International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

Series G

Supplement 64

(02/2018)

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

PON transmission technologies above 10 Gbit/s per wavelength

ITU-T G-series Recommendations – Supplement 64

ITU-T G-SERIES RECOMMENDATIONS

TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

INTERNATIONAL TELEPHONE CONNECTIONS AND CIRCUITS	G.100–G.199
GENERAL CHARACTERISTICS COMMON TO ALL ANALOGUE CARRIER-TRANSMISSION SYSTEMS	G.200–G.299
INDIVIDUAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON METALLIC LINES	G.300–G.399
GENERAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON RADIO-RELAY OR SATELLITE LINKS AND INTERCONNECTION WITH METALLIC LINES	G.400–G.449
COORDINATION OF RADIOTELEPHONY AND LINE TELEPHONY	G.450–G.499
TRANSMISSION MEDIA AND OPTICAL SYSTEMS CHARACTERISTICS	G.600–G.699
DIGITAL TERMINAL EQUIPMENTS	G.700–G.799
DIGITAL NETWORKS	G.800–G.899
DIGITAL SECTIONS AND DIGITAL LINE SYSTEM	G.900–G.999
MULTIMEDIA QUALITY OF SERVICE AND PERFORMANCE – GENERIC AND USER-RELATED ASPECTS	G.1000–G.1999
TRANSMISSION MEDIA CHARACTERISTICS	G.6000–G.6999
DATA OVER TRANSPORT – GENERIC ASPECTS	G.7000–G.7999
PACKET OVER TRANSPORT ASPECTS	G.8000–G.8999
ACCESS NETWORKS	G.9000–G.9999

For further details, please refer to the list of ITU-T Recommendations.

Supplement 64 to ITU-T G-series Recommendations

PON transmission technologies above 10 Gbit/s per wavelength

Summary

Supplement 64 to ITU-T G-series Recommendations describes characteristics of optical transmission above 10 Gbit/s per wavelength between the optical line termination (OLT) and the optical network unit (ONU). It reviews challenges of transmission above 10 Gbit/s in optical access. A set of assumed system requirements is developed as a basis for the discussion of candidate technologies. Some aspects considered include signal modulation selection, optical transmitter design, optical receiver design, and wavelength dependency. Coexistence with other optical access systems is also investigated as a key factor of wavelength planning.

The line rate per wavelength in the existing PON systems, such as GPON, XG(S)-PON, TWDM-PON, is up to 10 Gbit/s. For High-speed PON, line rate per wavelength will exceed 10 Gbit/s, in order to provide higher bandwidth capability for growing services' requirement.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T G Suppl. 64	2018-02-09	15	11.1002/1000/13589

Keywords

High-speed PON, modulation technologies.

* To access the Recommendation, type the URL http://handle.itu.int/ in the address field of your web browser, followed by the Recommendation's unique ID. For example, http://handle.itu.int/11.1002/1000/11830-en.

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.

Compliance with this publication is voluntary. However, the publication may contain certain mandatory provisions (to ensure, e.g., interoperability or applicability) and compliance with the publication is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the publication is required of any party.

INTELLECTUAL PROPERTY RIGHTS

ITU draws attention to the possibility that the practice or implementation of this publication may involve the use of a claimed Intellectual Property Right. ITU takes no position concerning the evidence, validity or applicability of claimed Intellectual Property Rights, whether asserted by ITU members or others outside of the publication development process.

As of the date of approval of this publication, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this publication. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at http://www.itu.int/ITU-T/ipr/.

