10 Gbit/s. The best performance being achieved using dispersion-shifted fibres in combination with lasers oscillating in a single longitudinal mode.

Also, this phase of lightwave systems was specified in some ITU-T Recommendations. Recommendation ITU-T G.653 specifies the characteristics of a dispersion-shifted single-mode optical fibre. Recommendations ITU-T G.652, ITU-T G.955 (ex-ITU-T G.956) and ITU-T G.957 were revised/extended in order to include optical systems operating at 1550 nm. Recommendation ITU-T G.974 specified the characteristics of the optical systems to be used for the submarine applications.

5.4 The fourth phase

A drawback of third phase 1550 nm systems is that the signal must be regenerated periodically by using electronic repeaters spaced apart typically by 70-80 km. This situation changed with the advent of fibre amplifiers in 1989.

The fourth phase of lightwave systems makes use of optical amplification for increasing the repeater spacing and of wavelength division multiplexing (WDM) for increasing the aggregate bit rate. The advent of the WDM technique started a revolution that resulted in doubling the system capacity every 6 months. In most WDM systems, fibre losses are compensated periodically using erbium-doped fibre amplifiers typically spaced 70-80 km apart. Such amplifiers were developed after 1985 and became available commercially by 1990. A 1991 experiment showed the possibility of data transmission over 21,000 km at 2.5 Gbit/s and over 14,300 km at 5 Gbit/s, using a recirculating-loop configuration. This performance indicated that an amplifier-based, all-optical, submarine transmission system was feasible for intercontinental communication. By 1996, not only transmission over 11,600 km at a bit rate of 5 Gbit/s had been demonstrated by using actual submarine cables, but commercial transatlantic and transpacific cable systems also became available. Since then, a large number of submarine lightwave systems have been deployed worldwide.

In order to specify the characteristics of optical fibres and systems operating with optical amplifiers and the WDM technique, many new Recommendations were developed in ITU-T. Recommendation ITU-T G.655 specifies a non-zero dispersion-shifted single-mode optical fibre. Recommendations ITU-T G.694.1 and ITU-T G.694.2 specify the spectral grids for DWDM and CWDM applications. Some Recommendations specify the characteristics of optical systems devoted to particular DWDM applications: Recommendation ITU-T G.959.1 (inter-domain applications without line OA), Recommendation ITU-T G.698.1 (metro access applications without line OA), Recommendation ITU-T G.698.2 (metro core/regional applications with line OA), Recommendation ITU-T G.696.1 (backbone applications with line OA), Recommendation ITU-T G.973 (submarine applications without line OA), Recommendation ITU-T G.977 (submarine applications with line OA). Recommendation ITU-T G.695 specifies CWDM systems for access/metro access applications.

5.5 The fifth phase

In the current development of lightwave systems, which we can consider as the fifth phase, there are several directions of evolution.

The first one is towards increasing the capacity transmitted on an optical fibre:

- i) by transmitting more and more channels through the WDM technique in the C-band (1530-1565 nm), by reducing the channel spacing. Commercial terrestrial systems with the capacity of 1.6 Tbit/s (160 optical channels at 10 Gbit/s) are now available with a channel spacing of 25 GHz;
- ii) by deploying the optical channels not only in the C-band, but also in the short wavelength S-band (1460-1530 nm) and in the long wavelength L-band (1565-1625 nm). The Raman amplification technique could be used for signals in all three wavelength bands. Moreover, a new type of fibre, known as the dry or low water peak fibre has been developed with the property that fibre losses are small over the entire wavelength region extending from 1.3 to 1.65 μm . Availability of such fibres and new amplification schemes may lead to lightwave systems with a larger number of WDM channels on a single optical fibre;
- iii) by increasing the bit rate of each channel within the WDM signal. Starting in 2000, many experiments used channels operating at 40 Gbit/s. Moreover, starting from 2006, some experiments demonstrated the feasibility of systems operating up to 110-130 Gbit/s per channel. Most of these new systems require an extremely careful management of their dispersion and new techniques to deal with polarization time variant effects (1st and 2nd order PMD, PDL, etc.).

The second direction of evolution is the reduction of the number of expensive optical/electrical/optical (OEO) conversions within the optical transport networks (OTN). The two main reasons for the reduction in the number of OEO conversions are that DWDM systems are

becoming capable of carrying light signals for thousands of kilometres without electrical regeneration and that photonic cross-connect (PXC) and optical add-drop multiplexers (OADMs) are becoming available with the capacity, space requirements, power consumption, reliability and cost, suitable for their use in the telecommunication networks. With this evolution it is possible to foresee that all optical networks (AONs) could extend to all potential routes of the backbone network of a medium size country with optical paths up to around 2,000 km.

The third direction (an alternative to the second one) is the implementation of multiple OEO regenerators at a cost comparable to that of an optical amplifier. This is today a realistic objective thanks to recent advances in photonic integrated circuits and silicon photonics. Forty WDM channels, 40 Gbit/s each channel, have been recently demonstrated on the same chip. Following this way of evolution, the OEO regenerators could be put practically in all the nodes of the network. The additional cost could compensate the technical problems related to the implementation of an AON (impairments accumulation, network planning rules, optical monitoring, etc.).

In the framework of these evolutions, several ITU-T Recommendations have already been prepared and the preparation of others is under way. Among those completed it is possible to quote Recommendation ITU-T G.656 for a fibre with non-zero dispersion for wideband optical transport, the extension of Recommendation ITU-T G.959.1 to include also 40 Gbit/s systems and 100 Gbit/s (striped across 4x25 Gbit/s lines) systems, Recommendation ITU-T G.680 which allows operators to take OADMs and PXC from different vendors and integrate them into an AON without having to add expensive OEO conversions.

5.6 Applications of optical fibres and systems technology in the telecommunication networks

Given that the first-generation systems had a capacity of 34-45 Mbit/s per fibre in 1980, the capacity of optical systems has jumped by a factor of more than 10,000 over a period of 30 years. In the same time also the applications of optical technology progressively moved from short distance links (a few tens of km) to the very long distance links of the backbone networks, completely substituting the traditional copper conductors. In the last few years, the optical fibres and systems technology also started to be deployed in the access networks.

6 Functional grouping of ITU-T Recommendations on optical technology

A possible functional grouping of ITU-T Recommendations on optical fibres and systems technology is shown in Table 1.

Table 1 – ITU-T G-series Recommendations by subject matter

Category	Recommendations	Title
Optical fibres and cables: definitions and test methods	ITU-T G.650.1	Definition and test methods for linear, deterministic attributes of single-mode fibre and cable
	ITU-T G.650.2	Definition and test methods for statistical and non-linear related attributes of single-mode fibre and cable
	ITU-T G.650.3	Test methods for installed single-mode optical fibre cable links
Optical fibres and cables: multimode fibres	ITU-T G.651	Characteristics of a 50/125 µm multimode graded index optical fibre cable

Table 1 – ITU-T G-series Recommendations by subject matter

Category	Recommendations	Title
	ITU-T G.651.1	Characteristics of a 50/125 μm multimode graded index optical fibre cable for the optical access network
Optical fibres and cables: single-mode fibres	ITU-T G.652	Characteristics of a single-mode optical fibre and cable
	ITU-T G.653	Characteristics of a dispersion-shifted single-mode optical fibre and cable
	ITU-T G.654	Characteristics of a cut-off shifted single-mode optical fibre and cable
	ITU-T G.655	Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable
	ITU-T G.656	Characteristics of a fibre and cable with non-zero dispersion for wideband transport
	ITU-T G.657	Characteristics of a bending loss insensitive single mode optical fibre and cable for the access network
Spectral grids	ITU-T G.694.1	Spectral grids for WDM applications: DWDM frequency grid
	ITU-T G.694.2	Spectral grids for WDM applications: CWDM wavelength grid
Physical optical interfaces	ITU-T G.691	Optical interfaces for single-channel STM-64 and other SDH systems with optical amplifiers
	ITU-T G.692	Optical interfaces for multichannel systems with optical amplifiers
	ITU-T G.693	Optical interfaces for intra-office systems
	ITU-T G.695	Optical interfaces for coarse wavelength division multiplexing applications
	ITU-T G.696.1	Longitudinally compatible intra-domain DWDM applications
	ITU-T G.698.1	Multichannel DWDM applications with single-channel optical interfaces
	ITU-T G.698.2	Amplified multichannel DWDM applications with single channel optical interfaces
	ITU-T G.957	Optical interfaces for equipments and systems relating to the synchronous digital hierarchy
	ITU-T G.959.1	Optical transport network physical layer interfaces
Free space optical systems	ITU-T G.640	Co-location longitudinally compatible interfaces for free space optical systems
All optical networks	ITU-T G.680	Physical transfer functions of optical networks elements
Optical monitoring	ITU-T G.697	Optical monitoring for DWDM systems
Optical safety	ITU-T G.664	Optical safety procedures and requirements for optical transport systems

Table 1 – ITU-T G-series Recommendations by subject matter

Category	Recommendations	Title
Optical amplifiers, components and subsystems	ITU-T G.661	Definitions and test methods for the relevant generic parameters of optical amplifier devices and subsystems
	ITU-T G.662	Generic characteristics of optical amplifier devices and subsystems
	ITU-T G.663	Application related aspects of optical amplifier devices and subsystems
	ITU-T G.665	Generic characteristics of Raman amplifiers and Raman amplified subsystems
	ITU-T G.666	Characteristics of PMD compensators and PMD compensating receivers
	ITU-T G.667	Characteristics of adaptive chromatic dispersion compensators
	ITU-T G.671	Transmission characteristics of optical components and subsystems
Optical fibre submarine cable systems	ITU-T G.971	General features of optical fibre submarine cable systems
	ITU-T G.972	Definition of terms relevant to optical fibre submarine cable systems
	ITU-T G.973	Characteristics of repeaterless optical fibre submarine cable systems
	ITU-T G.973.1	Longitudinally compatible DWDM applications for repeaterless optical fibre submarine cable systems
	ITU-T G.974	Characteristics of regenerative optical fibre submarine cable systems
	ITU-T G.975	Forward error correction for submarine systems
	ITU-T G.975.1	Forward error correction for high bit-rate DWDM submarine systems
	ITU-T G.976	Test methods applicable to optical fibre submarine cable systems
	ITU-T G.977	Characteristics of optically amplified optical fibre submarine cable systems
	ITU-T G.978	Characteristics of optical fibre submarine cables
Non-normative Supplements with informative content (also in the appendices of some Recommendations, e.g., Recommendations ITU-T G.696.1, ITU-T G.698.1, ITU-T G.698.2, and ITU-T G.680)	ITU-T G-series Sup.39	Optical system design and engineering considerations
	ITU-T G-series Sup.40	Optical fibre and cable Recommendations and standards guideline
	ITU-T G-series Sup.41	Design guidelines for optical fibre submarine cable systems
	ITU-T G-series Sup.47	General aspects of optical fibre and cable

7 Other standardization organizations working on optical technology

7.1 IEC Technical Committee 86 (TC 86)

Technical Committee 86 (fibre optics) is responsible in IEC to prepare the standards for fibre optic systems, modules, devices and components intended primarily for use with communications equipment. This activity covers terminology, characteristics, related tests, calibration and measurement methods, functional interfaces, optical, environmental and mechanical requirements to ensure reliable system performance. In particular, TC 86 is structured into three sub-committees.

SC 86A (fibres and cables) prepares international standards for optical fibres and optical cables embracing all types of communications applications. This activity covers terminology, generic characteristics, test and measurement methods and specifications for all types of single-mode and multimode optical fibres and all types of optical fibre indoor and outdoor cables to ensure reliable system performance and operation.

SC 86B (fibre optic interconnecting devices and passive components) prepares international standards for fibre optic interconnecting devices and passive components, embracing all types of communications applications. This activity covers terminology, characteristics, related test and measurement methods, and functional interfaces, including all mechanical, environmental and optical requirements to ensure interoperability and reliable performance of fibre optic interconnecting devices and passive components.

SC 86C (fibre optic systems and active devices) prepares international standards for fibre optic systems and active devices embracing all types of communications applications. This activity covers terminology, characteristics, test and measurement methods, and functional interfaces including all mechanical, environmental, optical, and electrical requirements to ensure interoperability and reliable system performance.

ITU-T is chiefly oriented to the needs of the public telecommunication networks and systems and gathers mostly experts from telecom operators and transmission equipment manufacturers. With regard to device/component product characteristics, ITU-T has generally focused on attribute definitions and their interaction with network functionality. In some cases, limits are recommended to ensure this functionality.

IEC is more oriented towards products with attention given to public networks but also for private, industrial, aerospace and automotive networks. IEC gathers experts mainly from device/component vendors and users. With regard to device/components product characteristics, IEC takes charge of all details associated with trade and commerce of the corresponding products. Such details can include items like measurement methods, environmental tests, configuration, attachments, powering, reliability issues, etc.

7.2 OIF

The Optical Internetworking Forum (OIF) promotes the development and deployment of interoperable networking solutions and services through the creation of implementation agreements for optical networking products, network processing elements, and component technologies. Implementation agreements are based on requirements developed cooperatively by end-users, service providers, equipment vendors and technology providers, and aligned with worldwide standards. The OIF perform worldwide interoperability testing, build market awareness and promote education for technologies, services and solutions. The OIF provides feedback to worldwide standards organizations to help achieve a set of implementable, interoperable solutions.

There are two OIF working groups mainly related to optical technology.

The OIF Physical and Link Layer (PLL) Working Group develops implementation agreements related to physical and data link layer interfaces between optical internetworking elements and between their internal components, reusing existing standards when applicable.

The Physical Layer User Working Group (PLUG) guides with its requirements the PLL Working Group. The PLUG is open to all OIF members, but only network equipment/systems vendors have the right to vote.

7.3 IEEE 802

The IEEE Project 802 LMSC (LAN/MAN Standards Committee) develops LAN and MAN standards, mainly for the lowest 2 layers of the reference model for open systems interconnection (OSI).

In particular, IEEE Working Group 802.3 prepares the physical layer specifications for the Ethernet rates (e.g., 1 GbE, 10 GbE, 40 GbE, 100 GbE) defining the frame rate, the maximum frame size, the MAC data rate and the line coding of the various hierarchical levels.

Afterwards it is an ITU-T responsibility to define how to transport these client signals over the optical transport network.

8 Application of ITU-T Recommendations related to optical fibres and systems technology

8.1 Optical fibres and cables: definitions and test methods of single-mode optical fibres and cables

From the beginning of the ITU-T standardization activities on optical fibres, it was clear that it would not be possible to specify the values of the various attributes which characterize an optical fibre without having previously specified the definitions of the attributes and the test methods for measuring their values.

To start with, definitions and test methods were put in the same ITU-T Recommendation as the values of the parameters. Only in 1993 definitions and test methods were removed from single-mode fibre Recommendations and used to create a dedicated ITU-T Recommendation.

Test methods are classified in two categories: reference test methods (RTMs) and alternative test methods (ATMs).

A reference test method is a test method in which a characteristic of a specified class of optical fibres or optical fibre cables is measured strictly according to the definition of this characteristic and which gives results which are accurate, reproducible and relatable to practical use.

An alternative test method is a test method in which a given characteristic of a specified class of optical fibres or optical fibre cables is measured in a manner consistent with the definition of this characteristic and gives results which are reproducible and relatable to the reference test method and to practical use.

Both reference test method and alternative test methods are usually specified in Recommendations ITU-T G.650.1 and ITU-T G.650.2 for each parameter and it is the intention that both the RTM and the ATM(s) may be suitable for normal product acceptance purposes. However, when using an ATM, should any discrepancy arise, it is recommended that the RTM be employed as the technique for providing the definitive measurement results.

Recommendations ITU-T G.650.1 and ITU-T G.650.2 contain definitions and test methods suitable mainly for factory measurements, while Recommendation ITU-T G.650.3 outlines the tests normally done on installed optical cable sections.

Definitions and test methods contained in these three ITU-T Recommendations are generally not appropriate for multimode fibre.

8.1.1 Recommendation ITU-T G.650.1 "Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable"

The purpose of Recommendation ITU-T G.650.1 is to provide definitions and test methods suitable mainly for factory measurements of the *linear, deterministic attributes* of the single-mode optical fibres and cables described in Recommendations ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655, ITU-T G.656 and ITU-T G.657.

These definitions and test methods are generally not appropriate for multimode fibre, such as that described in Recommendations ITU-T G.651 and ITU-T G.651.1. Some of the test methods, when so indicated, may also be used to characterize discrete optical components, such as those described in Recommendation ITU-T G.671.

Recommendation ITU-T G.650.2 (see clause 8.1.2) contains definitions and test methods for statistical and non-linear attributes of single-mode optical fibres and cables.

Recommendation ITU-T G.650.1 describes the following terms and definitions:

- i) general definitions (refractive index profile; RTM; ATM; cladding mode stripper; mode filter);
- ii) mechanical characteristics (primary coating; secondary coating; proof test level; stress corrosion parameter);
- iii) mode field characteristics (mode field; mode field diameter; mode field centre; mode field concentricity error; mode field non-circularity);
- iv) glass geometry characteristics (cladding; cladding centre; cladding diameter; cladding diameter deviation; cladding tolerance field; cladding non-circularity; core centre; core concentricity error);
- v) chromatic dispersion definitions (chromatic dispersion; group delay; chromatic dispersion coefficient; chromatic dispersion slope; zero-dispersion wavelength; zero-dispersion slope);
- vi) other characteristics (cut-off wavelength; cable cut-off wavelength; fibre cut-off wavelength; attenuation; macrobend loss).

Recommendation ITU-T G.650.1 contains RTM and ATMs for several parameters of the optical fibres: mode field diameter, cladding diameter, core concentricity error, cladding non-circularity, cut-off wavelength, attenuation, chromatic dispersion and proof testing.

A schematic diagram of the test apparatus is given for each test method together with the description of the main conditions for carrying out the tests. The measurement procedure and the presentation of the results are also described.

8.1.2 Recommendation ITU-T G.650.2 "Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable"

The purpose of Recommendation ITU-T G.650.2 is to provide definitions and test methods suitable mainly for factory measurements of the *statistical and non-linear attributes* of the single-mode optical fibres and cables described in Recommendations ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655, ITU-T G.656 and ITU-T G.657.

These definitions and test methods are generally not appropriate for multimode fibre, such as that described in Recommendation ITU-T G.651.1. Some of the test methods, when so indicated, may also be used to characterize discrete optical components, such as those described in Recommendation ITU-T G.671.

Recommendation ITU-T G.650.1 contains definitions and test methods for linear deterministic attributes.

Methods how to compensate impairments caused by polarization mode dispersion can be found in Recommendation ITU-T G.666.

Recommendation ITU-T G.650.2 describes the following terms and definitions related to polarization mode dispersion (PMD):

- i) the phenomenon of PMD;
- ii) principle states of polarization (PSP);
- iii) differential group delay (DGD);
- iv) PMD value;
- v) PMD coefficient.

The mathematical definitions of PMD are also given.

Recommendation ITU-T G.650.2 contains RTM and ATMs for the PMD.

Test methods for non-linear attributes are momentarily empty because these test methods are still under study. However, Appendix II of Recommendation ITU-T G.650.2 gives some information on effective area (A_{eff}), non-linear coefficient (n_2/a_{eff}) and stimulated Brillouin scattering.

A schematic diagram of the test apparatus is given for each test method together with the description of the main conditions for carrying out the tests. The measurement procedure and the presentation of the results are also described.

8.1.3 Recommendation ITU-T G.650.3 "Test methods for installed single-mode optical fibre cable links"

Recommendation ITU-T G.650.3 outlines the tests normally done on installed optical fibre cable links. It includes a collection of references to the main measurement methods and gives an indication of which are most suitable for installed cable sections, depending on the required inspection level needed.

Recommendation ITU-T G.650.3 contains test methods which are particularly suited to the characterization of single-mode optical fibre cable links. The methods are not intended for application to links that contain optical network elements, amplifiers, dispersion compensators, or passive splitters/combiners.

Recommendation ITU-T G.650.3 uses a tiered approach. The first level indicates measurements that may normally be done as part of installation. The second level indicates measurements that are normally done on exception, such as to satisfy service level agreements or to verify attributes of older links that may be used at high bit rates.

Test methods for characteristics of optical fibre cable links specified in Recommendation ITU-T G.650.3 include attenuation, splice loss, fibre uniformity, PMD and chromatic dispersion.

Recommendation ITU-T G.650.3 contains some non-normative appendices.

Appendix I of Recommendation ITU-T G.650.3 gives the analysis of OTDR traces.

Appendix II of Recommendation ITU-T G.650.3 lists ITU-T Recommendations on optical transmission systems where there are the requirements for the fibre parameters dealt with in Recommendation ITU-T G.650.3.

8.2 Optical fibres and cables: multimode fibres

8.2.1 Former Recommendation ITU-T G.651 "Characteristics of a 50/125 μm multimode graded index optical fibre cable" (deleted in 2008)

Former Recommendation ITU-T G.651, originally published in 1984, covered the geometrical and transmission properties of multimode fibres having a 50 μm nominal core diameter and a 125 μm nominal cladding diameter. This Recommendation was developed during the infancy of optical fibre solutions for public switched networks. At that time (pre-1984), these fibres were considered as the only practical solution for transmission distances in the 10's of kilometres and bit rates of up

to 40 Mbit/s. Single-mode G.652 fibres, which became available shortly after the publication of Recommendation ITU-T G.651, have almost completely replaced multimode fibres in public switched networks.