Table of Contents

Page

1 Scope ... 1

2 References ... 1

3 Definitions ... 2

3.1 Terms defined elsewhere ... 2

3.2 Terms defined in this Supplement ... 5

4 Abbreviations and acronyms ... 5

5 Conventions ... 7

6 System architectures ... 7

7 Requirements ... 8

7.1 Physical layer requirements ... 8

7.2 Service requirements ... 9

7.3 System level requirements ... 9

7.4 Operational requirements ... 10

7.5 Coexistence and migration ... 10

8 Candidate technologies above 10 Gbit/s per wavelength ... 10

8.1 Modulation technologies ... 10

8.2 Transmitter and receiver technologies ... 35

8.3 Optical amplifier technologies ... 38

8.4 Wavelength allocation options ... 41

8.5 Alternative wavelength options for future 25G and 50G PON ... 41

8.6 Forward error correction options for high-speed PON ... 41

Bibliography ... 44

Supplement 64 to ITU-T G-series Recommendations

PON transmission technologies above 10 Gbit/s per wavelength

1 Scope

This Supplement describes the characteristics of optical transmission above 10 Gbit/s per wavelength between the optical line termination (OLT) and the optical network unit (ONU). It reviews challenges of transmission above 10 Gbit/s in optical access. A set of assumed system requirements is developed as a basis for the discussion of candidate technologies. Some aspects considered include signal modulation selection, optical transmitter design, optical receiver design, and wavelength dependency. Coexistence with other optical access systems is also investigated as a key factor of wavelength planning.

2 References

[ITU-T G.652] Recommendation ITU-T G.652 (2016), *Characteristics of a single-mode optical fibre and cable*.

[ITU-T G.657] Recommendation ITU-T G.657 (2016), *Characteristics of a bending-loss insensitive single-mode optical fibre and cable*.

[ITU-T G.902] Recommendation ITU-T G.902 (1995), *Framework Recommendation on functional access networks (AN) – Architecture and functions, access types, management and service node aspects*.

[ITU-T G.989] Recommendation ITU-T G.989 (2015), *40-Gigabit-capable passive optical networks (NG-PON2): Definitions, abbreviations and acronyms*.

[ITU-T G.9807.1] Recommendation ITU-T G.9807.1 (2016), *10-Gigabit-capable symmetric passive optical network (XGS-PON)*.

[Agrawal-1] Agrawal, G., Anthony, P., Shen, T. (1988), *Dispersion penalty for 1.3-μm Lightwave systems with multimode semiconductor lasers*, J. Lightwave Technology, volume 6, number 5.

[Agrawal-2] Agrawal, G.P. and Dutta N.K. (1986), *Long-Wavelength Semiconductor Lasers*. New York: Van Nostrand Reinhold.

[Beijing Univ] *Fiber communication system*, Beijing University of posts and telecommunications publishing Group, p. 183.

[Ghelfi] Ghelfi, P., Bogoni, A., and Poti, L. (2003), *Numerical model of the dynamic absorption variation in QW-EAM for ultrafast all-optical signal* IEEE Proc.-Circuits Devices Syst., vol. 150, pp. 512-515.

[Houtsma] Houtsma, V., van Veen, D. and Harstead, E. (2016), *Unified Evolution-Ready 25/50/100 Gbps-EPON Architecture Proposal*, IEEE 802.3ca Task Force, May.

[Kazovsky] L. Kazovsky et al. (2011), *Broadband Optical Access Networks*, John Wiley & Sons, Inc.

[Laubach] Mark Laubach, Glen Kramer, Ryan Hirth, Bz Shen (2017), *FEC selection considerations*, IEEE 802.3ca Task Force, Huntington Beach, CA, January.

[Lender] Lender, A. (1963), *The Duobinary Techniques for High-Speed Data Transmission*, IEEE Trans. Consumer Electronics, vol. CE-82, pp. 214–218, May.

[Nada et al] Nada, M. et al. (2012), *High-sensitivity 25 Gbit/s avalanche photodiode (APD) receiver optical sub-assembly for 40 km transmission*, electronics letters, June 21, Vol. 48, No. 13.

[Powell] Powell, B. and Harstead Ed (2017), *FEC Selection for 25G/50G/100G EPON*, IEEE 802.3ca Task Force, Orlando, November.

[Shankar] Shankar, H. (2004), *Duobinary modulation for optical systems*, White Paper, Inphi Corporation.

[Sinsky] Sinsky et al. (2005), *High-Speed Electrical Backplane Transmission Using Duobinary Signaling*, IEEE Transactions on Microwave Theory and Techniques, vol. 53, no. 1, January, p.152.

[van Veen] van Veen, D., V. Houtsma, E. Winzer, P. and Vetter, P. (2012), *26-Gbps PON Transmission over 40-km using Duobinary Detection with a Low Cost 7-GHz APD-Based Receiver*, ECOC OSA Technical Digest.

[van Veen] van Veen, D., Houtsma, V. Chow, H., *Demonstration of Symmetrical 25 Gbps Quaternary PAM/Duobinary TDM-PON with multilevel interleaving of users*, Proceedings of ECOC 2015; 42nd European Conference on Optical Communication.

[van Veen] van Veen, D., Houtsma, V. (JLT vol.34 n.4), *A Study of Options for High-Speed TDM-PON Beyond 10G*.

[Winzer] Winzer, P., Essiambre, R., *Advanced modulation formats for high-capacity optical transport networks* [J]. Journal of Lightwave Technology, 2006, 24: 4711-4728.

[Yamamoto] Yamamoto, T. (2012), *High-speed directly modulated lasers*, Optical Fiber Communication Conference (OFC/NFOEC), March.

[Yao] Yao, S., Liu, X. and Liu, D. (2016), *The Impact of Differential Pre-coding on 25-Gbit/s EDB, NRZ, and NRZ-NFC*, IEEE 802.3ca Task Force, July.

[Yin] X. Yin, J. Verbist, T. De Keulenaer, B. Moeneclaey, J. Verbrugghe, X. Qiu and J. Bauwelinck (2015), *25Gbit/s 3-level Burst-Mode Receiver for High Serial Rate TDM-PONs*, Optical Fiber Communication Conference(OFC/NFOEC), March.

3 Definitions

3.1 Terms defined elsewhere

This Supplement uses the following terms defined elsewhere:

3.1.1 access network (AN) [ITU-T G.902]: An implementation comprising those entities (such as cable plant, transmission facilities, etc.) which provide the required transport bearer capabilities for the provision of telecommunications services between a service node interface (SNI) and each of the associated user-network interfaces (UNIs).

3.1.2 coexistence element [ITU-T G.9807.1]: A bidirectional functional element used to connect PON systems defined in different Recommendation series to the same ODN.

3.1.3 gigabit-capable passive optical network (G-PON) [ITU-T G.989]: A PON system supporting transmission rates in excess of 1.0 Gbit/s in at least one direction, and which implements the suite of protocols specified in the ITU-T G.984-series of Recommendations.

3.1.4 next generation PON (NG-PON) [ITU-T G.989]: In the context of ITU-T standards development activity, a generic term referencing the PON system evolution beyond G-PON. The concept of NG-PON currently includes NG-PON1, where the ODN is maintained from B-PON and G-PON, and NG-PON2, where a redefinition of the ODN is allowed from that defined in B-PON and G-PON.

3.1.5 optical access network (OAN) [ITU-T G.989]: A part of an access network whose network elements are interconnected by optical communication channels. Note that an OAN may or may not extend all the way to the UNI, so that the user-side interface of the OAN does not necessarily coincide with the UNIs of the AN.

3.1.6 optical distribution network (ODN) [ITU-T G.989]: A point-to-multipoint optical fibre infrastructure. A simple ODN is entirely passive and is represented by a single-rooted point-to-multipoint tree of optical fibres with splitters, combiners, filters and possibly other passive optical components. A composite ODN consists of two or more passive segments interconnected by active devices, each of the segments being either an optical trunk line segment or an optical distribution segment. A passive optical distribution segment is a simple ODN itself. Two ODNs with distinct roots can share a common subtree.

3.1.7 optical line termination (OLT) [ITU-T G.989]: A network element in an ODN-based optical access network that terminates the root of at least one ODN and provides an OAN SNI.

3.1.8 optical network terminal (ONT) [ITU-T G.989]: An ONU supporting a single subscriber.

3.1.9 optical network unit (ONU) [ITU-T G.989]: A network element in an ODN-based optical access network that terminates a leaf of the ODN and provides an OAN UNI.

3.1.10 passive optical network (PON) system [ITU-T G.989]: A combination of network elements in an ODN-based optical access network that includes an OLT and one or more ONUs and implements a particular coordinated suite of physical medium dependent layer, transmission convergence layer and management protocols.