Today, multimode fibres continue to be widely used in datacom applications like premises and data centers cabling supporting Ethernet and fibre channel systems standards over maximum distances ranging from 100 m up to 2000 m, depending on bit rate. With a change in the applications, the multimode fibre definitions, requirements and measurements evolved away from the original Recommendation ITU-T G.651 and were maintained or improved in others. For this reason Recommendation ITU-T G.651 was agreed to be deleted at the February 2008 meeting of Study Group 15.

The transmission characteristics from Recommendation ITU-T G.651 have been upgraded to the current more modern multimode optical fibre Recommendation ITU-T G.651.1 (see clause 8.2.2). A complete documentation for the modern requirements is in IEC 60793-2-10. It was agreed in 2008 to summarize the main parts of the former Recommendation ITU-T G.651 in a new appendix to Recommendation ITU-T G.651.1.

8.2.2 Recommendation ITU-T G.651.1 "Characteristics of a 50/125 µm multimode graded index optical fibre cable for the optical access network"

The purpose of Recommendation ITU-T G.651.1 is to provide specifications for a 50/125 µm multimode graded index optical fibre cable applied for the optical access network in specific environments. These environments are multi-tenant building sub-networks in which broadband services have to be delivered to individual apartments.

The recommended multimode fibre supports the cost-effective use of 1 Gbit/s Ethernet systems over link lengths up to 550 m, usually based upon the use of 850 nm transceivers.

Worldwide, various technologies for broadband access networks are advancing rapidly to provide the high capacity needed for the increasing customer demands with respect to new services. Apart from the technologies, also the network structures and customer densities vary considerably.

A specific segment, which is in the main scope of Recommendation ITU-T G.651.1, is the network in a multi-tenant building. Quite a large percentage of all customers in the world are living in these buildings. Due to the high connection density and the short distribution cable lengths, cost-effective high capacity optical networks can be designed and installed by making use of 50/125 µm graded index multimode fibres.

The effective use of this network type has been shown by its extended and experienced use for datacom systems in enterprise buildings with system bit rates ranging from 10 Mbit/s up to 10 Gbit/s. This use is supported by a large series of IEEE system standards and IEC fibre and cable standards which are used as the main references in Recommendation ITU-T G.651.1.

The recommended fibre type is an improved version of the well-known 50/125 µm multimode graded-index fibre formerly recommended in Recommendation ITU-T G.651, which has been deleted as of February 2008 (see clause 8.2.1).

The 50/125 µm graded-index multimode optical fibre cable described in Recommendation ITU-T G.651.1 is suitable to be used in the 850 nm region or in the 1300 nm region, or alternatively may be used in both wavelength regions simultaneously.

The geometrical, optical, transmission and mechanical parameters are described in the following two categories of attributes:

- i) fibre attributes are those attributes that are retained throughout cabling and installation;
- ii) cable attributes that are recommended for cables as they are delivered.

Recommendation ITU-T G.651.1 is intended to support the following related system standard:

– IEEE Standard for Information Technology 802.3TM-2008.

Recommendation ITU-T G.651.1 contains since 2008 an appendix summarizing the main parts of the deleted Recommendation ITU-T G.651.

8.3 Optical fibres and cables: single-mode fibres

These ITU-T Recommendations describe the geometrical, optical, transmission and mechanical attributes of various types of single-mode optical fibres and cables.

The meaning of the terms used and the guidelines to be followed in the measurements to verify the various characteristics are given in Recommendations ITU-T G.650.1, ITU-T G.650.2 and ITU-T G.650.3.

There are three categories of attributes which describe the geometrical, optical, transmission and mechanical parameters: fibre attributes, cable attributes and link attributes.

Fibre attributes are those that are retained throughout cabling and installation. Among the fibre attributes, only those providing a minimum essential design framework for fibre manufacture are recommended (e.g., mode field diameter, cladding diameter, cut-off wavelength, macrobending loss). Chromatic dispersion coefficient is also included in these attributes. There are two methods for specifying the limits of the chromatic dispersion, the original method, which is a box-like specification, and a newer method, in which the dispersion coefficient values are bound by a pair of curves.

Cable attributes are recommended for cables as they are delivered. The attenuation coefficient and the polarization mode dispersion (PMD) coefficient are included among the cable attributes since they are barely affected by the cabling process.

The attenuation coefficient is specified with a maximum value at one or more wavelengths in both the 1310 nm and 1550 nm regions.

The PMD is not specified in all tables. When required, cabled fibre polarization mode dispersion is specified on a statistical basis, not on an individual fibre basis. The manufacturer shall supply a PMD link design value, PMD_Q , that serves as a statistical upper bound for the PMD coefficient of the concatenated optical fibre cables within a defined possible link of M cable sections. The upper bound is defined in terms of a small probability level, Q , which is the probability that a concatenated PMD coefficient value exceeds PMD_Q . Measurements and specifications on uncabled fibre are necessary, but not sufficient to ensure the cabled fibre specification. The maximum link design value specified on uncabled fibre shall be less than or equal to that specified for the cabled fibre. The ratio of PMD values for uncabled fibre to cabled fibre depends on the details of the cable construction and processing, as well as on the mode coupling condition of the uncabled fibre.

Link attributes are characteristic of concatenated cables. A concatenated link usually includes a number of spliced factory lengths of optical fibre cable. The transmission parameters for concatenated links must take into account not only the performance of the individual cable lengths but also the statistics of concatenation.

The transmission characteristics of the factory length optical fibre cables will have a certain probability distribution which often needs to be taken into account if the most economic designs are to be obtained.

Link attributes are affected by factors other than optical fibre cables by such things as splices, connectors and installation.

The attenuation (in dB/km) can be calculated from the attenuation coefficients of the factory lengths, assuming a linear dependence on length. Loss of splices and line connectors should be

added together with a suitable margin for future modifications of cable configurations (additional splices, extra cable lengths, ageing effects, temperature variations, etc.).

The chromatic dispersion (in ps/nm) can be calculated from the chromatic dispersion coefficients of the factory lengths, assuming a linear dependence on length.

The differential group delay is the difference in arrival times of the two polarization modes at a particular wavelength and time. For a link with a specific PMD coefficient, the DGD of the link varies randomly with time and wavelength as a Maxwell distribution that contains a single parameter, which is the product of the PMD coefficient of the link and the square root of the link length. The system impairment due to PMD at a specific time and wavelength depends on the DGD at that time and wavelength.

Values for the link attributes are not indicated for the fibre specified in Recommendation ITU-T G.657 because its characteristics are specified for deployment in the access network.

8.3.1 Recommendation ITU-T G.652 "Characteristics of a single-mode optical fibre and cable"

This was the first ITU-T Recommendation for single-mode fibre and cable which, for this reason, the ITU-T G.652 fibres are often called "standard single-mode fibres". These fibres were the first to be widely deployed in the public network and they represent a majority of fibres that have been installed. The agreements that led to the first publication of Supplement 41 to ITU-T G-series formed a key foundation to the modern optical networks that are the basis of all modern telecommunications.

Supplement 41 to ITU-T G-series describes the geometrical, mechanical and transmission attributes of a single-mode optical fibre and cable which has zero-dispersion wavelength around 1310 nm. This fibre was originally optimized for use in the 1310 nm wavelength region, but can also be used in the 1550 nm region. This is the latest version of an ITU-T Recommendation that was first created in 1984. These revisions have been intended to maintain the continuing commercial success of this fibre in the evolving world of high-performance optical transmission systems.

Over the years, parameters have been added to Recommendation ITU-T G.652 and the requirements have been made more stringent to meet the changes in market and technological demands, and in manufacturing capability. An example is the addition of a requirement for attenuation at 1550 nm in 1988. In that year, the chromatic dispersion parameters and requirements were also defined.

Some other examples include the addition of low water peak fibres (LWP) with negligible sensitivity to hydrogen exposure and the addition of requirements for PMD. However at the advent of these new capabilities and perceived needs, there was a consensus that some applications would need these attributes for advanced technologies, bit rates and transmission distances, but there were also applications that would not need these capabilities so that some options had to be maintained.

For this reason, it was agreed to create different categories of ITU-T G.652. At the present time there are four categories, A, B, C and D, that are distinguished on the PMD_Q link design value specification and whether the fibre is LWP or not, i.e., water peak is specified (LWP) or it is not specified (WPNS), as shown in the following table.

Category	Maximum PMD_Q (ps/km ^{1/2})	Water peak
A	0.5	WPNS
B	0.2	WPNS
C	0.5	LWP
D	0.2	LWP

A non-normative appendix gives representative values of attenuation and chromatic dispersion which can be taken as basis for the design of concatenated optical fibre links in accordance with the guidelines outlined in Supplement 39 to ITU-T G-series (see clause 8.12.1). The same appendix gives an indication of the maximum link length at various channel bit rates allowed by different values of polarization mode dispersion (PMD_Q).

Other related documents to Recommendation ITU-T G.652 include the IEC specification for uncabled fibre, IEC 60793-2-50, and Recommendation ITU-T G.657. The IEC specification is aligned with all the ITU-T fibre and cable Recommendations but does specify some additional attributes such as coating dimensions and environmental tests. Sub-categories A1 and A2 of Recommendation ITU-T G.657 (see clause 8.3.6) are aligned with all the ITU-T G.652.D values but have more stringent bend loss requirements.

8.3.2 Recommendation ITU-T G.653 "Characteristics of a dispersion-shifted single-mode optical fibre and cable"

Recommendation ITU-T G.653 describes a dispersion-shifted single-mode optical fibre and cable which has a nominal zero-dispersion wavelength close to 1550 nm, and a dispersion coefficient which is monotonically increasing with wavelength. This fibre was initially developed for use in single-channel high bit rate and long distance transmission in the 1550 nm region (where the attenuation coefficient is smallest) by shifting the zero-dispersion wavelength of the ITU-T G.652 fibre to around 1550 nm. This fibre is optimized for use in the 1550 nm region, but may also be used at around 1310 nm subject to the constraints outlined in Recommendation ITU-T G.653. Some provisions are made to support transmission at higher wavelengths up to 1625 nm and lower wavelengths down to 1460 nm.

This was the second ITU-T Recommendation for single-mode fibre and cable and was first created in 1988. The current version contains two categories, A and B, that are distinguished on the PMD_Q link design value specification, the description of the chromatic dispersion coefficient, the geometrical parameters and the macrobending loss specifications.

ITU-T G.653.A fibre is the base category for a dispersion-shifted single-mode optical fibre and cable, and retains the original "box-type" specification for the dispersion coefficient. The zero-dispersion wavelength is within the operating wavelength range from 1525 nm to 1575 nm, so that it performs very well for single-channel systems (e.g., ITU-T G.957, ITU-T G.691, ITU-T G.693 systems), but non-linear effects are deleterious in dense wavelength division multiplexing systems with an equal channel spacing in the 1550 nm wavelength region. However, this category is also suitable for multichannel systems (e.g., ITU-T G.692, ITU-T G.977 systems) with an unequal channel spacing in the 1550 nm wavelength region (for more detail on unequal channel spacing see Appendix IV of Recommendation ITU-T G.692). The ITU-T G.653.A fibre is used for multichannel systems with equal channel spacing within the operating wavelength range from 1565 nm to 1625 nm where the chromatic dispersion has non-zero values (e.g., ITU-T G.698.1, ITU-T G.698.2 systems).

Many submarine applications can utilize this category. For some submarine applications, the full optimization can lead to choosing different limits than are found here. One example could be to allow cable cut-off wavelength to values as high as 1500 nm.

ITU-T G.653.B fibre attributes are similar to ITU-T G.653.A, but the more stringent PMD requirement allows STM-64 systems to use lengths greater than 400 km and ITU-T G.959.1 NRZ 40G applications. This category defines the chromatic dispersion coefficient requirements as a pair of bounding curves vs wavelength for wavelengths from 1460 nm to 1625 nm. This category may support coarse wavelength division multiplexing applications which do not have significant non-linear impairments.

8.3.3 Recommendation ITU-T G.654 "Characteristics of a cut-off shifted single-mode optical fibre and cable"

Recommendation ITU-T G.654 describes the geometrical, mechanical and transmission attributes of a single-mode optical fibre and cable which has its zero-dispersion wavelength around 1300 nm and which is loss-minimized and cut-off wavelength shifted at around the 1550 nm wavelength region.

At first, Recommendation ITU-T G.654 was created as "Characteristics of a 1550 nm wavelength loss-minimized single-mode optical fibre cable" in 1988, for the purpose of submarine cable system use. In 1997, the name of this Recommendation was changed to "Characteristics of a cut-off shifted single-mode optical fibre cable", in order to make clearer the features of this fibre.

The main features of the fibre described by Recommendation ITU-T G.654 are its longer cut-off wavelength and lower attenuation coefficient at 1550 nm compared to other single-mode optical fibres. The longer cut-off wavelength can allow lower macrobending loss fibre design, hence it is advantageous to submarine cables which require lower attenuation. The lowest values of attenuation coefficient depend on fabrication process, fibre composition and design, and cable design. Values of 0.15 to 0.19 dB/km in the 1550 nm region have been achieved. These features are suitable for long-haul transmission in the 1530-1625 nm region.

The current version of Recommendation ITU-T G.654 contains three categories: A, B and C.

ITU-T G.654.A is the base category which, considering its very low attenuation, can be used for long-distance digital transmission applications such as long-haul terrestrial line systems and submarine cable systems using optical amplifiers. This category is suitable for the systems specified in Recommendations ITU-T G.691, ITU-T G.692, ITU-T G.957 and ITU-T G.977 in the 1550 nm wavelength region.

ITU-T G.654.B has a larger upper limit of MFD than ITU-T G.654.A and reduced PMD requirement. This category is suitable for the systems described in the above quoted ITU-T Recommendations and for the ITU-T G.959.1 long-haul applications in the 1550 nm wavelength region. This category B can also be applied to longer distance and larger capacity WDM repeaterless submarine systems with remotely pumped optical amplifier described in Recommendation ITU-T G.973 and submarine systems with optical amplifiers described in Recommendation ITU-T G.977.

ITU-T G.654.C is similar to ITU-T G.654.A, but the reduced PMD requirement also supports the highest bit rate and long-haul applications among those of Recommendation ITU-T G.959.1.

8.3.4 Recommendation ITU-T G.655 "Characteristics of a non-zero dispersion shifted single-mode optical fibre and cable"

Recommendation ITU-T G.655 describes the geometrical, mechanical and transmission attributes of a single-mode optical fibre which has the absolute value of the chromatic dispersion coefficient greater than some non-zero value throughout the wavelength range from 1530 nm to 1565 nm. This dispersion reduces the growth of non-linear effects which are particularly deleterious in dense wavelength division multiplexing systems.

This is the latest revision of an ITU-T Recommendation that was first created in 1996.

Recommendation ITU-T G.655 was initially developed following the creation of the dispersion-shifted fibres (see Recommendation ITU-T G.653) and the advent of dense wavelength division multiplexing (DWDM) in long-distance optically-amplified and dispersion-compensated networks. As indicated above, allowance of zero or low values of dispersion in the operating window of these systems allows the growth of non-linear effects such as four-wave mixing. For this reason, the zero-dispersion wavelength had to be moved out of the operating window.

In the initial version of Recommendation ITU-T G.655, the dispersion requirements were expressed as a "box specification", in which the absolute value of the dispersion coefficient had to be

restricted to a range starting with a positive value and bound by another larger value over a wavelength range believed to encompass the operating window of the DWDM systems. Many possible technical tradeoffs and developments were anticipated so the initial ranges were allowed to be large enough to allow evolution. Examples of such tradeoffs include:

- i) degree of dispersion compensation, amplification and consequent optical noise;
- ii) DWDM channel density and range;
- iii) channel power levels;
- iv) the possibility of Raman amplification;
- v) the possibility of dispersion management.

Despite the looseness of the primary chromatic dispersion coefficient requirement and the mix of system strategies, large volumes of ITU-T G.655 fibres were deployed in the longer distance networks that emerged in the late 1990's and early 2000's. These fibres had, depending on the fibre manufacturer, different detailed but more restrictive limits on the chromatic dispersion coefficient, depending on the relevant technical strategy of their customers.

In 2005, following the bursting of the "telecommunications bubble", two main aspects emerged, which changed the standardization strategy for ITU-T G.655 fibres:

- i) the customers and network providers demanded more specific values for the chromatic dispersion coefficient vs wavelength. The "box specification" was not sufficiently useful;
- ii) two main varieties of these fibres were seen in the market: one with lower dispersion coefficient and another with medium dispersion coefficient, but much lower than ITU-T G.652 fibres.

To address these aspects, surveys of all the participating fibre manufacturers were conducted. The results of these surveys were used to define the chromatic dispersion coefficient limits vs wavelength for two new categories that are defined in Tables D and E of Recommendation ITU-T G.655, which have been included in the 2006 version of Recommendation ITU-T G.655. They distinguish the two main families of Recommendation ITU-T G.655 fibres that are supported by multiple vendors. Both of these categories limit the chromatic dispersion coefficient by a pair of bounding curves vs wavelength for the range of 1460 nm to 1625 nm. Although the dispersion can change sign at wavelengths less than 1530 nm, the inclusion of these lower wavelengths is intended to provide information to support coarse wavelength division multiplexing applications which do not have significant non-linear impairments, at channels from 1471 nm and higher.

Tables A, B and C have not been changed. Tables A and B are not included in the 2006 version of Recommendation ITU-T G.655, but are in the 2003 edition. Table C, based on a box specification that allows positive and negative dispersion coefficients for possible use in dispersion managed systems, was retained.

8.3.5 Recommendation ITU-T G.656 "Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport"

The purpose of Recommendation ITU-T G.656 is to provide the specifications of a single-mode fibre and cable with chromatic dispersion that is greater than some non-zero value throughout the wavelength range of 1460-1625 nm (i.e., from S-band to L-band).

In the current development of lightwave systems, one direction of evolution is towards increasing the capacity transmitted on an optical fibre. One of the solutions is by deploying the optical channels not only in the C-band, but also in the short wavelength S-band (1460-1530 nm) and in the long wavelength L-band (1565-1625 nm). This type of fibre can be utilized for both CWDM and DWDM systems throughout the wide wavelength region between 1460 and 1625 nm.

Recommendation ITU-T G.656 describes the geometrical, mechanical and transmission attributes of the fibre and cable. The chromatic dispersion of the fibre reduces the growth of non-linear effects which are particularly deleterious in DWDM systems over a wider wavelength range than the fibre described in Recommendation ITU-T G.655.

Recommendation ITU-T G.656 has a single category of fibre and cable. The category limits the chromatic dispersion coefficient by a pair of bounding curves vs wavelength for the range of 1460 nm to 1625 nm, which provides information to support CWDM applications such as Recommendation ITU-T G.695 and DWDM applications such as Recommendations ITU-T G.692, ITU-T G.696.1, ITU-T G.698.1, ITU-T G.698.2 and ITU-T G.959.1. The PMD requirement of the fibre and cable allows operation of STM-64 systems to lengths of up to 2000 km, depending on other system elements.

Appendix I of Recommendation ITU-T G.656 contains information for link attributes and system design.

8.3.6 Recommendation ITU-T G.657 "Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network"

The purpose of Recommendation ITU-T G.657 is to provide specifications for a bending loss insensitive single mode fibre to be used in access networks.

Worldwide, technologies for broadband access networks are advancing rapidly. Among these, the technology applying single mode fibre provides for a high-capacity transmission medium which can answer the growing demand for broadband services.

The experience with the installation and operation of single mode fibre and cable based networks is huge and ITU-T G.652 fibre characteristics have been adapted to 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 from 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 may be optimized for lower bending sensitivity compared to that of cabled fibre used in a general 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 types.

Recommendation ITU-T G.657 describes two categories of single-mode optical fibre cable which are suitable for use in the access networks, including inside buildings at the end of these networks.

Category A fibres of Recommendation ITU-T G.657 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.

In 2009 the 2nd edition of Recommendation ITU-T G.657 was approved with additional sub-categories. The former category ITU-T G.657.A has been renumbered to sub-category ITU-T G.657.A1. In addition a new sub-category was added: ITU-T G.657.A2 with the following definitions:

Sub-category ITU-T G.657.A1 fibres are appropriate for minimum design radius of 10 mm. This subcategory encompasses fully former ITU-T G.657(12/2006).A category.

Sub-category ITU-T G.657.A2 fibres are appropriate for minimum design radius of 7.5 mm.

Category B fibres of Recommendation ITU-T G.657 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.

Also in this section, the 2nd edition of Recommendation ITU-T G.657 introduced in 2009 an additional sub-category, while renumbering the former category ITU-T G.657.B to sub-category ITU-T G.657.B2. The new additional sub-category was introduced as sub-category ITU-T G.657.B3 with the following definitions:

Sub-category ITU-T G.657.B2 fibres are appropriate for minimum design radius of 7.5 mm. This subcategory encompasses fully former ITU-T G.657(12/2006).B category.