3.1.11 TWDM channel [ITU-T G.989]: In an NG-PON2 system, TWDM channel refers to the pair of one downstream wavelength channel and one upstream wavelength channel providing point-to-multipoint connectivity by using, respectively, time division multiplexing and multiple access mechanisms.

3.1.12 TWDM PON [ITU-T G.989]: A multiple wavelength PON system in which each wavelength channel may be shared among multiple ONUs by employing time division multiplexing and multiple access mechanisms.

3.1.13 wavelength channel [ITU-T G.989]: A unidirectional (downstream or upstream) optical communications channel characterized by a single unique central frequency or a set of unique central frequencies mapped to one WM tributary port.

3.1.14 wavelength multiplexer (WM) [ITU-T G.989]: A bidirectional functional element used to multiplex/ demultiplex between NG-PON2 wavelength channel pairs and channel groups.

3.1.15 10-gigabit-capable passive optical network (XG-PON) [ITU-T G.9807.1]: A PON system supporting nominal transmission rates on the order of 10 Gbit/s in at least one direction, and implementing the suite of protocols specified in the ITU-T G.987-series of Recommendations. XG-PON is the realization of NG-PON1.

3.1.16 XGS-PON [ITU-T G.9807.1]: A PON system that operates at a nominal line rate of 10 Gbit/s downstream and upstream.

3.1.17 dispersion [ITU-T G.989]: A physical phenomenon comprising the dependence of the phase or group velocity of a light wave in the medium, on its propagation characteristics such as optical frequency (wavelength) or polarization mode.

3.1.18 dynamic range [ITU-T G.989]: An optical receiver characteristic that is equal to the ratio of the receiver overload to the receiver sensitivity.

3.1.19 extinction ratio (ER) [ITU-T G.989]: With respect to a digital On-Off keying signal generated by an optical transmitter, the ratio of the average optical power level at the centre of the binary digit corresponding to the high intensity of light to the average optical power level at the centre of a binary digit corresponding to the low intensity of light.

For the burst-mode signal, averaging is performed over the time periods when the transmitter is enabled, but excluding the associated transient times (see clause 5.13 of [ITU-T G.989]). For the continuous mode signal, averaging is performed over the entire signal string.

3.1.20 fibre distance [ITU-T G.9807.1]: The overall length of fibre (and, if applicable, equivalent fibre runs representing delay-inducing components) between the R/S and S/R-CG reference points.

3.1.21 line code [ITU-T G.9807.1]: In the NG-PON2 context, a code which transforms a binary digital signal into an amplitude- and time-discrete waveform for transmission over a physical channel.

3.1.22 mean launch optical power [ITU-T G.9807.1]: An optical transmitter characteristic expressing the average optical power of an optical signal transmitted into the fibre and carrying a given digital sequence, referring to the optical power of an individual wavelength channel at the appropriate reference point (S/R-CG for downstream direction, R/S for upstream direction). When specified as a range, the minimum mean launch optical power provides the power level that the transmitter should guarantee at all times, and the maximum mean launch optical power provides the power level that the transmitter should never exceed. When applied to burst-mode transmission, the term pertains to the time interval during which the transmitter is enabled, and excludes possible starting and ending transient behaviour.

3.1.23 nominal central frequency [ITU-T G.989]: The specified frequency of a wavelength channel.

3.1.24 nominal line rate [ITU-T G.989]: The total number of bits that can be physically transferred per unit of time over a communication link. Nominal line rate accounts for useful data as well as for all possible protocol overheads and necessarily exceeds the effective data rate on any given protocol level.

3.1.25 ODN fibre distance class [ITU-T G.9807.1]: A categorization of an ODN based on the predefined values of minimum and maximum fibre distance between the S/R-CG and any of R/S reference points.

3.1.26 ODN optical path loss class (ODN Class) [ITU-T G.9807.1]: A categorization of an ODN based on the predefined values of minimum and maximum optical path loss over all possible paths between the S/R-CG and any of the R/S reference points and over all possible operating wavelengths of a specific PON system.

3.1.27 operating wavelength band [ITU-T G.989]: The spectral interval defined by its boundaries λ_{min} and λ_{max} which includes all possible central operating wavelengths for a particular application.