Sub-category ITU-T G.657.B3 fibres are appropriate for minimum design radius of 5 mm.

The different suffix numbers of these sub-categories have been chosen to refer more easily to the minimum specified bending radius of 10 mm, 7.5 mm or 5 mm, see also the following Figure 8-1.

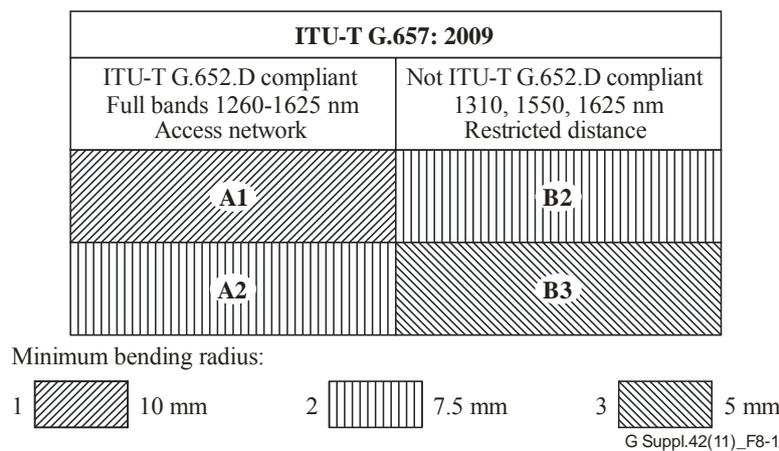


Figure 8-1 – Relation between fibre sub-categories and bending radius

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, in apartment buildings and single dwelling houses.

8.4 Spectral grids

The "conventional" C-band defined in Supplement 39 to ITU-T G-series has a spectral width of 35 nm (1530-1565 nm) which exceeds 40 THz (0.8 nm = 100 GHz; 1 THz = 1000 GHz). If the utilization of an optical fibre is limited to an optical channel at 10 Gbit/s there is a big waste of the available capacity.

A better utilization of the transmission capacity of an optical fibre can be obtained with the wavelength division multiplexing technique. With this technique, multiple optical carriers at different wavelengths are modulated using independent electrical bit streams, combined in an optical multiplexer and then they are transmitted on the same fibre. At the receiver, the signal is demultiplexed in an optical demultiplexer into separate channels. In this way, as an example, many 10 Gbit/s channels can be transmitted over the same fibre.

The ultimate capacity of a WDM fibre system depends on how closely together channels can be packed in the wavelength domain. The minimum channel spacing is limited by interchannel crosstalk and it is related to many factors: the channel bit rate, the modulation format, the filter passband, the central wavelength variations (laser manufacturing and temperature variations).

Recommendation ITU-T G.671 defines three categories of WDM systems:

- i) coarse WDM (CWDM) having a channel wavelength spacing less than 50 nm but greater than 1000 GHz (about 8 nm at 1550 nm and 5.7 nm at 1310 nm);
- ii) dense WDM (DWDM) having a channel spacing less than or equal to 1000 GHz;
- iii) wide WDM (WWDM) having a channel wavelength spacing greater than or equal to 50 nm.

Recommendation ITU-T G.694.1 defines a set of frequency grids for DWDM applications.

Recommendation ITU-T G.694.2 defines a frequency grid for CWDM applications.

At present there is no specification of a frequency grid for WWDM applications.

8.4.1 Recommendation ITU-T G.694.1 "Spectral grids for WDM applications: DWDM frequency grid"

The purpose of Recommendation ITU-T G.694.1 is to provide the definition of frequency grids to support dense wavelength division multiplexing (DWDM) applications. Four specific frequency grids are defined:

- i) 12.5 GHz spacing;
- ii) 25 GHz spacing;
- iii) 50 GHz spacing;
- iv) 100 GHz spacing.

All four frequency grids include 193.1 THz as one of their members and there are no frequency limits beyond which the grid is not defined.

Additional wider spacing frequency grids can be used by taking integer multiples of 100 GHz spacing i.e., 200 GHz, 300 GHz, 400 GHz, etc.

ITU-T Recommendations defining applications that utilize these DWDM frequency grids include Recommendations ITU-T G.692, ITU-T G.698.1, ITU-T G.698.2 and ITU-T G.959.1.

8.4.2 Recommendation ITU-T G.694.2 "Spectral grids for WDM applications: CWDM wavelength grid"

The purpose of Recommendation ITU-T G.694.2 is to provide the definition of a wavelength grid to support coarse wavelength division multiplexing (CWDM) applications. This grid is designed to allow simultaneous transmission of several wavelengths with sufficient separation to permit the use of uncooled sources.

The channel spacing of 20 nm was determined mainly by three factors:

- i) the laser manufacturer is allowed a wavelength variation around the nominal wavelength in order to achieve a higher yield and/or relax fabrication tolerances;
- ii) the use of uncooled lasers will cause the wavelength to change with temperature within the specified temperature range of the laser;
- iii) sufficient guardband between the channels to allow the use of low cost filter technologies.

Applications using this CWDM grid are specified in Recommendation ITU-T G.695 (see clause 8.5.4).

8.5 Physical optical interfaces

These ITU-T Recommendations provide physical layer specifications for optical transmission systems and are divided into two general types: transversely compatible and longitudinally compatible.

In Recommendations ITU-T G.691, ITU-T G.693, ITU-T G.695, ITU-T G.698.1, ITU-T G.698.2, ITU-T G.957 and ITU-T G.959.1, the applications are defined to be "transversely compatible", which implies that the ends of an optical section may be terminated by equipment from different manufacturers. This is illustrated in Figure 8-2. Therefore, a full set of parameter definitions and associated values at interface point MPI-S and MPI-R are necessary to enable such an interface.

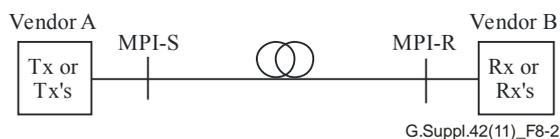


Figure 8-2 – Single-span physical layer transverse compatibility

NOTE – The interface points labelled MPI-S and MPI-R in Figure 8-2 have different labels (and different interface parameters) in the various ITU-T Recommendations, but the same principle applies to both single-channel and multichannel interfaces.

In contrast to the above, an application that is defined to be "longitudinally compatible" implies that both ends of an optical section are terminated by equipment from the same manufacturer. In this case, a more limited set of parameters than for transversely compatible systems is required. A single-span longitudinally compatible system is illustrated in Figure 8-3.

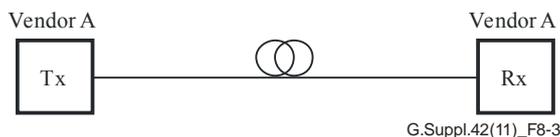


Figure 8-3 – Single-span physical layer longitudinal compatibility

For multi-span systems, longitudinal compatibility is also possible. This is similar to the single-span longitudinally compatible system, where all the active equipment comes from a single source. This is illustrated in Figure 8-4. As in the case of single span, only a limited number of parameters are required to be specified.

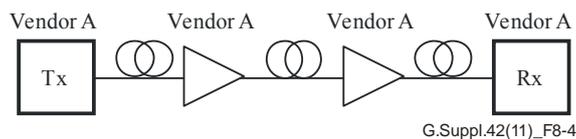
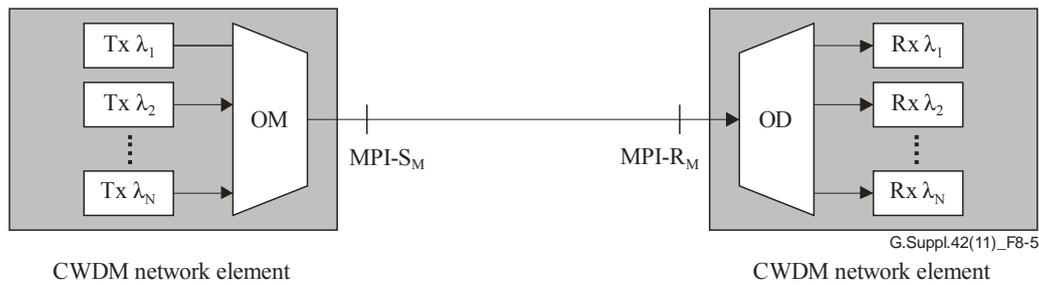


Figure 8-4 – Multi-span physical layer longitudinal compatibility

More information on transverse and longitudinal compatibility can be found in Supplement 39 to ITU-T G-series.

The specification method used in this group of ITU-T Recommendations is categorized into two types.

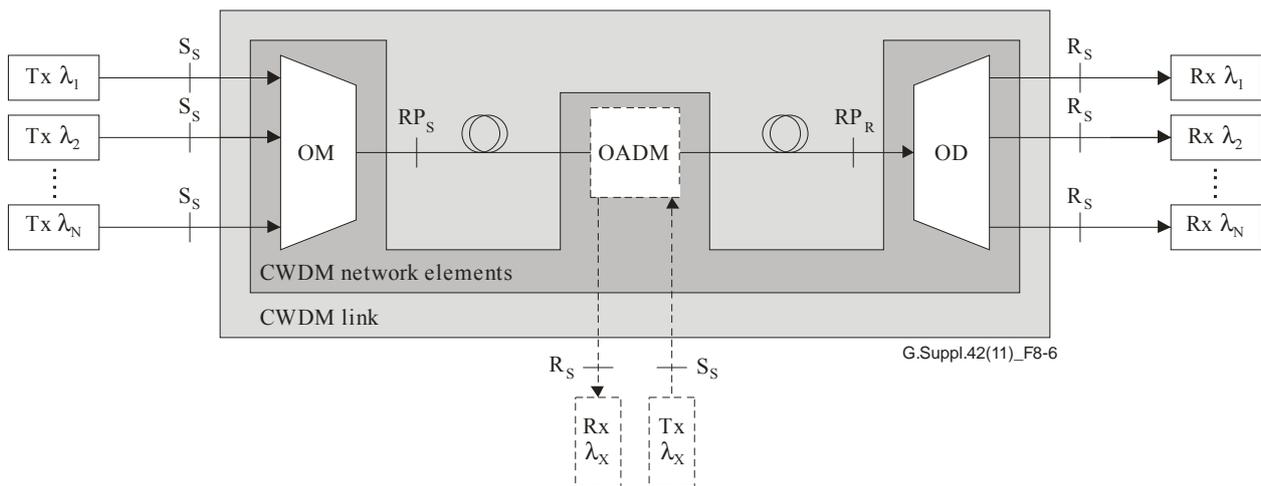
The first one is a "black-box" approach which means that it is not intended to restrict or specify the internal elements and/or the connections between the elements within the black-box. There are, however, functional requirements for the black-box. This approach enables transverse compatibility at the multichannel points (see Figure 8-5).



NOTE – This figure applies both to CWDM and DWDM systems.

Figure 8-5 – "Black-box" approach

The second type is a "black link" approach which means that optical interface parameters for only (single-channel) optical tributary signals are specified. Additional informative descriptions are provided for the fibre link parameters of the multichannel section such as maximum attenuation, chromatic dispersion, and polarization mode dispersion. This approach enables transverse compatibility at the single-channel point using a direct wavelength-multiplexing configuration. However, it does not enable transverse compatibility at the multichannel points. In this approach, the OM and OD are treated as a single set of optical devices and OADMs can be included (see Figure 8-6).



NOTE – This figure applies both to CWDM and DWDM systems.

Figure 8-6 – Linear "black link" approach

For each of the Recommendations covered in this clause, the various parameter sets are termed the "applications" of the Recommendation and each one is given its own short reference code (called the "application code"). The structure of this code varies from one Recommendation to another depending on the characteristics required to distinguish one application from another.

Two elements of the application code that are common to all of the Recommendations are an indication of the bit rate and the type of fibre that the application operates over. To illustrate how these application codes work, two examples are given. The first (Figure 8-7) is from Recommendation ITU-T G.957 which has a very simple application code structure and the second (Figure 8-8) is a more complex example from Recommendation ITU-T G.698.2.

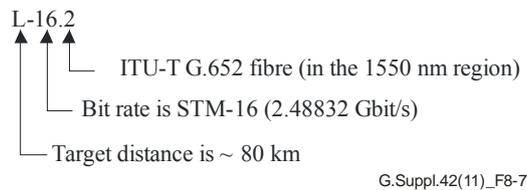


Figure 8-7 – Example ITU-T G.957 application code

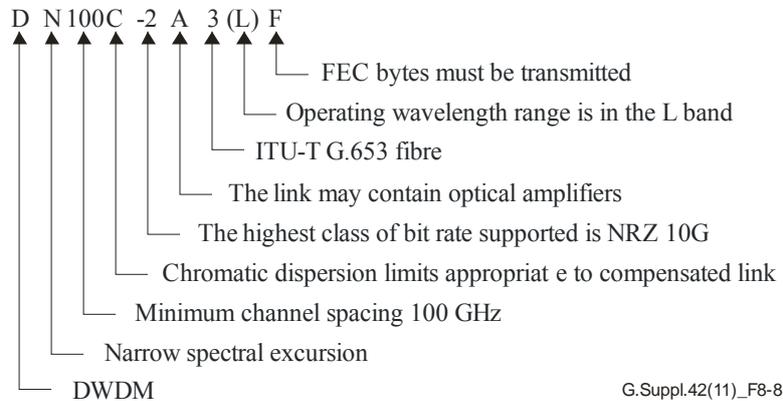


Figure 8-8 – Example ITU-T G.698.2 application code

Details of the structure and interpretation of the application codes for each Recommendation can be found in clause 5.

For all of these Recommendations with the exception of Recommendation ITU-T G.698.2, the application code includes some indication of the distance that can be covered by the link. In the example for ITU-T G.957 in Figure 8-7, the letter L indicates a "target distance" of approximately 80 km. These target distances are for classification purposes only and do not guarantee that a link of that distance can be accommodated (or conversely, that a link that is somewhat longer cannot). The specifications for each application code are given in terms of the maximum (and sometimes minimum) attenuation that the link must have, the limits for chromatic dispersion, the maximum reflections and (in most cases) the maximum differential group delay (DGD) – a parameter related to polarization mode dispersion that can be tolerated.

The applications in each Recommendation do not cover all possible combinations of distance category, optical tributary signal class, and fibre type. The included applications are intended to satisfy a broad range of network requirements with low-cost implementations.

8.5.1 Recommendation ITU-T G.691 "Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers"

The purpose of Recommendation ITU-T G.691 is to provide optical interface specifications to enable transverse (multi-vendor) compatibility of single-channel STM-4, STM-16 and STM-64 inter-office systems using optical preamplifiers and/or optical booster amplifiers. Specifications to enable transversely compatible single-channel STM-64 intra-office and short-haul systems not requiring optical amplification are also quoted.

Systems with line amplifiers are not within the scope of this Recommendation.

Recommendation ITU-T G.691 is an extension of Recommendation ITU-T G.957 based on the addition of optical amplifiers and the STM-64 data rate.

In Recommendation ITU-T G.691 single-channel optical systems with the following features are described:

- STM level: STM-4 (\approx 622 Mbit/s), STM-16 (\approx 2.5 Gbit/s), STM-64 (\approx 10 Gbit/s);

- wavelength of the source: 1310 nm, 1550 nm;
- type of optical fibre: ITU-T G.652, ITU-T G.653, ITU-T G.655;
- target distances ranging from 20 km to 160 km.

The first version of Recommendation ITU-T G.691 (approved in 2000) included all of the single-channel STM-4 and STM-16 applications with target distances above 80 km and all of the single-channel STM-64 applications for any target distance. When Recommendation ITU-T G.959.1 (see clause 8.5.9) was developed at the beginning of 2001, a number of STM-16 and STM-64 applications were transferred from Recommendation ITU-T G.691 to Recommendation ITU-T G.959.1 so that they could be applied to both STM-64 and also to OTU2. Likewise, at the end of 2001, all of the STM-64 applications with target distances of 2 km or less were transferred to Recommendation ITU-T G.693 (see clause 8.5.3) which covers very short-reach applications. Consequently, in the current version of Recommendation ITU-T G.691 these applications simply refer to the equivalent application in Recommendation ITU-T G.959.1 or ITU-T G.693.

Recommendation ITU-T G.691 also contains a description of various approaches to dispersion accommodation. These are: passive dispersion compensation (PDC), self-phase modulation (SPM), prechirp (PCH), dispersion supported transmission (DST) and possible combinations of some of these techniques.

Recommendation ITU-T G.691 contains an annex (Extinction ratio and eye mask penalties) and five appendices:

- Polarization mode dispersion;
- Description of SPM as dispersion accommodation;
- Dispersion accommodation by means of DST;
- Measurement of the chirp parameter α of the optical transmit signal;
- Upgradability considerations.

8.5.2 Recommendation ITU-T G.692 "Optical interfaces for multichannel systems with optical amplifiers"

Recommendation ITU-T G.692 applies to optical interfaces for multichannel optical line systems with optical amplifiers for terrestrial long-haul applications.

During the development of Recommendation ITU-T G.692, it was intended to define and to provide values of optical interface parameters for transversely compatible inter-office and long-haul systems of four, eight and sixteen channels operating at bit rates of up to STM-16 on ITU-T G.652, ITU-T G.653 and ITU-T G.655 fibres, with nominal span lengths of 80 km, 120 km and 160 km with and without line amplifiers. Target distances between regenerators are up to 640 km when line amplifiers are deployed. However, while Recommendation ITU-T G.692 does contain the application codes and parameter definitions, nearly all of the parameter values required to enable transverse compatibility are currently missing.

In the original version of Recommendation ITU-T G.692 (1998), a frequency grid anchored at 193.1 THz with inter-channel spacing at integer multiples of 50 GHz and 100 GHz was specified as the basis for selecting channel central frequencies. In 2002 these frequency grids were moved to Recommendation ITU-T G.694.1 (see clause 8.4.1).

Recommendation ITU-T G.692 applies principally to point-to-point multichannel systems. Specific issues of optical add-drop are not considered.

Recommendation ITU-T G.692 covers optical line systems that include the following features:

- maximum number of channels: 4, 8 or 16;
- signal channel types: STM-4 or STM-16;
- transmission over a single fibre: unidirectional or bidirectional.

Also included in Recommendation ITU-T G.692 are a number of informative appendices which contain information on a variety of topics including:

- i) a channel-allocation methodology for applications on ITU-T G.653 fibre based on unequal channel spacing (Appendix V);
- ii) some system aspects regarding bidirectional transmission (Appendix VII);
- iii) 16 and 32 channel transmission (Appendix VIII);
- iv) STM-64 transmission (Appendix IX).

Additional information and cable section parameter values for longitudinal compatible point-to-point, multichannel line systems with or without line amplifiers can be found in Recommendation ITU-T G.696.1 (see clause 8.5.5).

8.5.3 Recommendation ITU-T G.693 "Optical interfaces for intra-office systems"

The purpose of Recommendation ITU-T G.693 is to provide optical interface specifications to enable transverse (multi-vendor) compatibility of nominal 10 Gbit/s and 40 Gbit/s aggregate bit rate intra-office systems for link distances up to 2 km over ITU-T G.652, ITU-T G.653 and ITU-T G.655 fibres.

For these short distance applications, main optical path total attenuation will, in general, be dominated by the loss contributions of connectors and passive optical devices rather than by fibre loss itself.

Recommendation ITU-T G.693 covers:

- i) target distances: 0.6 km and 2 km (main optical path);
- ii) highest class of optical tributary signal supported: NRZ 10G and NRZ 40G;
- iii) maximum attenuation categories of the main optical path: 4 dB, 6 dB, 12 dB, 16 dB;
- iv) source and fibre type: 1310 nm sources on ITU-T G.652 fibre, 1550 nm sources on ITU-T G.652 fibre, 1550 nm sources on ITU-T G.653 fibre, 1550 nm sources on ITU-T G.655 fibre.

Some applications require forward error correction (FEC) bytes as specified in [ITU-T G.709].

Figure 8-9 shows configurations corresponding to several applications defined in Recommendation ITU-T G.693, with different combinations of attenuation category and target distance. The figure illustrates that, in selecting an application, the choice of attenuation category is determined by the devices in the main optical path, e.g., whether or not a photonic cross-connect is present, while the choice of target distance is determined by the relative proximity of the equipments with which the ITU-T G.693 interface interconnects.