3.1.28 optical path loss [ITU-T G.9807.1]: The reduction in the optical power of light having traversed the ODN expressed as a ratio in decibel units. This loss may be caused by the fibre, connectors, splices, splitters, wavelength couplers, attenuators and other passive optical components.

3.1.29 optical path penalty (OPP) [ITU-T G.989]: The apparent degradation of receiver sensitivity due to impairments from fibre transmission and an apparent increase in ODN loss due to Raman depletion. The optical path penalty accounts for the effects of reflections, intersymbol interference, mode partition noise, fibre dispersion, and fibre non-linearities.

3.1.30 optical return loss (ORL) [ITU-T G.989]: The total reflection at the source reference point of the optical signal propagation path, measured as a ratio of the transmitted optical power to the reflected optical power.

3.1.31 overload [ITU-T G.9807.1]: A receiver parameter equal to the maximum average received optical power that produces the specified BER reference level, referring to the optical power of an individual wavelength channel at the appropriate reference point (S/R-CG for upstream direction, R/S for downstream direction) measured with the worst case signal, but without the optical path impairments.

3.1.32 reflectance [ITU-T G.989]: The reflection from any single discrete reflection point in the optical signal propagation path, which is defined to be the ratio of the reflected optical power present at a point, to the optical power incident to that point.

3.1.33 sensitivity [ITU-T G.9807.1]: A receiver parameter equal to the minimum average received optical power that produces the specified BER reference level, referring to the optical power of an individual wavelength channel at the appropriate reference point (S/R-CG for upstream direction, R/S for downstream direction) measured with the worst case signal, but without the optical path impairments.

3.1.34 side mode suppression ratio (SMSR) [ITU-T G.989]: The ratio of the power of the largest peak of the transmitter spectrum to that of the second largest peak. The second largest peak may be next to the main peak, or far removed from it. Within this definition, spectral peaks that are separated from the largest peak by the clock frequency are not considered to be side modes.

3.1.35 spectral width [ITU-T G.989]: The full width of the largest spectral peak, measured 15 dB down from the maximum amplitude of the peak.

3.1.36 tunability [ITU-T G.989]: In the NG-PON2 context, a property of an ONU to change its wavelength.

3.2 Terms defined in this Supplement

This Supplement does not define any terms.

4 Abbreviations and acronyms

This Supplement uses the following abbreviations and acronyms:

ADC Analog-to-Digital Converter

APD Avalanche Photodiode

BCH Bose–Chaudhuri–Hocquenghem

BER Bit Error Ratio

CD Chromatic Dispersion

CDR Clock Data Recovery

CE Coexistence Element

CT Channel Terminal

DAC Digital-to-Analog Converter

DBA Dynamic Bandwidth Allocation/Assignment

DC Dispersion Compensation

DD Direct Detection

DFB Distributed-feedback

DFE Decision Feedback Equalization

DML Directly Modulated Lasers

DMT Discrete Multi-Tone

DSP Digital Signal Processing

EAM	Electroabsorption Modulator
EDB	Electrical Duo-Binary
EDFA	Erbium-doped Optical Fibre Amplifier
EML	Electronic-absorption Modulated Laser
EML	External Modulated Laser
ER	Extinction Ratio
FDE	Frequency Domain Equalization
FDMA	Frequency Domain Multiple Access
FEC	Forward Error Correction
FFE	Feed-Forward Equalization
FFT	Fast Fourier Transform
G-PON	Gigabit-capable Passive Optical Network
HT	High Throughput
IFFT	Inverse Fast Fourier Transform
IM	Intensity Modulator
ISI	Inter Symbol Interference
LDPC	Low-Density Parity-Check
LPF	Low-Pass Filter
MAC	Media Access Control
MLSE	Maximum Likelihood Sequence Equalization
MZM	Mach-Zehnder Modulator
NG-PON2	Next Generation Passive Optical Network Phase 2
NLS	Non-Linear Schrodinger
NOOZ	NRZ On-Off Keying
NRZ	Non-Return to Zero
ODB	Optical Duo-Binary
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
OPL	Optical Path Loss
OPP	Optical Path Penalty
PAM4	4-level Pulse Amplitude Modulation
PON	Passive Optical Network
PRBS	Pseudo Random Bit Sequence
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency

RS	Reed-Solomon
Rx	Receiver
SNR	Signal Noise Ratio
SOA	Semiconductor Optical Amplifier
SPC	Single Parity Check
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
Tx	Transmitter
TWDM	Time and Wavelength Division Multiplexing
WDM	Wavelength Division Multiplexing
WM	Wavelength Multiplexer
XG-PON	10-Gigabit-capable Passive Optical Network
XGS-PON	10-Gigabit-capable Symmetric Passive Optical Network

5 Conventions

None.

6 System architectures

The high-speed passive optical network (PON) systems comprise one or more wavelength channel pairs which are separated in the wavelength domain. The operational principles of time division multiplexing (TDM) and time division multiple access (TDMA) apply in an individual wavelength channel pair. The high-speed PON systems comprising multiple wavelength channel pairs make use of a wavelength multiplexer. Figure 6-1 represents the general architecture of a high-speed PON system.

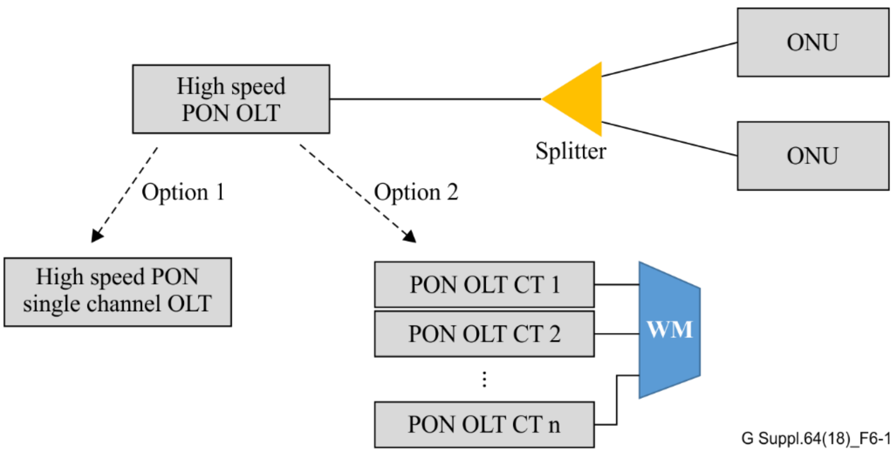


Figure 6-1 – High speed PON architecture

The high-speed PON systems, which use multiple wavelength channel pairs, generally support the optical network unit (ONU) tunability (allowing an ONU to change attachment to a wavelength channel pair in time) and wavelength channel bonding (accommodating the ONUs that are capable of operating on more than a single wavelength channel pair at a time).

7 Requirements

The requirements of a high speed PON could be described from several aspects, as stated below:

– Physical layer requirements
– Service requirements
– System level requirements
– Operational requirements
– Coexistence and Migration

7.1 Physical layer requirements

– Nominal line rate per channel

The high-speed PON systems support the nominal line rates per channel equal to 25G, 50G, or higher.

– Nominal line rate symmetry

In the context of 50G per channel PON systems, high speed PON may support the following bit rates combinations:

- nominally 50 Gbit/s down, 10 Gbit/s up
- nominally 50 Gbit/s down, 25 Gbit/s up
- nominally 50 Gbit/s down, 50 Gbit/s up

In the context of 25G per channel PON systems, high speed PON may support the following bit rates combinations:

- nominally 25 Gbit/s down, 10 Gbit/s up
- nominally 25 Gbit/s down, 25 Gbit/s up

– **OPL**

– A high speed PON must be able to support associated optical path loss (OPL) classes to operate on nominally class B+, N1, N2, C+ and E1 loss ODNs which have been massively deployed worldwide.

– **Split ratio**

As many ODN infrastructure with 1:32 to 1:64 split have been constructed, 1:64 split (subject to the overall loss budget) shall be the minimum requirement for a high speed PON.

– **Fibre distance**

A high speed PON must support the maximum fibre distance of at least 20 km.