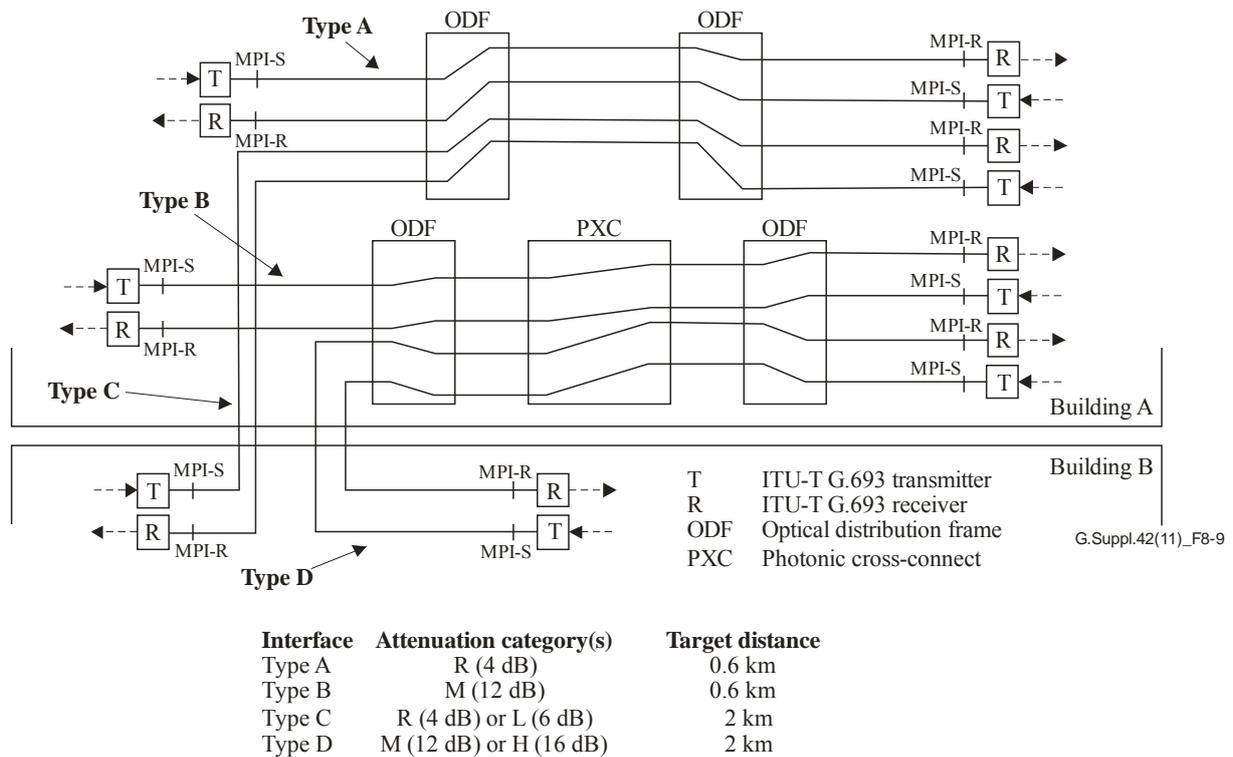


Figure 8-9 – Examples of system configurations using applications defined in Recommendation ITU-T G.693

For the choice of the most suitable application code, it is necessary to know the length of the intra-office link, the bit rate of the connection, the type of fibre available and the total loss of the network elements (e.g., ODF, PXC, connectors) present in the link.

8.5.4 Recommendation ITU-T G.695 "Optical interfaces for coarse wavelength division multiplexing applications"

The purpose of Recommendation ITU-T G.695 is to provide optical interface specifications towards the realization of transversely compatible coarse wavelength division multiplexing (CWDM) systems.

In general CWDM systems are considered as a cheaper and simpler alternative to DWDM systems for particular applications in the access/metro network. This is especially valid for bit rates up to 2.5 Gbit/s, where less expensive uncooled lasers may be used in CWDM products because of the wide channel spacing (20 nm). These lasers require less precise wavelength control, as well as lower-cost passive components. On the other side, the maximum number of optical channels in a CWDM system is lower than that of DWDM systems. In a recent revision of Recommendation ITU-T G.695 application codes for 10 Gbit/s rates have been added either to provide network upgrade scenarios or to provide OTN interfaces for the new 4-channel applications at the OTL3.4 bit rate (OTU3 striped across four physical lanes) according to [ITU-T G.709]. These latter interfaces are intended to enable a fairly low-cost reuse of optical devices developed for the new [IEEE 802.3ba] 10 km multi-lane 40GE interfaces.

The principle purpose of Recommendation ITU-T G.695 is to enable transversely (multi-vendor) compatible interfaces. Applications are defined using two different methods, one using multichannel interface parameters (black-box approach) and the other using single-channel interface parameters (black link approach) (see clause 8.5). Both unidirectional and bidirectional applications are specified.

In particular, Recommendation ITU-T G.695 defines and provides values for optical interface parameters of physical point-to-point and ring CWDM system applications at bitrates up to 10 Gbit/s on single-mode optical fibres with target distances ranging from 10 km to 90 km.

Applications are specified for links without line amplifiers, but they may optionally contain OADMs.

Recommendation ITU-T G.695 describes CWDM optical line systems that include the following features:

- i) maximum number of channels: up to 16 with a channel spacing of 20 nm, as specified in Recommendation ITU-T G.694.2 (see clause 8.4.2);
- ii) bit rate of signal channel: NRZ 1.25 Gbit/s, 2.5 Gbit/s and 10 Gbit/s.

Specifications are organized according to application codes. Applications are defined for short-haul and long-haul on fibres specified in Recommendation ITU-T G.652 (see clause 8.3.1), Recommendation ITU-T G.653 (see clause 8.3.2) and Recommendation ITU-T G.655 (see clause 8.3.4).

In Appendix I of ITU-T G.695, the assumed maximum and minimum attenuation and chromatic dispersion values at the operating wavelengths foreseen in Recommendation ITU-T G.695 are given to evaluate the expected reach (for high-loss fibres and for low-loss fibres) of the specified CWDM systems.

The maximum number of express OADMs in a path is constrained by several parameters. In Appendix III of ITU-T G.695, some formulas and calculations are given to calculate the maximum number of express OADMs as a function of the following parameters: maximum channel insertion loss for the application code being used, maximum optical multiplexer insertion loss, maximum optical demultiplexer insertion loss, numbers of connectors and their insertion loss, attenuation coefficient of the fibre, insertion loss of the OADM.

8.5.5 Recommendation ITU-T G.696.1 "Longitudinally compatible intra-domain DWDM applications"

Recommendation ITU-T G.696.1 provides physical layer specifications for intra-domain (IaD) DWDM optical networking applications with or without line amplifiers which (for links with line amplifiers) may cover distances of more than 1,000 km.

The goal is to enable longitudinally compatible applications (see clause 8.5) inside an administrative domain. The primary purpose of Recommendation ITU-T G.696.1 is to enable multiple vendors to design DWDM transmission equipment for fibre links that are compliant with Recommendation ITU-T G.696.1. The corresponding reference configuration is shown in Figure 8-10.

Recommendation ITU-T G.696.1 specifies only longitudinally compatible applications because the specification of transversally compatible applications for DWDM systems with many line optical amplifiers (even if it gives more flexibility in the deployment of the systems) is very difficult and requires unacceptable margin. This is due to the fact that the design of very long DWDM systems is the result of a sophisticated optimization/compromise among a lot of different parameters/constraints which makes the coexistence in the same DWDM system of equipment from different manufacturers (as happens in transversally compatible applications) extremely difficult to standardize.

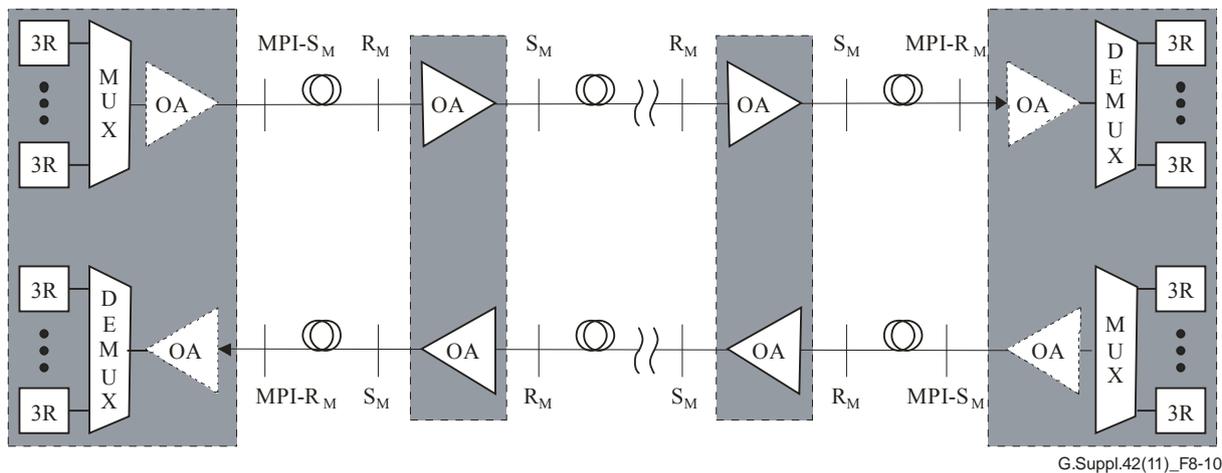


Figure 8-10 – Reference configuration for a multi-span DWDM system

Recommendation ITU-T G.696.1 defines the generic term client class that refers to the client bit rate within an optical channel before additional FEC bytes have been added. Various specific client classes have then been introduced, namely 1.25G, 2.5G, 10G, 40G.

The specifications are organized according to application codes, which take into account parameters such as operating wavelength ranges of the optical amplifiers, combinations of channel counts, client classes, span distances, fibre types and system configurations.

Theoretical limits and design considerations for DWDM systems are indicated in an appendix. In particular, ASE noise (characterized by OSNR) and PMD limits are illustrated by both general equations and specific examples based on reference systems with up to 35 spans (2,800 km in length on the assumption of a mean value of 80 km per span).

Other effects that limit transmission distance are mentioned as well, such as accumulated gain ripples and stimulated Raman effects, non-uniform span length, optical non-linearity, residual dispersion, accumulated PDL effects, filtering and crosstalk. A number of techniques used to mitigate impairments are summarized, including dynamic gain equalization, line coding (i.e., modulation format), number of optical channels and their spacing, fibre types, mixing different types of fibre within one span, receiver (detection scheme) and digital equalization. The motivation and benefits for mixed transmission of 10 Gbit/s, 40 Gbit/s and 100 Gbit/s transmission wavelengths are briefly outlined as well as the corresponding issues and challenges of mixed ASK/PSK or mixed PSK/PSK transmission. Finally, for 100G applications, particular technologies are indicated, such as advanced modulation formats including DP-QPSK, to overcome OSNR and PMD limitations.

8.5.6 Recommendation ITU-T G.698.1 "Multichannel DWDM applications with single-channel optical interfaces"

The purpose of Recommendation ITU-T G.698.1 is to provide optical interface specifications towards the realization of transversely compatible dense wavelength division multiplexing (DWDM) systems primarily intended for metro applications.

Recommendation ITU-T G.698.1 defines and provides values for single-channel optical interface parameters of physical point-to-point and ring DWDM applications (with transmission distance in the range of about 30 km to about 80 km) on single-mode optical fibres through the use of the "black link" approach (see clause 8.5).

Applications containing amplifiers within the black link are outside of the scope of Recommendation ITU-T G.698.1. These applications are described in Recommendation ITU-T G.698.2 (see clause 8.5.7).

In Recommendation ITU-T G.698.1 (as well as in Recommendation ITU-T G.698.2) DWDM systems are described that include the following features:

- i) Channel frequency spacing: 100 GHz and wider (defined in Recommendation ITU-T G.694.1, see clause 8.4.1) for 2.5 and 10 Gbit/s applications;
- ii) Channel frequency spacing: 50 GHz (defined in Recommendation ITU-T G.694.1, see clause 8.4.1) for 10 Gbit/s applications.

Specifications are organized according to application codes. In the current version of Recommendation ITU-T G.698.1, 2.5G and 10G NRZ applications both with and without forward error correction (FEC) are listed. Applications are defined for fibres specified in Recommendation ITU-T G.652 (see clause 8.3.1), Recommendation ITU-T G.653 (see clause 8.3.2) and Recommendation ITU-T G.655 (see clause 8.3.4) in the C- or L-band.

Figure 8-11 shows as an example the linear black link approach in the unidirectional configuration. Here, the S_S and R_S reference points can be seen. Included in the DWDM network elements in this example is an OADM.

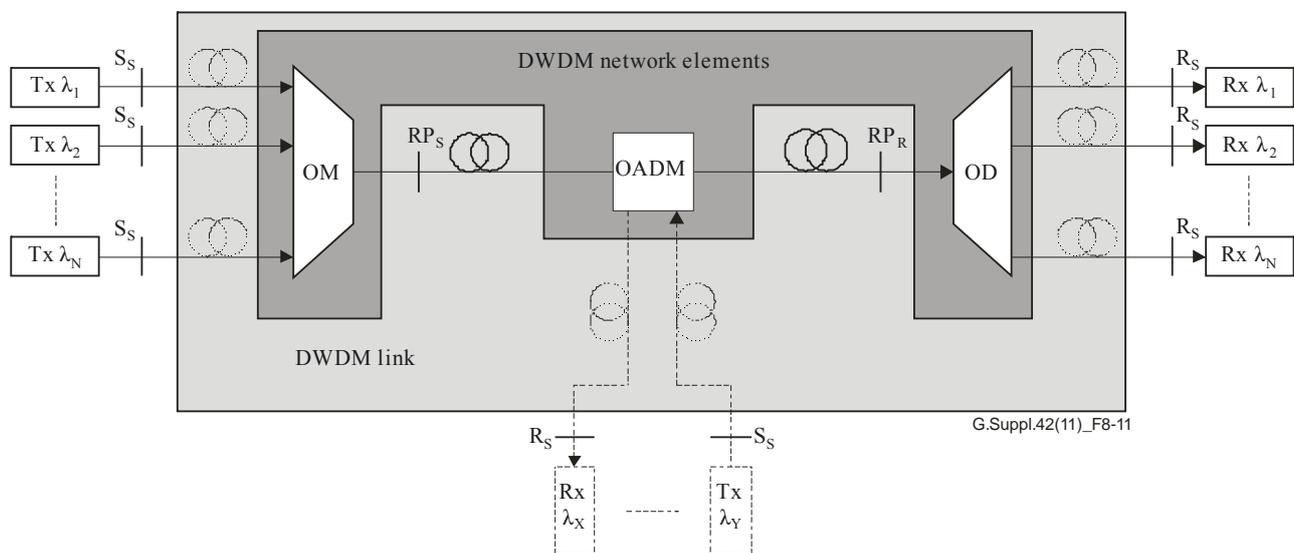


Figure 8-11 – Example of a linear configuration using black link approach

It must be mentioned that this configuration is only an example. Ring applications or also linear configurations with more OADMs are also possible, as well as applications without any OADM included.

In an appendix, which does not form an integral part of Recommendation ITU-T G.698.1, some indications are given on the way to evaluate the maximum number of OADMs which can be supported in a link and the maximum length of the link itself.

The maximum number of OADMs which can be supported is constrained by the parameters which characterize the optical path between S_S and R_S (see for example Figure 8-11). In the appendix, some formulas and calculations are given to describe possible limitations and restrictions in regard to the following parameters: maximum channel insertion loss, maximum ripple, maximum chromatic dispersion, reflections, maximum differential group delay and maximum interferometric crosstalk.

8.5.7 Recommendation ITU-T G.698.2 "Amplified multichannel dense wavelength division multiplexing applications with single channel optical interfaces"

The purpose of Recommendation ITU-T G.698.2 is to provide optical interface specifications towards the realization of transversely compatible dense wavelength division multiplexing (DWDM) systems primarily intended for metro applications which include optical amplifiers.

Recommendation ITU-T G.698.2 defines and provides values for single-channel optical interface parameters of physical point-to-point and ring DWDM applications on single-mode optical fibres through the use of the "black link" approach (see clause 8.5).

The definition of single channel optical interfaces for DWDM systems enables the elimination of transponders which would otherwise be needed in multi-vendor DWDM optical transmission networks. Appendix II of Recommendation ITU-T G.698.2 clearly shows the cases of interconnection of DWDM line systems with transmitters and receivers compliant and non-compliant with the interfaces specified in Recommendation ITU-T G.698.2.

Specifications are organized according to application codes. An example is given in Figure 8-12. These application codes are focused on features of the single-channel interfaces and do not define the elements or the structure of the DWDM link.

The current version of Recommendation ITU-T G.698.2 covers:

- i) highest class of optical tributary signal: NRZ 2.5G and NRZ 10G;
- ii) operating wavelength range: C-band, L-band;
- iii) channel frequency spacing: 50 GHz and 100 GHz (defined in Recommendation ITU-T G.694.1, see clause 8.4.1);
- iv) type of optical fibre: ITU-T G.652 and ITU-T G.653 fibres for C-band (1530-1565 nm), ITU-T G.653 fibre for L-band (1565-1625 nm);
- v) black link dispersion compensation regime: dispersion compensated (the black-link chromatic dispersion values are appropriate to a link that includes dispersion compensators between points S_S and R_S), dispersion un-compensated (the black link chromatic dispersion values are appropriate to a link that does not include any dispersion compensators or is only partially compensated).

Some applications require forward error correction (FEC) bytes as specified in [ITU-T G.709].

Future revisions of Recommendation ITU-T G.698.2 are expected to include application codes for bit rates up to 40 Gbit/s.

Figure 8-12 shows a ring application to illustrate the "black link" approach together with the single channel reference points R_S and S_S . The arrangement of elements within the black link is only an example, and Recommendation ITU-T G.698.2 does not intend to place constraints on the construction of such a black link.

For the choice of the most suitable application code, it is necessary to know the bit rate of the connection, the type of the fibre available, the wavelength range the DWDM link was designed for, the requirements of the DWDM link on the spectral excursion of the transmitters (narrow or wide spectral excursion), the minimum OSNR supplied by the DWDM link, and the range of the optical power at point R_S .

The requirements of the DWDM link on the spectral excursion of the transmitters are related to the optical bandwidth of the wavelength multiplexers, de-multiplexer and OADMs as well as the total number of these devices cascaded in the black link.

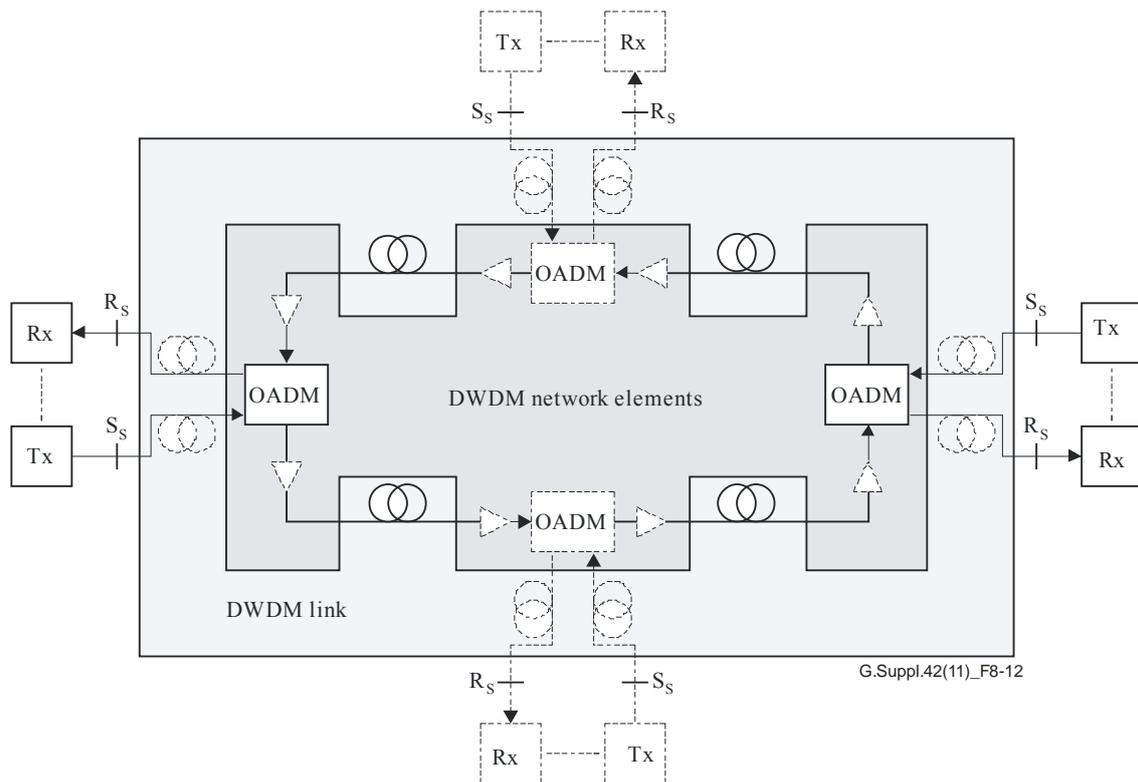


Figure 8-12 – Example of a ring configuration using black link approach

8.5.8 Recommendation ITU-T G.957 "Optical interfaces for equipments and systems relating to the synchronous digital hierarchy"

Recommendation ITU-T G.957 covers optical interface specifications for equipments and systems supporting the synchronous digital hierarchy (SDH) defined in [ITU-T G.707] and operating on single-mode optical fibres conforming to Recommendations ITU-T G.652, ITU-T G.653 and ITU-T G.654.