– **Fibre characteristics**

A high speed PON must be able to be deployed using fibre types described in [ITU-T G.652], which is widely used for legacy PON systems. Fibre types described in [ITU-T G.657] should also be compatible for a high speed PON deployment.

– **Optical wavelengths**

The allocation of optical wavelengths is contingent upon specific PON technologies used for high speed PON.

7.2 Service requirements

A high speed PON is required to fully support various services for residential subscribers, and business customers' applications. Besides, a high speed PON should support legacy services which are already running in the legacy PON systems.

As legacy PON systems do, a high speed PON must accommodate services that require a maximum mean signal transfer delay of 1.5 ms.

7.3 System level requirements

As a shared-medium based system, some system requirements such as the following should be supported:

– **Authentication/identification**: To protect against impersonation/spoofing, authentication and identification mechanisms must be supported in a high speed PON. Inherited from legacy PON systems, identification of ONU serial number and/or a registration ID used for the ONU registration process shall be supported.

– **Encryption**: To protect against snooping at the ONUs, all unicast data in the downstream direction shall be able to be encrypted with a strong and well characterized algorithm in a high speed PON.

– **DBA**: The high speed PON optical line terminal (OLT) shall support the dynamic bandwidth allocation (DBA) algorithm for the efficient sharing of upstream bandwidth among the connected ONUs and the traffic-bearing entities within the individual ONUs based on the dynamic indication of their activity.

– **Eye safety**: All necessary mechanisms must be provided in OLT side and ONU side to insure that no eye damage can be caused to the end users unaware of the risks, especially if fibre is terminated inside the home.

Besides, power saving modes should be supported to achieve energy efficiency, as power saving has become an increasingly important concern in the interest of reducing operators' OPEX. Refer to clause A.9.1 power saving and energy efficiency in [ITU-T G.9807.1] for more details.

7.4 Operational requirements

A high speed PON must support full PON real-time management through ONU management and control functions.

The protection architecture of high speed PON should be considered, to enhance the reliability of the access networks.

7.5 Coexistence and migration

To protect major investments on deploying legacy PON including fibre infrastructure, a high speed PON coexistence with a legacy PON should be considered, including:

– XG-PON/XGS-PON;

– GPON;

– NG-PON2.

Seamless migration capability between legacy PON systems and high speed PON systems should be considered.

8 Candidate technologies above 10 Gbit/s per wavelength

8.1 Modulation technologies

8.1.1 NRZ modulation

8.1.1.1 NRZ modulation in O-band

Non-return to zero (NRZ) modulation is the simplest and most cost effective way to transmit data over optical fibre. At 10 Gbit/s, directly modulated lasers (DML) are adequate in O-band for 20 km transmission, but in long wavelength band, such as in S-band, C-band and L-band, electronic-absorption modulated lasers (EML) are necessary due to the dispersion limitation.

As bit rates increase up to above 10 Gbit/s, mitigation of increased chromatic dispersion (CD) is required. The dispersion tolerance (@1 dB dispersion penalty) for 25 GBit/s and 40 Gbit/s (using the model in [Agrawal-1]), and the corresponding usable spectrum in ITU-T G.652 fibres (20 km length) without dispersion compensation (DC) is shown in Table 8-1.

Table 8-1 – NRZ usable spectrum

NRZ bit rate	Dispersion tolerance (Chirp = 0)	Usable spectrum (20 km, no DC)
10 Gbit/s	1000 ps/nm	All of O-, E-, S, C, and L bands
25 Gbit/s	190 ps/nm	1260-1410 nm
40 Gbit/s	75 ps/nm	1290-1340 nm

In case of EML based transceiver, the dispersion tolerance would be reduced further from the above limit.

In full O-band, due to the very small chromatic dispersion coefficient, a 25 Gbit/s EML laser with NRZ modulation can support 20 km fibre transmission. In the zero dispersion wavelength range (near 1310nm) and O minus band (small negative dispersion), even the 25 Gbit/s directly-modulated distributed-feedback (DFB) lasers with NRZ can be used for 20 km transmission.