The purpose of Recommendation ITU-T G.957 is to provide optical interface specifications for SDH equipment, described in Recommendation ITU-T G.783, to achieve the possibility of transverse (multi-vendor) compatibility on elementary cable sections of single-channel STM-1, STM-4 and STM-16 intra-office and inter-office systems which do not use any type of optical amplifiers. The transverse (multi-vendor) compatibility means the possibility of mixing various manufacturers' equipments within a single optical section (see clause 8.5).

Recommendation ITU-T G.957 was the first Recommendation on optical systems. It was prepared in the latter part of the 1980's and approved in its first version in 1990. At that date, optical amplifiers were not yet available on the market and the reach without regeneration was limited. This explains why maximum distance foreseen for the systems specified in Recommendation ITU-T G.957 is limited at 80 km (at 1550 nm) and why all are single-channel systems.

During the development of Recommendation ITU-T G.959.1 (see clause 8.5.9), a number of the STM-16 applications in Recommendation ITU-T G.957 were used as the basis for similar applications in Recommendation ITU-T G.959.1 where they apply to both STM-16 and OTU1. However, since these applications are specified for a bit error ratio (BER) of 10^{-10} in Recommendation ITU-T G.957 and the BER requirement is 10^{-12} in Recommendation ITU-T G.959.1, it was decided to leave these applications as they are in Recommendation ITU-T G.957 and create new ones in Recommendation ITU-T G.959.1 with slightly different parameter values.

In Recommendation ITU-T G.957, the single-channel optical systems specified have the following features:

- target distances ranging from 2 km to 80 km;
- STM level: STM-1 (\approx 155 Mbit/s), STM-4 (\approx 622 Mbit/s), STM-16 (\approx 2.5 Gbit/s);
- wavelength of the source: 1310 nm, 1550 nm;
- type of optical fibre: ITU-T G.652, ITU-T G.653, ITU-T G.654.

The intra-office and short-haul inter-office application codes have been chosen as low-cost equipment implementations. The long-haul application codes have been chosen to provide maximum length repeater spans consistent with limits set by technology of that moment and the objective of transverse compatibility.

Recommendation ITU-T G.957 also contains a description of how to use the parameters of the application codes to obtain a common system design approach for engineering SDH optical links. In particular: design assumptions, worst-case design approach, statistical design approach, upgradeability considerations and joint engineering are dealt with.

Recommendation ITU-T G.957 contains two annexes (normative) and four appendices (informative). Annex A provides information on the choice of range of operating wavelengths which is determined by fibre attenuation and by fibre dispersion. Appendix III presents a possible method for determining the contribution to aging effects in the specification of receiver sensitivity. Appendix IV gives two examples for accomplishing upgradeability.

8.5.9 Recommendation ITU-T G.959.1 "Optical transport network physical layer interfaces"

The purpose of Recommendation ITU-T G.959.1 is to provide transversely compatible optical interface specifications to enable multi-vendor interoperability of nominal 2.5 Gbit/s, 10 Gbit/s, 25 Gbit/s (used to transport OTU4 striped across 4 lanes) and 40 Gbit/s systems for links without line amplifiers.

Earlier Recommendations (Recommendations ITU-T G.957 and ITU-T G.691) included similar specifications at 2.5 Gbit/s and 10 Gbit/s but these only applied to the specific SDH rates of 2.48832 and 9.95328 Gbit/s for STM-16 and STM-64 respectively. When Recommendation ITU-T G.959.1 was developed to cover the equivalent OTN rates (2.666 and 10.709 Gbit/s) it was decided to introduce the concept of "optical tributary signal class" rather than making the new specifications specific to the OTN rates. Consequently, many of the application codes in Recommendation ITU-T G.959.1 begin with the letter "P" (indicating that they are "plural" codes) and apply to an optical tributary signal class rather than to a specific bit rate. An example of this is the application P1I1-2D2 which applies to the optical tributary signal class NRZ 10G and therefore the same optical specifications can be applied to a link carrying STM-64 as to one carrying OTU2.

Because transmission of the FEC bytes in the OTN frame is defined to be optional in [ITU-T G.709], the optical specifications for application codes that begin with the letter "P" take no account of any improvement in the optical power budget that the use of FEC may bring. There are, however, some application codes (those that do not begin with the letter "P") that require the FEC bytes to be transmitted and take account of this in the optical specifications. These latter codes can only be applied to a link carrying one specific OTN rate (OTU1, OTU2, OTU3 or OTU4).

Unlike the earlier Recommendations, Recommendation ITU-T G.959.1 includes not only interfaces with a single channel per optical fibre but also multichannel applications using DWDM.

Recommendation ITU-T G.959.1 covers:

- i) target distances ranging from 2 km to 160 km;
- ii) highest class of optical tributary signal supported: NRZ 2.5G, NRZ 10G, NRZ 25G and NRZ 40G;
- iii) single- and multichannel applications;
- iv) source and fibre type: 1310 nm sources on ITU-T G.652 fibre, 1550 nm sources on ITU-T G.652 fibre, 1550 nm sources on ITU-T G.653 fibre, 1550 nm sources on ITU-T G.655 fibre.

Some applications require forward error correction (FEC) bytes as specified in [ITU-T G.709] to be transmitted.

In many cases, deciding on the bit rate, target distance, fibre type and whether FEC bytes are required to be transmitted or not is sufficient to select a single application code. For some applications in the NRZ 10G class there is a choice of whether the receiver is capable of dispersion compensation or not, and for some applications in the NRZ 40G class a choice must be made as to whether adaptive dispersion compensation is included or not.

8.6 Free space optical systems

8.6.1 Recommendation ITU-T G.640 "Co-location longitudinally compatible interfaces for free space optical systems"

Recommendation ITU-T G.640 provides a procedure for establishing that two co-located free space optical (FSO) transmission systems will not interfere with each other.

Free space optical systems carry high speed data through the air on a beam of light transmitted by highly focused sources, located on rooftops or in building windows and linked by line of sight. The technology is very similar to fibre optics, except the medium is air instead of fibre.

Early FSO technology had issues with the free space laser signals being lost during inclement weather (mainly fog) and building movements due to the solar and wind loading, decreasing the system's availability.

In the last few years, improvements in FSO technology (e.g., receivers with higher sensitivity, tracking systems) has enabled the achievement of higher availability on distances of 1-2 km and with a capacity up to 2.5 Gbit/s.

There are particular situations (e.g., emergency, back-up, crossing rivers) where FSO presents the opportunity to realize short point-to-point links at a lower installed cost and in a fraction of the time when compared to fibre links.

In the deployment of FSO systems, a frequent situation is to have terminals of different systems co-located.

Recommendation ITU-T G.640 defines optical interfaces for "co-location longitudinally compatible" free space optical transmission systems thereby enabling interference-free coexistence of more than one point-to-point free space optical system at a location.

The reference planes in Figure 8-13 are defined as follows:

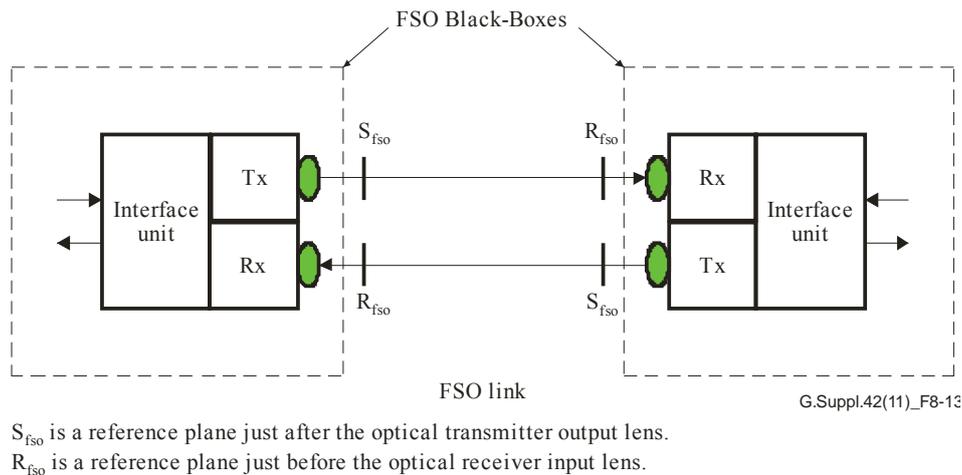


Figure 8-13 – Free space optical link reference diagram

For bidirectional systems, the two directions have to be considered separately.

The free space between the S_{fso} and R_{fso} reference planes in an FSO system is a shared medium employed by many other users for a variety of different purposes. In order to establish criteria for the co-location of FSO systems, the crosstalk ratio C generated by one system interfering with another is described, and the effect of the weather on this crosstalk ratio is considered.

The optical power penalty caused by this crosstalk is then defined for two cases:

- i) Case A, where the two systems can be at the same wavelength;
- ii) Case B, where the two systems cannot be at the same wavelength.

Recommendation ITU-T G.640 also includes definitions of parameters such as (acceptance angle, beam divergence, inter-channel crosstalk, inter-channel crosstalk penalty, interferometric crosstalk, interferometric crosstalk penalty, transmitter "or receiver" setting error and Rayleigh distance) that are relevant for the characterization of free space optical systems.

The procedure for establishing whether the conditions required to be met to prevent interference in some examples of co-located longitudinal compatibility FSO systems and information on optical safety considerations relevant to FSO systems are also provided.

Also included in Recommendation ITU-T G.640 is Appendix I which contains three examples on crosstalk calculations.

8.7 All optical networks

8.7.1 Recommendation ITU-T G.680 "Physical transfer functions of optical network elements"

The present optical transport networks (OTNs) are evolving towards optical networks with an ever-decreasing number of O/E/O conversions within their boundaries. The two main reasons for this evolution are the following:

- i) DWDM systems are becoming capable of transporting light signals for some thousands of kilometres without electrical regeneration;
- ii) Photonic cross-connects (PXC) and optical add-drop multiplexers (OADMs) are becoming available with capacity, space requirements, power consumption, reliability and cost suitable for their use in the telecommunication networks.

This evolution will lead to the deployment of a domain of optical transparency that can be large enough to ensure that all the potential routes of the backbone network of a medium size country (optical paths up to around 2,000 km) could be realized all optically.

Considering the OTN evolution described above, Recommendation ITU-T G.680 defines a "degradation function" of optical network elements (ONEs) such as photonic cross-connects (PXC), optical add-drop multiplexers (OADMs), etc., making up an optical network.

This is done in terms of a list of parameters which characterize physical impairments such as optical noise, chromatic dispersion, etc., and is intended to be independent from the network architecture that the devices are deployed in.

The present version of Recommendation ITU-T G.680 covers the reference situation 1 where the optical path between two consecutive electrical regenerators is composed of dense wavelength division multiplexing (DWDM) line segments from a single vendor and OADMs and PXC from other vendors as shown in Figure 8-14.

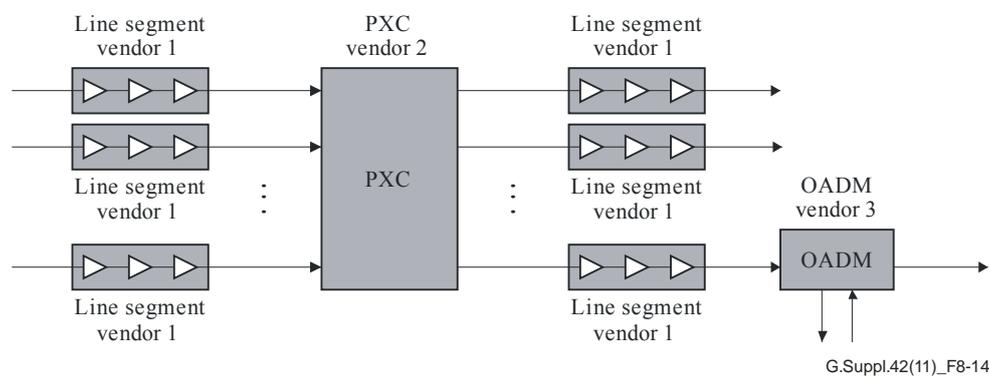


Figure 8-14 – Illustration of situation 1

A future revision of Recommendation ITU-T G.680 is expected to cover the reference situation 2, where the optical path between two consecutive 3R regenerators is composed of DWDM line segments from different vendors and OADMs and PXC from different vendors.

With regard to the reference situation 1, the information provided in Recommendation ITU-T G.680 (when taken together with the corresponding parameters from the DWDM line segments including any non-linear effects) enables the evaluation of the impact on line system performance of the combination of transfer parameters (OSNR, residual dispersion, PMD, PDL, channel ripple, transient phenomena, channel uniformity) related to the cascade of ONEs inserted in the optical path between the ingress and egress 3R electrical regenerators.

For each kind of ONE considered in Recommendation ITU-T G.680 a general functional description and a reference diagram is provided.

Principles for calculating the effect of cascading multiple ONEs on the degradation of the optical signal quality are given for each parameter on its own and for the combined effect of all of them.

There are four informative appendices to Recommendation ITU-T G.680.

In the first appendix, examples of transfer parameter values for OADMs and PXC are provided.

In the second appendix, numerical examples of the impact of cascaded ONEs on the various impairments are provided.

In Appendices III and IV, an example of how Recommendation ITU-T G.680 may be used and the potential users are identified. Moreover, a description of their different roles in that use is also provided.

In particular, Appendix III makes reference to one application of Recommendation ITU-T G.680, i.e., to enable, at the moment of the activation/rerouting of an optical channel, the calculation of the overall degradation of the chosen route (an example is indicated in Figure 8-15) on the basis of the "degradation function" of each ONE involved and to evaluate whether the overall degradation is compatible with the error performance objectives at the O/E/O 3R end-point.

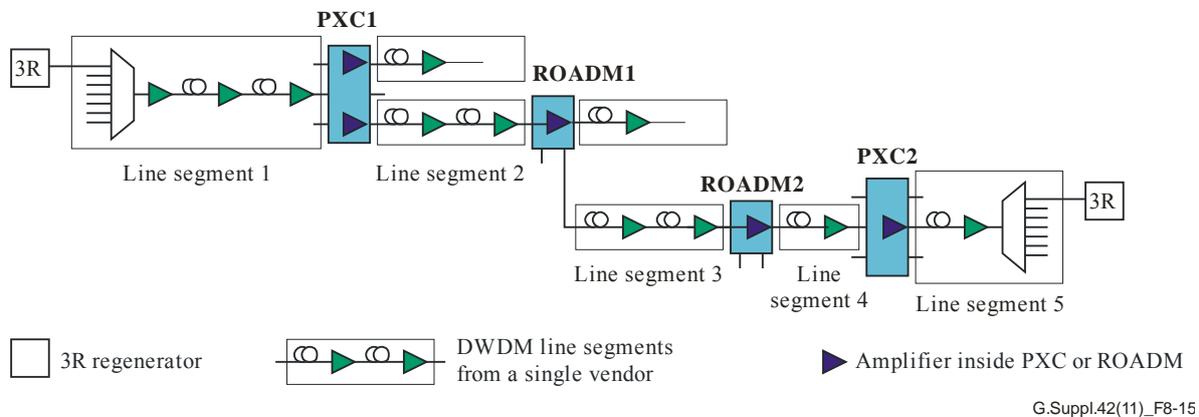


Figure 8-15 – Example optical transmission system

8.8 Optical monitoring

8.8.1 Recommendation ITU-T G.697 "Optical monitoring for dense wavelength division multiplexing systems"

Recommendation ITU-T G.697 addresses the optical monitoring of a subset of optical parameters that can be measured in a non-intrusive way, allowing in-service monitoring.

DWDM technology is improving at a rapid pace, continuously stretching the channel count, channel speeds and reach limits. Long-haul multi-span DWDM systems are capable of taking optical signals thousands of kilometres without electrical terminations or regeneration. This continuing trend is driving the increasing importance of optical monitoring.

The monitoring of an optical network can be performed following different approaches: in SDH or OTN networks, for instance, specific bytes are dedicated to carry and provide information on the quality of the transport layer. In these cases, accessing and retrieving such information would require the conversion of the optical signal back to the electrical domain and processing of the frame at that level. In contrast to this, optical monitoring provides the function of monitoring the optical signal directly without processing the electrical frame.

Optical monitoring can help in DWDM systems to perform the following activities:

- i) configuration management for system and channel activation, addition of new channels, etc.;
- ii) fault management to detect and to isolate faults;
- iii) degradation management in order to keep the system running and to detect degradations before a fault occurs.

Recommendation ITU-T G.697 firstly provides a short overview on the optical monitoring concept in the OTN, especially in relation to the digital monitoring defined in other documents, such as Recommendations ITU-T G.826 and [ITU-T G.709].

After having clarified the concept of optical monitoring, it defines and classifies the following different type of methods for measuring the optical signal degradation:

- i) Signal monitoring (direct methods) such as time domain and frequency domain methods;

- ii) Equipment monitoring (indirect methods) that make use of an empirical correlation between equipment failures.

Moreover, Recommendation ITU-T G.697 explains how monitoring can be performed by embedded monitoring equipment or by external monitoring equipment, addressing some of the advantages and issues related to the use of one type instead of the other.

An exhaustive list of impairments which can impact the quality of the optical signal is provided and the reader is referred to other ITU-T Recommendations for a more detailed description. Potentially most of those impairments can be related to parameters that can be measured. Based on the status of the current technology and associated cost, Recommendation ITU-T G.697 focuses on a subset of five parameters: total power, channel power, channel wavelength, OSNR and Q-Factor. It also shows the correlation between these monitored parameters and the impairments such as variation of attenuation, frequency (or wavelength) deviation from nominal and optical channel power changes due to gain variations.

Appendix III contains information concerning the performance obtainable from currently available optical monitoring technology and on how the impairments affect the optical signal quality.

In Appendix IV is given a list of monitoring choices which could be considered in DWDM systems, with the indication of some alternative positions of embedded monitoring points and external monitoring points for measuring the various parameters.

The recently added Appendix V contains a possible encoding scheme for the communication of information relating to optical parameters.

8.9 Optical safety

8.9.1 Recommendation ITU-T G.664 "Optical safety procedures and requirements for optical transport systems"

The purpose of Recommendation ITU-T G.664 is to provide guidelines and requirements for techniques to enable optically safe working conditions (for the human eye and skin) on optical interfaces of the optical transport network, in particular, for systems employing high-power Raman amplification techniques.

The actual definition and specification of optically safe levels are considered to be outside the scope of Recommendation ITU-T G.664. Even more, they are considered outside the scope of ITU-T. The IEC is the organization responsible for these matters. Therefore, in Recommendation ITU-T G.664 specific references are made to [IEC 60825-1], [IEC 60825-2] and [IEC/TR 61292-4].

Furthermore, Recommendation ITU-T G.664 gives some clarification of terms used in the above-mentioned IEC documents. One specific example is the clarification of the difference between "laser class" and "hazard level", a difference being of specific relevance to optical fibre communication systems.

The historical background of Recommendation ITU-T G.664 is very important for understanding its content and its objectives.

When (around 1990) the first transversely compatible optical interface Recommendation ITU-T G.957 was created, the optical levels specified therein were not considered completely safe according to the version of [IEC 60825-1] that was then valid. In order to achieve interworking between equipment from different vendors, it was considered necessary to specify a transversely compatible procedure that would guarantee optically safe levels under all working conditions, including fibre break. Therefore, in the first version of Recommendation ITU-T G.664, the automatic laser shutdown (ALS) procedure was specified.

More recently, the IEC decided that much higher levels were considered optically safe and newer versions of [IEC 60825-1] and [IEC 60825-2] were issued. As a consequence, all of the optical levels currently specified in any of the ITU-T optical interface Recommendations on transversely compatible optical interfaces (Recommendations ITU-T G.691, ITU-T G.693, ITU-T G.695, ITU-T G.698.1, ITU-T G.698.2, ITU-T G.957, ITU-T G.959.1) are considered to be safe in "restricted locations". As a result, for none of these systems it is necessary to perform optical shutdown or power reduction to achieve optically safe working conditions. Therefore, in the present version of Recommendation ITU-T G.664, the description and specification of the ALS procedure has been moved from the normative (mandatory) main body to a non-normative (informative) appendix in order to capture it for historical reasons. It should be specifically mentioned that the capturing of the ALS procedure in this appendix does not imply that it should be used.

The same considerations apply to the automatic power shut-down (APSD) procedure specified several years later for systems using optical amplifiers.

Despite the fact that, as noted above, none of the existing ITU-T optical interface Recommendations contains optical power levels that are not considered safe, there are many non-interworking based (proprietary or single-vendor) systems that are operated at potentially hazardous or dangerous optical power levels. Examples are optical transport systems using Raman amplification and DWDM systems with large channel counts. Recommendation ITU-T G.664 provides guidance on maintaining optically safe working conditions to the designers and users of these systems outlining some basic requirements for designing automatic power reduction (APR) techniques which are recommended by the IEC documents for maintaining safe conditions in these particular cases. Furthermore, some examples of APR techniques are described in an informative appendix to Recommendation ITU-T G.664. It should be noted that APR refers to a situation in which the optical power is not switched off totally, but reduced to a level sufficiently low to be considered safe.

8.10 Optical amplifiers, components and subsystems

The main purpose of this group of Recommendations is to give a minimum list of performance parameters for optical amplifiers, components and subsystems.

The definitions of these parameters are also included in these Recommendations.

In some cases, values of the parameters are also given, but in most cases the values are not indicated because they should be specified in relation to the specific application that the optical amplifier, component or subsystems is used in.

As for the test methods, for practically all the parameters reference is made to the test methods specified by the IEC.

The rationale for this subdivision of activities between ITU-T and IEC is in the following.

The main attendance in ITU-T is from operators and system manufacturers.

The ITU-T approach to standardization is top-down. Starting from the operators' network requirements, the requirements for the systems and for the equipment are defined together with the vendors. These systems are then specified and some requirements arise for the components/subsystems.

The main attendance in IEC is from component/subsystem manufacturers.

The IEC approach to the standardization is bottom-up, starting from the manufacturers and purchasers' requirements. Their specifications are made for components and subsystems, also considering the purchasers' requirements. In particular, test methods are studied very carefully as an essential factor in the relation between manufacturers and purchasers.

8.10.1 Recommendation ITU-T G.661 "Definitions and test methods for the relevant generic parameters of optical amplifier devices and subsystems"

Recommendation ITU-T G.661 provides the definitions of the relevant parameters, common to the different types of optical amplifiers (OAs), optically amplified subsystems and optical network elements (ONEs) containing OAs.

Parameters specified for OAs are those characterizing the transmission, operation, reliability and environmental properties of the OA seen as a "black-box" from a general point of view.

In Recommendation ITU-T G.661, different OA application categories are defined depending on the technology used and the utilization of the OA itself. These categories are identified by a capital letter, a number and a lower case letter.

The capital letter represents the technology used: A for Erbium-doped fibre amplifiers, B for fibre amplifiers using other doped fibres, C for Raman amplifiers, D for semiconductor optical amplifiers (SOAs) and E for planar optical waveguide amplifier (POWAs). For the utilization, the numbers 1-7 and the lower case letters a-c are used.

The parameter definitions of OAs are divided into two parts. The first part lists those parameters relevant for OA devices, namely power amplifiers, pre-amplifiers, line amplifiers, distributed amplifiers and ONEs containing OAs (the numbers in the brackets refer to the utilization numbers in the categories). The second part lists the parameters relevant for optically amplified elementary subsystems, namely the optically amplified transmitter (OAT) and the optically amplified receiver (OAR).

In Recommendation ITU-T G.662 (see clause 8.10.2), the appropriate subset of these parameters is specified according to the type and application of the particular OA device or subsystem.

Parameter definitions applicable specifically to distributed Raman amplifiers, however, can be found in Recommendation ITU-T G.665 (see clause 8.10.4).

In addition, the test methods of these parameters are described as far as applicable for OA devices and subsystems covered by ITU-T. As stated in the introduction to this clause, the guidelines to be followed for the measurement of most of the parameters are generally given in [IEC 61290].

Recommendation ITU-T G.661 applies to all commercially available OAs using optically pumped fibres (OFAs based either on rare-earth doped fibres or on the Raman effect), semiconductors (SOAs), and waveguides (planar optical waveguide amplifiers).

Two appendices are added to Recommendation ITU-T G.661.

In the first appendix, the main differences between optical fibre amplifiers and semiconductor optical amplifiers, including their respective applications, are discussed.

In the second appendix, additional terms for the environmental, mechanical, physical and reliability aspects of optical amplifier devices and subsystems are provided for information. These terms are normative terms in [IEC 61291-1].

8.10.2 Recommendation ITU-T G.662 "Generic characteristics of optical amplifier devices and subsystems"

Recommendation ITU-T G.662 applies to discrete optical amplifier (OA) devices and subsystems to be used in transmission networks. It covers both optical fibre amplifiers (OFAs) and semiconductor optical amplifiers (SOAs).

The object of Recommendation ITU-T G.662 is to identify those generic characteristics specifiable for the use of OA devices (as power amplifiers, pre-amplifiers or line amplifiers) and OA subsystems (as optically amplified transmitters or optically amplified receivers), primarily for applications in digital transmission, ensuring the maximum compatibility with ITU-T G-series

Recommendations relating to line systems and equipments such as, for example, Recommendations ITU-T G.957 or ITU-T G.959.1.

Different OA application categories are defined depending on the technology used and the utilization of the OA itself:

- the power amplifier (BA) is a high saturation-power OA device to be used directly after the optical transmitter to increase its signal power level;
- the pre-amplifier (PA) is a very low noise OA device to be used directly before an optical receiver to improve its sensitivity;
- the line amplifier (LA) is a low noise OA device to be used between passive fibre sections to increase the distance covered before regeneration is necessary or in correspondence with a point-multipoint connection to compensate for branching losses in the optical access network;
- the optically amplified transmitter (OAT) is an OA subsystem in which a power amplifier is integrated with an optical transmitter, resulting in a higher power transmitter;
- the optically amplified receiver (OAR) is an OA subsystem in which a pre-amplifier is integrated with an optical receiver, resulting in a higher sensitivity receiver;
- the distributed amplifier is a device configuration that provides amplification over an extended length of the optical fibre used for transmission, as by Raman pumping, and is thus distributed over part or all of the transmission span.

For each of the above devices, Recommendation ITU-T G.662 provides a minimum list of relevant parameters necessary for their specification.

8.10.3 Recommendation ITU-T G.663 "Application-related aspects of optical amplifier devices and subsystems"

The purpose of Recommendation ITU-T G.663 is to identify which aspects should be considered for each application of optical amplifier (OA) devices (booster amplifier, pre-amplifier and line amplifier).

Application of OAs in optical transmission systems offers a number of advantages. Chief among these advantages is the ability to realize very significant unrepeated system lengths as well as very long unregenerated system lengths. OAs also enable the realization of wavelength division multiplexing systems in a cost-effective way. OAs also offer potential advantages with respect to network upgrade options due to their independence from modulation format and bit rate.

However, the application of OAs also brings to light some potentially serious system impairments, which result from the high power levels produced by the OAs and the long distances between regeneration. These transmission effects include optical fibre non-linearities, polarization effects and effects due to the amplification characteristics of the OA itself. Chromatic dispersion also becomes increasingly significant for the long unregenerated systems enabled by the OA. In addition to determining chromatic dispersion limitations, the dispersion characteristics of the fibre influence the severity of the impairment produced by several of the dominant non-linear effects.

The current version of Recommendation ITU-T G.663 includes definitions of key terminologies relevant to the application of OA devices.

Example parameter values for optical fibre amplifier devices are shown for single-channel point-to-point systems in Appendix I of Recommendation ITU-T G.663.

The rest of the appendices provide some information that should be useful in fulfilling the objective of Recommendation ITU-T G.663. Appendix II explains transmission-related aspects such as fibre optical non-linearities, polarization properties, fibre dispersion properties, and other OA-related properties. Appendix III contains the definition of the relevant characteristic parameters of the

pre-amplifier which allow, by standard formulas, to obtain the minimum input power which ensures a BER = 10^{-12} at the terminal receiver equipment. Appendix IV gives possible generic operation, administration, and maintenance aspects for OA sub-systems and devices.

8.10.4 Recommendation ITU-T G.665 "Generic characteristics of Raman amplifiers and Raman amplified subsystems"

Recommendation ITU-T G.665 identifies the definitions and test methods of performance parameters of the following fibre Raman amplifiers and Raman amplified subsystems:

- i) forward pumped Raman amplifiers;
- ii) reverse pumped Raman amplifiers;
- iii) bidirectionally pumped Raman amplifiers;
- iv) discrete Raman amplifiers (including composite discrete Raman/erbium amplifiers);
- v) composite forward pumped Raman and discrete amplifiers;
- vi) composite reverse pumped Raman and discrete amplifiers;
- vii) composite bidirectionally pumped Raman and discrete amplifiers.

Distributed Raman amplifiers are amplifiers where the amplification effect is achieved via the stimulated Raman scattering (SRS) effect in a portion of the optical fibre used for transmission. Such amplifiers are deemed to be distributed since part or all of the transmission fibre is used for amplification purposes.

A discrete Raman amplifier is an amplifier for optical signals whose amplification effect is also achieved via the fibre SRS effect, where all of the physical components of the amplifier are completely contained inside the device.

There are several types of possible Raman amplifier applications. As an example, there is the possibility of increasing the optical signal-to-noise ratio enabling an increase of the reach in particular DWDM systems (e.g., for submarine links without line amplifiers) or the possibility of increasing the number of channels in DWDM systems by obtaining a wider gain bandwidth by using Raman amplification. However, Raman amplification is not without some challenges. Distributed Raman amplification systems often use very high powers (sometimes more than 1 W (+30 dBm)) to obtain the desired per-span amplification. To mitigate exposure risks in the handling of the power levels present in Raman amplifiers, deployment of automatic laser shutdown and particular personnel training are necessary (see clause 8.9.1).

Recommendation ITU-T G.665 provides for each of the above amplifier types a reference diagram together with a generic set of characteristic parameters including the appropriate measurement points for each one and a reference to a test method.

The definitions of the various parameters are split into the following categories:

- i) optical signal power parameters;
- ii) gain parameters;
- iii) gain spectrum parameters;
- iv) noise parameters;
- v) pump power parameters;
- vi) pump leakage parameters;
- vii) polarization-dependent parameters;
- viii) channel addition/removal response;
- ix) reflectance parameters;

- x) insertion loss parameters;
- xi) other parameters.

Included in Recommendation ITU-T G.665 are three informative appendices: Appendix I covers measurements of multi-path interference (MPI), Appendix II gives details of physical and equivalent models of distributed Raman amplifiers, and Appendix III describes the differences in interface conventions between ITU-T and IEC for optical links and components.

8.10.5 Recommendation ITU-T G.666 "Characteristics of polarization mode dispersion compensators and of receivers that compensate for polarization mode dispersion"

Recommendation ITU-T G.666 contains parameters and definitions for devices providing polarization mode dispersion (PMD) compensation needed for transmission and detection of optical signals in a system exhibiting high levels of PMD which would otherwise cause unacceptable levels of system outage. PMD becomes an increasingly serious problem as the bit rate and the length of optical transmission systems increase. As a result, PMD compensation is an important technology for very high rate long distance systems.

Requirements and key parameters are defined in Recommendation ITU-T G.666 for first and higher order PMD compensators (PMDC) including dynamic PMD characteristics. The PMD compensating devices described include both single- and multichannel applications.

Line PMD compensators are distinguished from PMD compensating receivers which may comprise electrical as well as optical forms of PMD compensation (Figure 8-16).

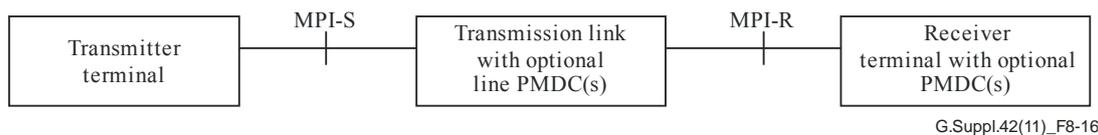


Figure 8-16 – Generic configuration of a transmission system with PMDCs

Recommendation ITU-T G.666 also contains the definition of terms relevant to the PMDC applications. For each type of PMDC, a reference configuration is given together with a list of parameters suitable for its characterization.

There are two informative Appendices to Recommendation ITU-T G.666.

Appendix I covers approaches to the measurement of the parameters of PMDCs. A test configuration contains a transmission link with PMD tuning capabilities (thus including a PMD emulator) followed by a test instrumentation to measure the PMDC characteristics. Two types of PMD emulator implementations are described: the first example is suitable for the evaluation of a PMDC receiver with respect to dynamic DGD tolerance and the second example supports the evaluation of a PMDC receiver with respect to static PMD tolerance for first order and second order PMD.

In Appendix II, single-channel and multichannel PMDC receiver implementation options are indicated including electrical as well as optical realization schemes.

8.10.6 Recommendation ITU-T G.667 "Characteristics of adaptive chromatic dispersion compensators"

Recommendation ITU-T G.667 contains definitions and parameters for devices providing adaptive chromatic dispersion compensation needed for transmission and detection of optical signals in a system exhibiting dynamic variation of chromatic dispersion which would otherwise impair system operation.

The adaptive dispersion compensating devices described include both single- and multichannel applications.

ADCs are expected to be used in at least two applications:

- The first is to use the ADC to compensate for slow changes of link dispersion over time due to environmental effects, such as temperature. This is referred to as a slow change link dispersion application (examples of this application are in Appendix II of Recommendation ITU-T G.667).
- The second is to use the ADC to compensate for sudden step changes of link dispersion due to switching or other transmission link re-configuration processes. This is referred to as a step change link dispersion application (one example of this application is given in Appendix II of Recommendation ITU-T G.667).

Recommendation ITU-T G.667 distinguishes line adaptive dispersion compensators (ADCs) from ADC transmitters and receivers which may comprise electrical as well as optical forms of chromatic dispersion compensation (Figure 8-17).

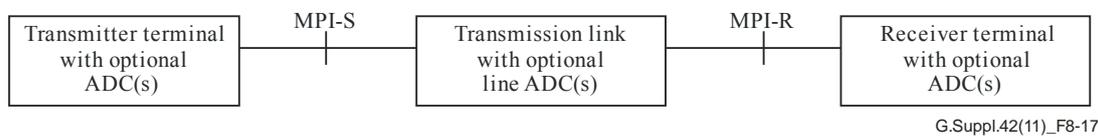


Figure 8-17 – Generic configuration of a transmission system with ADCs

Recommendation ITU-T G.667 also contains the definition of the terms relevant to ADC devices. For each type of ADC device, a reference configuration is given together with a table with the parameters suitable for its characterization.

There are two informative appendices to Recommendation ITU-T G.667.

In Appendix I, information on single-channel and multichannel adaptive chromatic dispersion compensation implementations is provided.

In Appendix II, the principles of adaptive dispersion compensation are illustrated (Figure 8-18). Also included in Appendix II are some configurations that employ adaptive dispersion compensators incorporating a dispersion monitoring function implemented with a variety of methods.

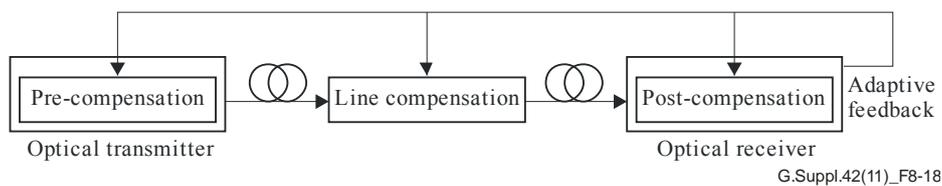


Figure 8-18 – Adaptive dispersion compensation principles

8.10.7 Recommendation ITU-T G.671 "Transmission characteristics of optical components and subsystems"

The objective of Recommendation ITU-T G.671 is to identify the transmission-related parameters for each of the components listed below and define the values of such parameters specifiable for each of the most relevant system applications. Systems where these components are anticipated to be applied are covered by the following ITU-T Recommendations:

- i) long-haul terrestrial networks: networks using equipment with interfaces according to Recommendation ITU-T G.957 and Recommendations of optical interfaces for single-channel and multichannel systems with optical amplifiers including Recommendations ITU-T G.691, ITU-T G.692, ITU-T G.698.1, ITU-T G.698.2 and ITU-T G.959.1;
- ii) access networks: networks using equipment according to ITU-T G.98x-series Recommendations related to optical access networks.

Where possible, common parameter values are defined across all applications, but where necessary, specific values to each of the application groups may be given.

In particular, transmission characteristics in the various operating conditions of the following optical components are defined:

- i) optical add-drop multiplexer (OADM) subsystem;
- ii) asymmetric branching component;
- iii) optical attenuator;
- iv) optical branching component (wavelength non-selective);
- v) optical connector;
- vi) dynamic channel equalizer (DCE);
- vii) optical filter;
- viii) optical isolator;
- ix) passive dispersion compensator;
- x) optical splice;
- xi) optical switch;
- xii) optical termination;
- xiii) tuneable filter;
- xiv) optical wavelength multiplexer (MUX)/demultiplexer (DMUX):
 - coarse WDM device;
 - dense WDM device;
 - wide WDM device.

More than sixty-five definitions of the various components, parameters and terms are provided in Recommendation ITU-T G.671.

8.11 Optical fibre submarine cable systems

Optical fibre submarine cable systems are an important element of telecommunication networks because they allow the connection of terminal stations divided by a sea. These links can be of very different lengths starting from a few kilometres (for linking to islands just offshore) up to several thousands of kilometres (for linking different continents through the oceans). These very different applications require very different transmission capabilities.

Submarine systems are substantially different from terrestrial ones in many aspects because the environmental conditions where they operate drive more severe requirements. There are essentially two basic requirements:

- i) a very high reliability for the submerged plant considering that each fault needs the intervention of a cable-ship and each of these interventions lasts some days;
- ii) a very long operational lifetime considering the high costs of development, manufacturing and laying of a submarine link with the stringent reliability objectives noted above.

As a consequence, all of the Recommendations on optical fibre submarine cable systems deal not only with the electrical/optical characteristics, but also with the mechanical/reliability characteristics. Moreover, a detailed description is made of the tests to be carried out during the various phases of the realization from manufacturing to final acceptance.

There is another aspect which sets submarine systems apart from terrestrial ones and affects the four Recommendations related to systems (Recommendations ITU-T G.973, ITU-T G.973.1, ITU-T G.974, ITU-T G.977). Submarine systems are interconnected to terrestrial ones at the two terminal stations and at these interfaces they have to be compliant with the SDH/OTN interfaces ([ITU-T G.707]/[ITU-T G.709]). For the specification of the submarine system itself (the connection between the two terminal stations) the situation is different from that of the terrestrial systems for two main reasons:

- i) the components of a terrestrial link often come from different vendors (fibres, cables, DWDM equipment, OADM, etc.), while the supply of a submarine link is usually made "turnkey" by a single vendor. This means that a single company supplies all that is necessary for the realization of the link between the two interfaces with the terrestrial networks;
- ii) the installation of all of the submerged equipment required for the final capacity of the system (optical amplifiers, branching units, etc.) is carried out at the time of the laying of the system.

These two differences have an impact on the way the specifications are written. For terrestrial systems, as pointed out in clause 8.5, the applications specified are either longitudinally compatible or transversely compatible in order to enable some level of multi-vendor interoperability. For submarine systems, neither of these types of compatibility are generally very useful because the equipment for all of the links and for all the optical fibres of the submarine cable are sourced from the same supplier at the time of the laying of the system. As a consequence, the Recommendations on submarine optical systems do not specify any particular application code with the values of the parameters at one particular interface, but they are focused on the identification of the parameters and of the characteristics of the submarine systems which should be carefully defined for each link. The specific values for these parameters for each system to be realized will be defined between the operator and the supplier with the objective of achieving the stringent quality objectives.

Based on the above general considerations, SG 15 has prepared and agreed several Recommendations which specifically deal with optical fibre submarine cable systems (Recommendations ITU-T G.971, ITU-T G.972, ITU-T G.973, ITU-T G.973.1, ITU-T G.974, ITU-T G.975, ITU-T G.975.1, ITU-T G.976, ITU-T G.977 and ITU-T G.978) (see clauses 8.11.1 to 8.11.10).

8.11.1 Recommendation ITU-T G.971 "General features of optical fibre submarine cable systems"

The purpose of Recommendation ITU-T G.971 is to provide generic information on the Recommendations dealing with optical fibre submarine cable systems and to identify the main features of this category of systems.

Relationships among Recommendations relevant to optical submarine cable systems are shown in Figure 8-19. This figure shows that the Recommendations can be divided into five categories: definitions, test methods, fibres and cables, forward error correction and optical systems.

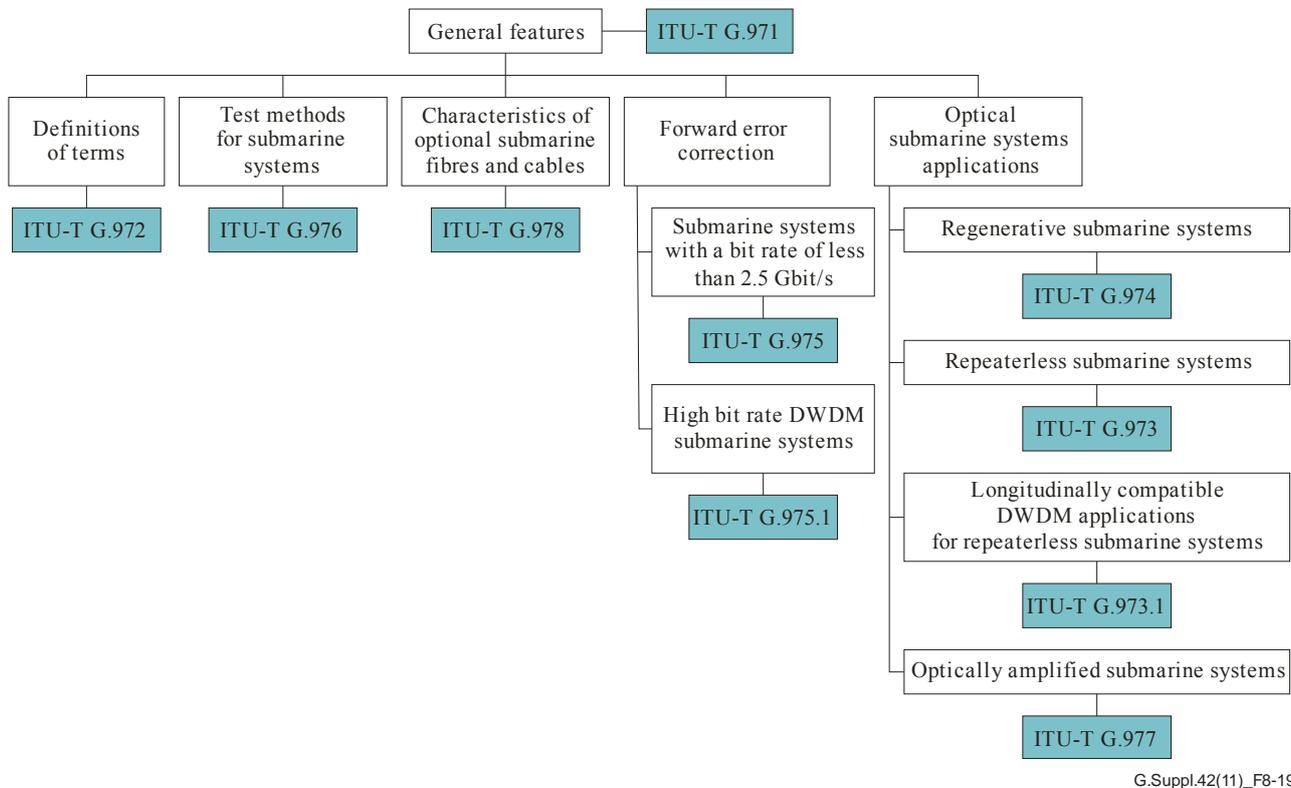


Figure 8-19 – Relationship among Recommendations relevant to optical submarine cable systems

The main features which are common to all optical fibre submarine cable systems (lifetime, reliability, mechanical and transmission characteristics) are described in Recommendation ITU-T G.971.

Moreover, Recommendation ITU-T G.971 describes common implementation aspects of submarine cable systems, such as manufacturing, installation and maintenance.

One of the main implementation aspects of installation and maintenance is related to the cable-ships:

- i) the submarine cable laying is normally performed using a recognized cable-ship after any necessary route surveys in deep and shallow water have been carried out;
- ii) the submarine cable may also be buried in the seabed to increase cable protection. Burial can be undertaken during laying using a sea plow towed by the laying cable-ship, or after laying using a self-propelled submersible robot or other means;
- iii) optical fibre submarine cable systems can be subject to faults due, in particular, to external aggression and to component failure. The repair of these faults at sea is usually performed using dedicated repair cable-ships to facilitate repair and limit loss of traffic.

Considering the importance of the cable-ships (for laying and for repairing the cables) and of the submersible equipment (for protecting the cables) Recommendation ITU-T G.971 also contains in an appendix data on more than 30 cable-ships and on more than 30 submersible equipments of various countries.

8.11.2 Recommendation ITU-T G.972 "Definition of terms relevant to optical fibre submarine cable systems"

Recommendation ITU-T G.972 provides the definitions of terms relevant to optical fibre submarine cable systems.

The definitions are divided into the following groups:

- i) elements of system configuration;
- ii) system aspects;
- iii) terminal equipment;
- iv) optical submarine repeaters and branching units;
- v) optical fibre submarine cable;
- vi) manufacturing and installation;
- vii) maintenance of the submarine portion.

It is clear from the above list that all the aspects of the optical submarine cable systems are covered in the 182 definitions contained in Recommendation ITU-T G.972, which is a very useful tool for people involved in the field.

A small number of terms defined in Recommendation ITU-T G.972 are associated with definitions in Recommendations ITU-T G.601, ITU-T G.602 and ITU-T G.701. Reference to these definitions is given.

Some definitions make reference to a figure of Recommendation ITU-T G.971 where the basic concept of optical fibre submarine cable systems and boundaries is shown, together with the system interfaces at the terminal stations (where the submarine system is interfaced with the terrestrial digital links or with another submarine cable system).

Appendix I of Recommendation ITU-T G.972 gives the alphabetical list of terms defined in the Recommendation.

8.11.3 Recommendation ITU-T G.973 "Characteristics of repeaterless optical fibre submarine cable systems"

Recommendation ITU-T G.973 is concerned primarily with the system performance and interface requirements of repeaterless optical fibre submarine cable systems; it considers both single wavelength systems and wavelength division multiplexing systems.

The purpose of a repeaterless optical fibre submarine cable system is to establish transmission links between two or more terminal stations located in a restricted geographical area. To reduce cost and complexity of this type of submarine system, no in-line optical amplifier is used. As a consequence, no power feeding equipment is necessary. As far as the branching unit devices are concerned, those considered in Recommendation ITU-T G.973 are the passive ones, therefore avoiding electronic components as well as supervision and power feeding.

In particular, Recommendation ITU-T G.973 covers not only submarine systems with no optical amplifiers, but also submarine systems using discrete optical fibre amplifiers as power amplifiers, pre-amplifiers and/or remote optically pumped amplifiers (ROPA) (either erbium-doped transmission fibres using remote pumping from the terminal or using the distributed Raman amplification pumped from the terminal). Examples of configurations covered by Recommendation ITU-T G.973 are indicated in Figure 8-20.

Recommendation ITU-T G.973 refers to the system characteristics required to guarantee the performance, the reliability (usually 25 years starting at the provisional acceptance date of the system) and the capacity upgradeability. In the current version of Recommendation ITU-T G.973,

characteristics and performance of terminal equipments and submarine system interfaces are detailed with references to PDH, SDH and OTN terrestrial system Recommendations.

The submarine cable specifications can be found in Recommendation ITU-T G.978 (see clause 8.11.10).

Annexes A and B of Recommendation ITU-T G.973 describe a physical implementation of repeaterless optical fibre submarine cable systems and the implications of the use of ROPA on the optical power budget.

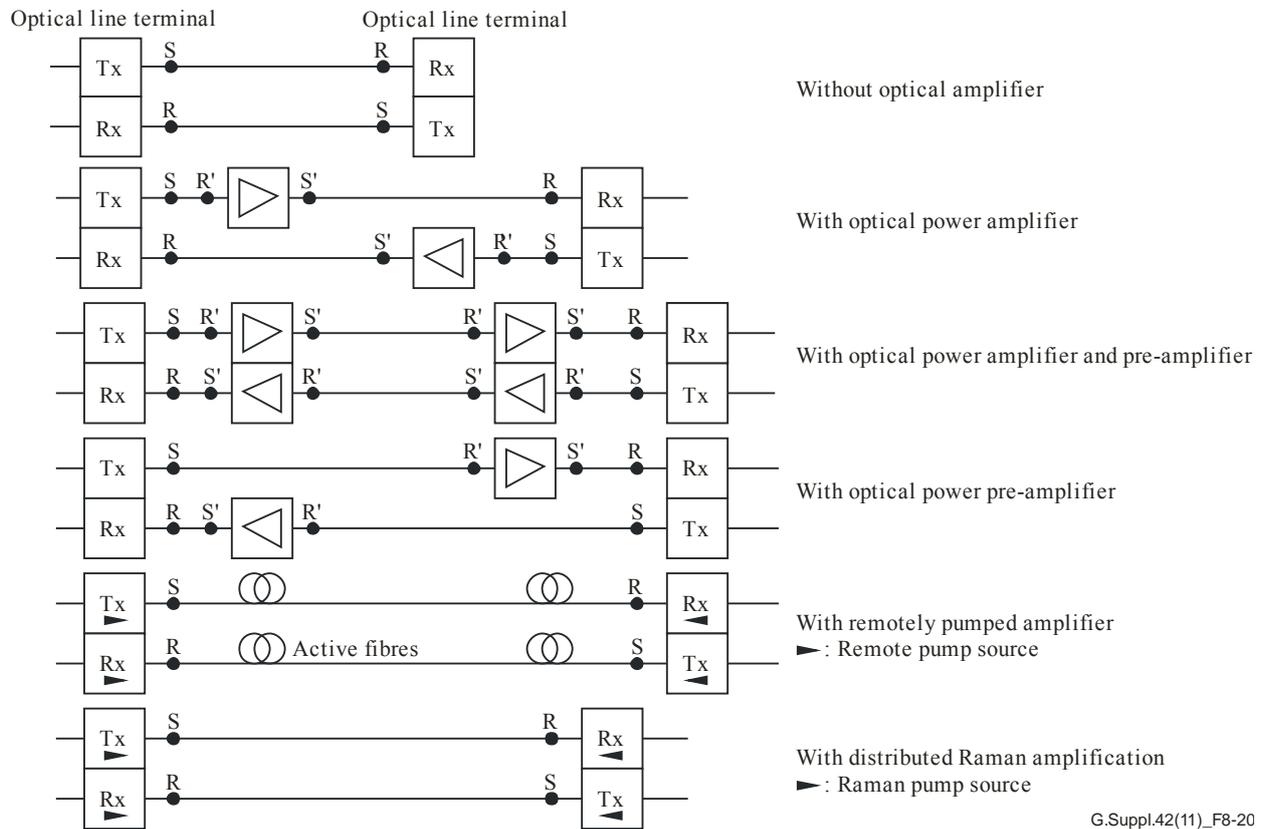


Figure 8-20 – Possible repeaterless system configurations

8.11.4 Recommendation ITU-T G.973.1 "Longitudinally compatible DWDM applications for repeaterless optical fibre submarine cable systems"

Recommendation ITU-T G.973.1 provides physical layer specifications for dense wavelength division multiplexing (DWDM) applications in point-to-point repeaterless optical fibre submarine cable systems with the primary purpose of enabling longitudinally compatible applications.

The relevant reference points applicable to the DWDM application for point-to-point repeaterless optical fibre submarine cable systems are shown in Figure 8-21.

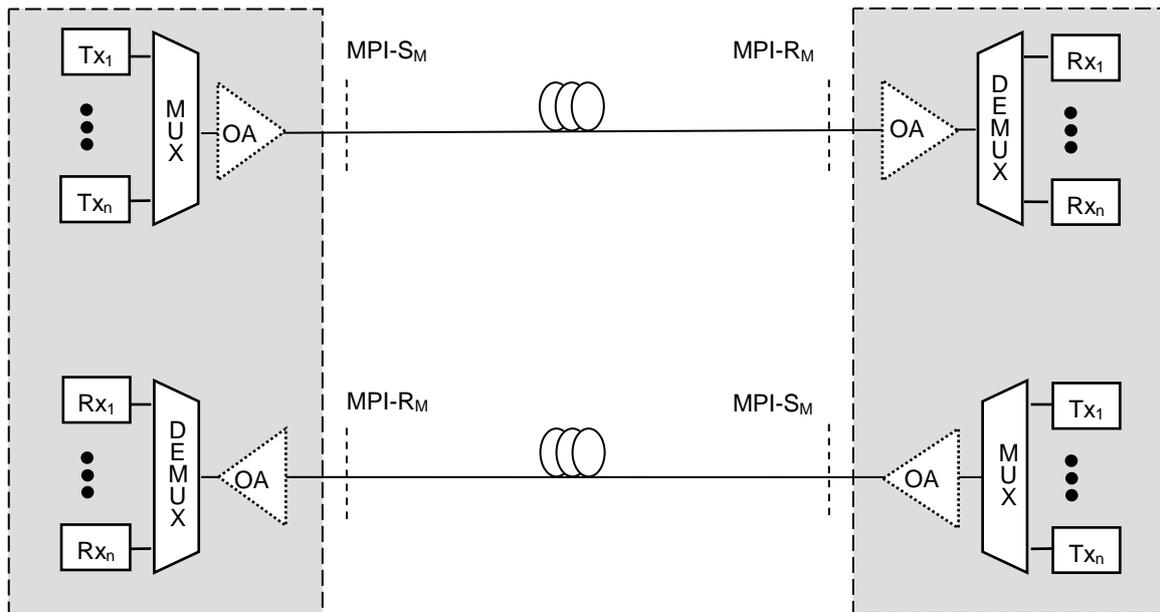


Figure 8-21 – Reference configuration for DWDM system

This Recommendation focuses on repeaterless optical fibre submarine cable systems without remotely pumped optical amplifiers and presumes that the optical tributary signals transported within optical channels are digital.

As said above, the applications covered by this Recommendation are single-span longitudinally compatible. The systems are defined to be "longitudinally compatible" when both ends of an optical section are terminated by equipment from the same manufacturer. Systems from different vendors can be installed on the various optical fibres of the cable. In this case only the cable characteristics (attenuation, dispersion, DGD) are specified. A single-span longitudinally compatible system is illustrated in Figure 8-22.

It is of interest to underline that for multi-span systems, longitudinal compatibility is so far impossible to achieve because all fibre pairs make use of the same repeaters. It means that each amplifier module of each fibre is located in the same repeater housing which is supplied by one single vendor. The same applies for the other equipment of the wet plant (e.g., equalizers, branching units).

The specifications take into account parameters such as maximum attenuation, fibre types, wavelength ranges, maximum chromatic dispersion, minimum local chromatic dispersion coefficient, maximum differential group delay, and minimum effective area.

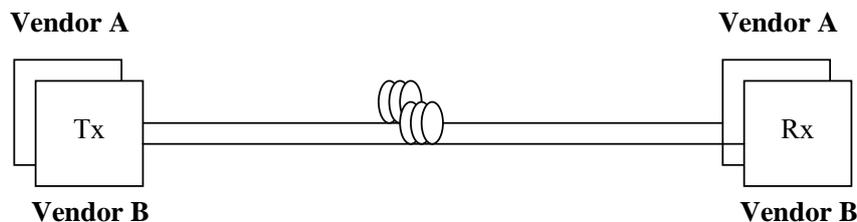


Figure 8-22 – Single-span longitudinal compatibility

The Recommendation gives also indication on the possibility of upgrading the system capacity.

As a matter of fact, it may be advantageous to increase the transmission capacity by increasing the signal bit rate and/or the number of transmission channels by the WDM technique. Such upgrading can be beneficial because the reuse of cables can be achieved cost-effectively over the optical cable long life, typically 25 years. Bit rate upgradeability demands that systems be constructed with cables optimized for the higher bit rate, while the lower bit-rate terminal transmission equipment (TTE) may be initially used. Even after upgrading, the bit rate of TTE output must comply with SDH or OTH specifications to ensure compatibility with standard terrestrial equipment.

8.11.5 Recommendation ITU-T G.974 "Characteristics of regenerative optical fibre submarine cable systems"

Recommendation ITU-T G.974 applies to regenerative optical fibre submarine cable systems which include one or more regenerators in the submarine repeaters. The regenerators contain optoelectronic units and are designed to receive an incoming optical signal and to convert it into an electronic signal, filter, amplify, and convert it back into an optical signal before launching it as an output signal. The digital interfaces in the regenerative system are in accordance with the relevant Recommendations (Recommendations ITU-T G.702, ITU-T G.703, [ITU-T G.707], etc.) to interconnect to terrestrial systems at the terminal stations.

Recommendation ITU-T G.974 provides the system performance and interface requirements of regenerative optical fibre submarine cable systems, which include the following electric/optical and reliability characteristics of the whole system and components such as terminal equipment and repeaters:

- i) digital signal interface;
- ii) error and jitter performance;
- iii) optical power budget;
- iv) system reliability.

It contains relevant parameters necessary for specification, but any defined values for each parameter are not specified because of the specific features of submarine systems. However, Annex A gives the typical physical implementation practices commonly employed on regenerative systems. It also contains information about the power feeding equipment and the supervisory and remote maintenance equipment.

The submarine cable specifications can be found in Recommendation ITU-T G.978 (see clause 8.11.10).

The emergence of the optical amplifier such as the erbium-doped fibre amplifier in the 1990s, which amplifies optical signals directly without having to convert them into electronic signals, has had a significant impact on the submarine repeatered systems. It has a number of benefits compared to conventional regenerative repeaters. For example, the optical amplifiers are applicable to WDM applications and have feasibility to operate independent of the signal bit rates, while the regenerative repeater does not support WDM applications and needs to be designed for a specific signal bit rate, so upgrading them to a higher bit rate after installation is impossible. As a consequence, most of the recent repeatered optical fibre submarine systems employ optical fibre amplifiers as line repeaters, and regenerative submarine systems are becoming obsolete. The specifications of optically amplified optical submarine cable systems are provided in Recommendation ITU-T G.977 (see clause 8.11.9).

8.11.6 Recommendation ITU-T G.975 "Forward error correction for submarine systems"

The purpose of Recommendation ITU-T G.975 is to specify the implementation of a forward error correction (FEC) function in multigigabit-per-second optical submarine cable systems. The applications being addressed in Recommendation ITU-T G.975 are both optically amplified

repeated systems (Recommendation ITU-T G.977) and repeaterless optical systems (Recommendation ITU-T G.973).

FEC is an important way of improving the performance of large-capacity long-haul optical transmission systems. Employing FEC in optical transmission systems yields system designs that can accept relatively large BER (much more than 10^{-12}) in the optical transmission line (before decoding). FEC application may allow the optical parameters to be significantly relaxed and encourages the construction of large capacity long-haul optical transmission systems in a cost-effective manner.

In particular, the implementation of a forward error correction (FEC) function provides significant gains over the overall optical power budget of the link and lowers at the same time the line BER floor of the system. The resulting gain over the optical power budget can then be used to improve either:

- i) the line parameters:
 - for repeaterless submarine applications, the FEC function will possibly be used to increase the maximum span length;
 - for optically amplified submarine applications, the FEC function will possibly be used to either increase the distances or relax optical component and line fibre specifications;
- ii) the overall quality of communication for protection against unwanted degraded operating conditions (component or cable failure, due to ageing for instance).

Two FEC schemes are recommended for optical transmission systems. They are "in-band FEC" for SDH systems, and "out-of-band FEC" for submarine optical systems and for optical transport networks (OTNs). The terminology "in" or "out" refers to the client bandwidth. Signals including space for FEC bits outside the client bandwidth have a higher bit rate than the equivalent signal before the FEC is added. This increases the line bit rate and it is the counterpart to the above improvements.

Recommendation ITU-T G.975 recommends a FEC frame format based on the Reed-Solomon (255, 239) code and describes its performance. In particular Recommendation ITU-T G.975 covers:

- i) the general principles of the FEC function (FEC coder and FEC decoder) for data rates of 2.5 Gbit/s and integer multiples of 2.5 Gbit/s;
- ii) the main features of the FEC function implemented in the submarine systems (code algorithm, code properties, frame structure, scrambling, redundancy ratio);
- iii) the performance of the RS (255, 239) code and the expected coding gain on the optical transmission power budget.

8.11.7 Recommendation ITU-T G.975.1 "Forward error correction for high bit-rate DWDM submarine systems"

The purpose of Recommendation ITU-T G.975.1 is to describe a set of forward error correction (FEC) codes that have higher correction ability than the Reed-Solomon (RS) (255, 239) code defined in Recommendation ITU-T G.975 (see clause 8.11.6). These codes are often termed "super FEC codes".

The objectives of the use of a FEC code in optical transmission systems is outlined in clause 8.11.6 and described in detail in Supplement 39 to ITU-T G-series Recommendations.

A super FEC code, with more effective error correction than the RS (255, 239) code, can be required not only for submarine optical fibre systems, but also for terrestrial systems in order to achieve adequate transmission quality in the evolving/new DWDM systems with higher bit rate (e.g., over 10 Gbit/s), longer transmission distance and larger capacity.

It is not the intention of Recommendation ITU-T G.975.1 to pursue transverse compatibility of a super FEC code.

The main body of Recommendation ITU-T G.975.1 only contains a description of super FEC features, the definition of the super FEC function and the parameters for super FEC. In particular, the following important parameters for the super FEC code are described:

- i) correction ability (bit error ratio characteristics, coding gain, net coding gain, Q limit);
- ii) redundancy ratio;
- iii) latency.

No super FEC is specified in the main body of Recommendation ITU-T G.975.1 and therefore the selection of the FEC frame structures described is a matter of joint engineering.

In Appendix I of Recommendation ITU-T G.975.1, several super FEC codes and their characteristics are described. Some of these codes provide additional coding gain compared to the standard ITU-T G.709 FEC, while maintaining the exact data rate of the ITU-T G.709 OTUk, i.e., 7% overhead. Some others, giving higher coding gain, require higher overheads.

8.11.8 Recommendation ITU-T G.976 "Test methods applicable to optical fibre submarine cable systems"

The purpose of Recommendation ITU-T G.976 is to highlight the test methods of optical fibre submarine cable systems by listing the main tests applicable to these systems and by describing the relative test methods.

For the test methods of optical fibre cables, there are three Recommendations, Recommendations ITU-T G.650.1, ITU-T G.650.2 and ITU-T G.650.3. However, these Recommendations are mainly designed for use by terrestrial systems.

As compared with terrestrial systems, submarine systems require much higher reliability for the cables and equipment because of their longer lifetime and higher installation cost. As a consequence, not all of the test methods specified in the three above Recommendations can be used for submarine cables and systems.

Testing is required at different periods in a system's life (development, manufacturing, operation) and for different purposes. The purposes of testing are the following (each category contains several tests for cables and equipment):

- i) qualification tests;
- ii) quality assurance tests;
- iii) installation tests;
- iv) cable system commissioning tests;
- v) maintenance tests.

Recommendation ITU-T G.976 contains references to general test methods studied for terrestrial cables and systems which are applicable to optical fibre submarine cable systems, even if sometimes they may need an adaptation to meet with submarine systems requirements.

Recommendation ITU-T G.976 also contains descriptions of test methods which are specific to submarine systems (e.g., cable hydraulic pressure resistance, tensile test with twist restrained).

The tests are divided into the following categories:

- i) tests on the optical fibres of the optical fibre submarine cable;
- ii) tests on the optical fibre submarine cable;
- iii) tests on optical fibre amplifiers of optical submarine repeaters;
- iv) tests on the terminal transmission equipment.

- v) tests on the power feeding equipment;
- vi) tests on the link;
- vii) tests on the maintenance.

For each of the above categories, several tests are described, such as transmission, mechanical, handling, reliability and installing operation.

8.11.9 Recommendation ITU-T G.977 "Characteristics of optically amplified optical fibre submarine cable systems"

Recommendation ITU-T G.977 describes characteristics of repeatered optical submarine systems using optical fibre amplifiers as line repeaters.

It refers to the system characteristics required to guarantee the performance, reliability (usually 25 years starting at the provisional acceptance date of the system) and capacity upgradeability.

To meet these requirements, characteristics and performance of terminal equipments are detailed with references to terrestrial Recommendations. The following submerged equipments are also defined in the current version of Recommendation ITU-T G.977:

- i) optical submarine repeaters;
- ii) branching units;
- iii) optical submarine equalizers.

Mechanical, electrical and optical characteristics, but also supervisory and fault location facilities and reliability considerations, are detailed for all of them.

The submarine cable specifications can be found in Recommendation ITU-T G.978 (see clause 8.11.10).

The physical implementation of optically amplified fibre submarine systems is described in Annex A, where a power budget table example, including calculation rules, also describes how the system performance will be met as regards error performance.

From a general point of view, the characteristics, performance specifications and requirements of the submerged equipment described in Recommendation ITU-T G.977 are mostly identical whatever the number of wavelengths used. Indeed, a single wavelength system appears as a specific case of WDM system using one wavelength and in turn, WDM system can be considered as a specific case of dense WDM system with a small number of wavelengths. As a consequence, general statements mentioned in Recommendation ITU-T G.977 can be applied to all submarine systems using optical repeaters. In the future, when necessary, more detailed Recommendations will highlight the specificity of these three types of system.

8.11.10 Recommendation ITU-T G.978 "Characteristics of optical fibre submarine cables"

Recommendation ITU-T G.978 deals with the characteristics of the optical fibre submarine cables used in Recommendations ITU-T G.973, ITU-T G.973.1, ITU-T G.974 and ITU-T G.977, and covers:

- i) transmission characteristics, mechanical characteristics and resistance to the environment of optical fibres in submarine cables;
- ii) transmission characteristics of elementary cable sections;
- iii) mechanical characteristics and resistance to the environment of optical fibre submarine cables.

Several types of optical fibres are used in the submarine systems. Among them:

- i) single-mode fibres defined in Recommendation ITU-T G.65x-series;
- ii) positive dispersion single-mode fibre (PDF);

- iii) negative dispersion single-mode fibre (NDF);
- iv) large effective area single-mode fibre (LEF);
- v) dispersion compensating single-mode fibre (DCF).

Depending on the system specifications (data bit rate and coding, number of wavelengths, amplifier span, amplifier output power, length of the link, etc.), various combinations of these fibre types may be used in the same link and/or in the same elementary cable section to ensure system performance.

Recommendation ITU-T G.978 outlines that the transmission characteristics of the fibres installed in an elementary cable section (the whole length of optical fibre cable between two pieces of equipment such as repeaters, branching units or terminal transmission equipment) should be within a specified limit of variation from the characteristics of the fibre before cabling. In particular, the design of the cable, cable joints and fibre should be such that fibre bending and microbending create a negligible attenuation increase. This is to be taken into account for determining the minimum fibre bending radius in the cable and in the equipment (optical cable joints, termination, repeaters, etc.).

The optical fibre submarine cable should be designed with particular requirements in respect of the terrestrial cables in order to take into account the specific laying/recovery and environmental conditions.

In particular, the optical fibre submarine cable should provide protection against marine life, fish-bite and abrasion, and armour against aggression and ship activities. Different types of protected cable are used. The following are described in Recommendation ITU-T G.978:

- i) the lightweight cable (LW cable); suitable for laying, recovery and operation, where no special protection is required;
- ii) the lightweight protected cable (LWP cable); suitable for laying, recovery and operation, where special protection is required;
- iii) the single armoured cable (SA cable); suitable for laying, burial, recovery and operation and is suitably protected for specific areas in shallow water;
- iv) the double armoured cable (DA cable); suitable for laying, burial, recovery and operation and is suitably protected for specific areas in shallow water;
- v) the rock armoured cable (RA cable); suitable for laying, recovery and operation and is suitably protected for specific areas in shallow water.

Recommendation ITU-T G.978 contains typical application depths for each of the above types of cable.

8.12 Informative Supplements with informative content: Supplements and appendices on optical technology

Normally, any information that is considered to be merely illustrative or supplementary to a Recommendation is included as an appendix to that Recommendation.

The content of an appendix is not essential to the completeness or comprehensibility of a Recommendation and an appendix is not considered to be an integral part of the Recommendation. Its content is not normative.

Some appendices contain very interesting material which is helpful for the understanding and the application of the related Recommendation (e.g., the appendices of Recommendations ITU-T G.663, ITU-T G.696.1, ITU-T G.698.1, ITU-T G.698.2, ITU-T G.680). The content of the most interesting appendices is illustrated in the above clauses related to each Recommendation.

However, there are particular cases where separate publication of such illustrative information is preferred and it is published in the form of Supplements to the series of Recommendations.

As for the appendices, the text of a Supplement contains material which is supplementary to and associated with the subject matter of one or more Recommendations, but is not essential to their completeness or understanding and implementation.

Supplements are only informative and are not considered to be an integral part of any Recommendation.

In case of conflict between the material contained in a Supplement and the material of the relevant Recommendations, the latter always prevails.

There are four other Supplements dealing with optical technology: the first is related to optical fibres and cables (Supplement 40 to ITU-T G-series Recommendations), the second to the optical system design (Supplement 39 to ITU-T G-series Recommendations), the third to the design of the optical fibre submarine cable systems (Supplement 41 to ITU-T G-series Recommendations) and the fourth to general aspects of optical fibre and cable (Supplement 47 to ITU-T G-series Recommendations).

8.12.1 Supplement 39 to ITU-T G-series "Optical system design and engineering considerations"

Supplement 39 to ITU-T G-series Recommendations provides information on the background and methodologies used in the development of optical interface Recommendations such as Recommendations ITU-T G.957, ITU-T G.691 and ITU-T G.959.1.

Supplement 39 to ITU-T G-series Recommendations describes design and engineering considerations for unamplified and amplified single-channel and multichannel digital optical line systems supporting PDH, SDH and OTN signals in intra-office, inter-office and long-haul terrestrial networks.

One intent of Supplement 39 to ITU-T G-series Recommendations is to consolidate and expand on related material that is currently included in several Recommendations, including Recommendations ITU-T G.955, ITU-T G.957, ITU-T G.691, ITU-T G.692 and ITU-T G.959.1.

Supplement 39 to ITU-T G-series Recommendations covers a wide range of information, including:

Spectral bands. Some background information on the evolution of these bands, known as C-band, L-band, etc., is given.

Parameters of system elements. This expands on the descriptions of the main terms used throughout the optical interface Recommendations. It also provides pointers to the Recommendations in which the primary definitions are located. There are five main sections:

- i) line coding;
- ii) transmitters;
- iii) optical amplifiers;
- iv) optical path;
- v) receivers.

Line coding considerations. The main types of line coding are identified in terms of the phase constellations, the spectral characteristics and the time-domain characteristics as well as the implementations. After these characteristics are identified, there is a section that describes the system impairment implications with respect to optical path parameters such as polarization mode dispersion and chromatic dispersion.

Optical network topology. Different topological classes are defined including point-to-point links, bus structures, ring and meshed networks. Each class is introduced by a generic approach.

"Worst case" system design. All the parameters and limits in the optical interface Recommendations are worst case in the sense that the system is expected to operate at or below the specified bit error

ratio through to end of life within the power and penalty budget and for the stipulated optical path characteristics.

Some of the optical path limits may be derived from statistical considerations, but after they have been agreed, these are the limits that apply. Maximum optical path attenuation is an example, where a maximum value of 22 dB is used for many 80 km target length application codes. This value results from an assumption that the maximum attenuation coefficient, including all splices and environmental effects is 0.275 dB/km – a result derived from statistical experience and not derived from worst case optical fibre cable values. An actual link may not be 80 km and the actual link attenuation may be more or less than 22 dB. If the actual link is less than 22 dB, the system is expected to operate correctly. If the actual link is more than 22 dB this must be corrected or a modified link specification agreed between the link owner and the equipment supplier (joint engineering).

Following this understanding, there are detailed analysis, discussion and exemplary figures for the following main topics:

- i) power budget concatenation;
- ii) chromatic dispersion;
- iii) polarization mode dispersion;
- iv) BER and Q-factor;
- v) noise concatenation;
- vi) optical crosstalk;
- vii) concatenation of non-linear effects.

Statistical system design. The values of the parameters are often based on statistical considerations of concatenations. In particular, the following main topics are dealt with:

- i) generic methodology;
- ii) statistical design of loss;
- iii) statistical design of chromatic dispersion;
- iv) statistical design of polarization mode dispersion;

The sections on loss and chromatic dispersion include detailed data derived from contributions based on actual measurements and their statistics on different types of fibres. The section on polarization mode dispersion includes the basic concatenation formula for PMD values and relates this to the statistical variation in differential group delay values.

Forward error correction (FEC). FEC is rapidly becoming an important way of improving the performance of high-capacity long-haul optical transmission systems and is already well established in wireless communication systems. Employing FEC in optical transmission systems yields system designs that can accept relatively large BER (much more than 10^{-12}) in the optical transmission line (before decoding).

The following main topics are dealt with:

- i) in-band FEC for SDH systems;
- ii) out-of-band FEC for optical transport networks (OTNs);
- iii) coding gain and net coding gain (NCG);
- iv) theoretical NCG bounds for some non-standard out-of-band FECs;
- v) statistical assumption for coding gain and NCG;
- vi) candidates for parameter relaxation;
- vii) candidates for improvements in system performance.

Physical layer transverse and longitudinal compatibility. It is the desire of most operating companies to be able to install transmitters, receivers and other equipment associated with common application codes from any suppliers on either end of any of the fibres within their network and expect them to operate correctly.

In the course of the evolution of the optical interface Recommendations, this has not always been possible. In the initial development of dense wavelength division multiplexing, for example, the channel frequency plan from one supplier could be different from another. This resulted from, among other factors, the use of different technologies.

Despite these obstacles, Recommendations including values that would ensure that the transmission equipment from two suppliers would operate correctly on the same optical path were developed on the theory that this would provide a way forward. Supplement 39 to ITU-T G-series Recommendations identifies the main aspects of these different types of compatibility, including examples as well as a section on joint engineering.

Best practices for optical power safety. A listing of the aspects of optical power safety considerations is given, along with some guidance on each item.

8.12.2 Supplement 40 to ITU-T G-series "Optical fibre and cable Recommendations and standards guideline"

The main purpose of Supplement 40 to ITU-T G-series Recommendations is to provide relations among optical fibre and cable Recommendations such as ITU-T G.651.1, ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655, ITU-T G.656, ITU-T G.657, ITU-T G.978, ITU-T G.650.1, ITU-T G.650.2, ITU-T G.650.3 developed in Study Group 15 and the Recommendations of the L-series, which at present are also under the responsibility of Study Group 15. Moreover, Supplement 40 to ITU-T G-series Recommendations maps on optical fibre and cable standards to those developed under IEC.

Supplement 40 to ITU-T G-series Recommendations should also make easier for readers to correlate the specifications found in the fibres, components, terrestrial system interfaces and submarine optical systems Recommendations, which are described in this Supplement.

Supplement 40 to ITU-T G-series Recommendations contains:

- i) relationships among the various Recommendations and Supplements pertaining to optical fibre and cable;
- ii) features of existing optical fibre categories and their application areas;
- iii) a list of the optical fibre properties related to operation and maintenance with information on the ITU-T Recommendations and IEC specifications and where the information can be found. The safety aspects are included in this list.

Other issues are dealt with in several appendices.

Appendix I describes the criteria for preparing and for revising the optical fibre Recommendations. Guidelines are given for the cases where it is necessary to conduct measurement round robins.

In Appendix II, Recommendations relevant to the optical fibre cable structures to be used for specific applications (e.g., duct, buried, aerial, submarine) are listed with the indication of the relevant ITU-T L-series Recommendations.

In Appendix III, Recommendations concerning the fibre optics hardware and passive components mostly used in the construction of an optical network (e.g., connectors, branching devices, optical distribution frames) are listed with the indication of the relevant ITU-T L-series Recommendations.

In Appendix IV, Recommendations relevant to construction and installation practices (e.g., micro-trench, mini-trench, air-assisted floating and blowing installation techniques) are listed with the indication of the relevant ITU-T L-series Recommendations.

In Appendix V, a comparison table with the status of optical fibre ITU-T Recommendations and the correspondent IEC specifications is shown.

Appendix VI contains a comparison table of ITU-T Recommendations and IEC specifications related to the single-mode and multi-mode optical fibre test methods.

The comparison contained in the two above quoted tables is very detailed because one of the objectives is to avoid any overlap between ITU-T Recommendations and IEC specifications.

8.12.3 Supplement 41 to ITU-T G-series "Design guidelines for optical fibre submarine cable systems"

Supplement 41 to ITU-T G-series Recommendations describes design and engineering considerations for repeatered, repeaterless and optically amplified systems supporting SDH and OTN signals in optical submarine cable systems. In particular, Supplement 41 to ITU-T G-series Recommendations focuses on the specific matters relevant to the optical fibre submarine cable systems.

Supplement 41 to ITU-T G-series Recommendations describes a common way of thinking of the requirements for designing the optical fibre submarine cable systems and aims at consolidating and expanding on materials related to several Recommendations, including Recommendations ITU-T G.971, ITU-T G.972, ITU-T G.973, ITU-T G.973.1, ITU-T G.974, ITU-T G.975, ITU-T G.975.1, ITU-T G.976, ITU-T G.977 and ITU-T G.978.

Supplement 41 to ITU-T G-series covers a wide range of information, including:

Parameters of system elements. This expands on the descriptions of the main terms used throughout the optical interface Recommendations. It also provides pointers to the Recommendations in which the primary definitions are located. There are five main sections:

- i) transmitter;
- ii) submarine cable;
- iii) submarine repeater;
- iv) cable joint;
- v) receiver.

Optical network topology. Different topological classes are defined. Some of them are made up only by point-to-point links: point-to-point, star, ring and festoon. Others use one or more branching units: branched star, trunk and branch and branched ring. Each class is introduced by a generic description.

System design. All the parameters and limits in the optical interface Recommendations are worst case in the sense that the system is expected to operate at or below the specified bit error rate through to end of life within the power and penalty budget and for the stipulated optical link characteristics.

Optical power budget is the principle tool for submarine design. It is a contractual performance budget which guarantees the system performance to be better than the minimum required BER performance defined in Recommendation ITU-T G.826 and/or Recommendation ITU-T G.828.

The optical power budget starts from a simple linear quality factor (Q-factor) which only takes into account degradation due to the ASE noise of amplifiers. Then the optical power budget allocates the penalties/impairments for all types of degradation (due to transmission, terminal equipments, etc.). The degradation is estimated using a combination of theoretical analysis, computer simulations and direct measurements on experimental test-beds. Some of them may be derived from statistical considerations, but after they have been agreed, these are the limits that apply.

Power feeding. The power feeding equipment (PFE) supplies DC power to the repeaters. Using sea water as a return path, the PFE supplies a constant DC current through the metallic conductor of the cable. The power feeding could be supplied by a single or the double ends of the submarine segment. The power feeding budget estimates all necessary voltage drops to confirm the PFE's configuration at both ends of the path.

Following this understanding, there are detailed analysis, discussion and examples for the following main topics:

- i) power budget concatenation;
- ii) Q-factor calculation;
- iii) optical noise accumulation;
- iv) propagation impairments (polarization, non-linear effects, pre-emphasis, wet plan supervisory, etc.);
- v) segment margins (ageing, repairs, components faults);
- vi) chromatic dispersion and mapping;
- vii) power feeding sub-system design.

Reliability considerations. Reliability is one of the main considerations to be taken into account for a submarine system to avoid as much as possible costly repairs in the wet plant during the system lifetime, which is usually guaranteed for 25 years.

The principle terms used to characterize the reliability are defined as well as the different types of failure. To increase the reliability of submarine systems, components used are carefully selected to guarantee a failure rate that is as low as possible. Moreover, redundant key components configurations are usually employed to ensure that the reliability target is met. However, some external events can also damage the submarine cable and an excellent reliability of components and subsystems is not sufficient.

Nearly 90% of the failures are caused by fishing activities and ship anchor damage. To protect the cable against these various factors, the wet plant can be buried in shallow water except in rocky areas where seabed conditions do not allow burial. Additionally, the cable route is selected to avoid as much as possible geological hazards.

Upgradeability considerations. Most of the submarine systems initially operate below the final capacity they are designed for, allowing carriers to apply the well-known "pay-as-you-grow" concept. The original supply contract covers their progressive equipage commercially and technically (standard upgrades). In some cases, the designed capacity can be exceeded by using enhanced technologies in the terminal equipment. Upgrades then become challenging. They depend on the system design as well as on the margins available at the time it is considered. The different ways to increase the total capacity of a submarine system are described and commented on.

Physical layer compatibility. It is the desire of most operating companies to be able to install transmitters, receivers and other equipment from any suppliers on either end of any of the fibres within their network and expect them to operate correctly.

Theoretical configurations allowing physical layer longitudinal and transverse compatibility are described using the same terminology as the one used in terrestrial systems Recommendations. Definitions are also provided for the possible configurations that might form the basis for future standardization of repeatered and repeaterless submarine cable systems.

8.12.4 Supplement 47 to ITU-T G-series "General aspects of optical fibre and cable"

The main purpose of Supplement 47 to ITU-T G-series Recommendations is to provide information concerning the transmission properties of the cabled single-mode fibres during use, and to promote

the proper and effective use of ITU-T G.65x-series Recommendations single-mode fibres and cables.

The optical transmission systems have become more diversified and sophisticated, based on recent progress on the technologies of the high-speed and WDM transmission systems. In these advanced optical systems, it is sometimes essential to understand both linear and nonlinear characteristics of an optical fibre in detail.

For example, in DWDM systems, the wavelength dependence of chromatic dispersion is important to use the wavelength resources effectively, and it is often required to manage the dispersion value of the transmission line carefully. In higher-bit-rate systems with 10 Gbit/s or more, polarization mode dispersion becomes the major limiting factor for transmission performance. Here, it is known that both chromatic and polarization mode dispersions change, depending on the environmental conditions, such as ambient temperature.

Some fibre parameters are closely related to the fibre length and/or concatenated condition. For example, the cut-off wavelength varies depending on a piece length of the concatenated cable. The nonlinear parameters such as SBS (stimulated Brillouin scattering) power rating and FWM (four-wave mixing) efficiency, are also related to the fibre length, the attenuation and the uniformity along the transmission line.

Supplement 47 to ITU-T G-series Recommendations covers the general transmission characteristics of single-mode optical fibres and cables related to the practical use conditions that are not shown in the fibre Recommendations. It comprises two main sections, "Environmental characteristics" and "Length-related characteristics."

In the section concerning environmental characteristics of optical fibre and cable, the following topics are dealt with:

- i) temperature dependence of chromatic dispersion;
- ii) temperature dependence of polarization mode dispersion.

In the section concerning length-related characteristics of optical fibre and cable, the following topics are dealt with:

- i) cut-off wavelength;
- ii) stimulated Brillouin scattering power rating;
- iii) four-wave mixing efficiency.

It is also known that some values of linear and nonlinear fibre parameters vary depending on dopant material and its concentration. These parameters may be crucial to design an optical link in advanced systems. In such cases, it may be necessary to know the material characteristics of the optical fibre and to carefully choose the optical fibre. In Appendix I, the optical fibre characteristics related to the fibre material are described for reference. There are the following four topics:

- i) Rayleigh scattering;
- ii) material dispersion;
- iii) non-linear refractive index;
- iv) Raman gain coefficient.

This Supplement is useful for system operators and designers when upgrading existing systems to high-speed transmission systems based on the installed transmission line and/or when designing a new transmission line for a high-speed and large capacity transmission system.

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