If the wavelength spectrum could be limited to the spectrum between 1290-1330 nm for a typical ITU-T G.652 fibre with zero dispersion wavelength locates at 1310 nm, then even 40 Gbit/s NRZ transmission for EML laser without dispersion compensation is viable. Of course, if we consider the worst case, which the zero dispersion wavelength of fibre may locate randomly between 1300 nm~1324 nm, the usable wavelength band will be much smaller.

The chromatic dispersion coefficient of ITU-T G.652 fibre in an O band is determined by Equation 8-1 and is shown in Figure 8-1.

$$\frac{\lambda S_{0\max}}{4}\left[1-\left(\frac{\lambda_{0\max}}{\lambda}\right)^4\right] \le D(\lambda) \le \frac{\lambda S_{0\max}}{4}\left[1-\left(\frac{\lambda_{0\min}}{\lambda}\right)^4\right] \tag{8-1}$$

where:

$$S_{0\max} = 0.092\, ps/(\text{nm}^2\text{*km}),\ \ \lambda_{0\max} = 1324\text{ nm},\ \ \lambda_{0\min} = 1300\text{ nm}$$

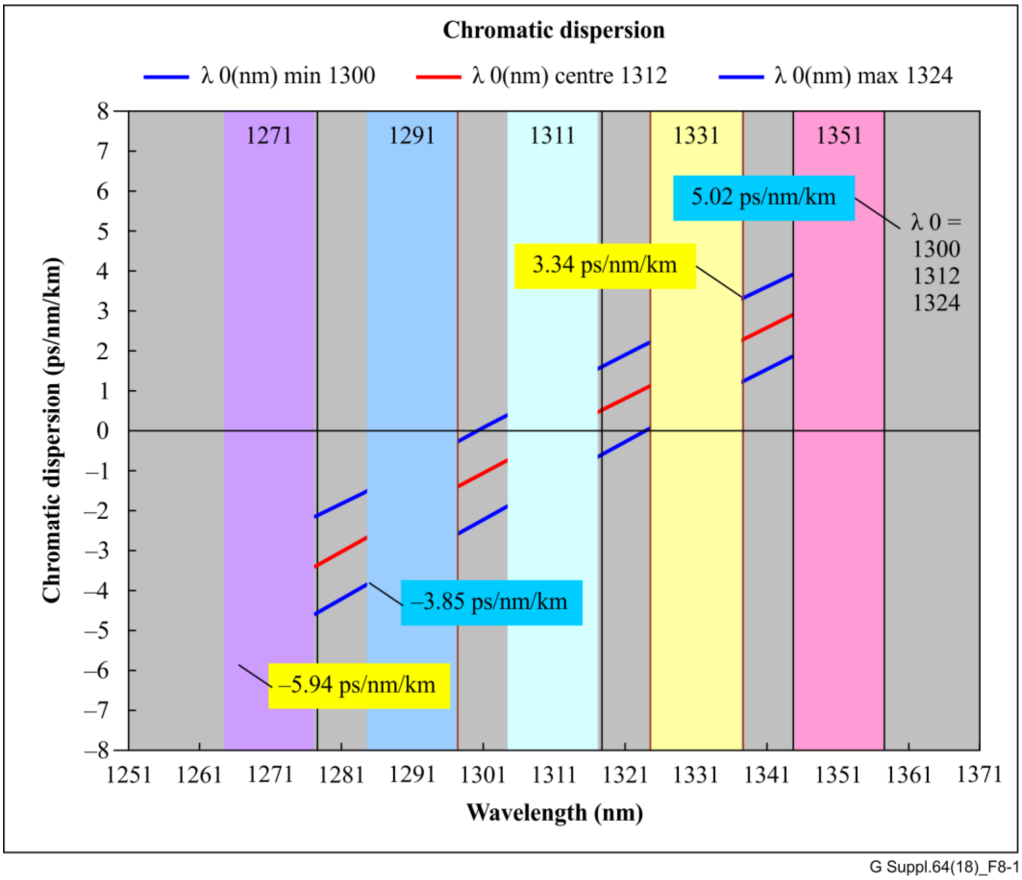


Figure 8-1 – Chromatic dispersion coefficient of ITU-T G.652 fibre in O-band

Based on Equation 8-1, for ITU-T G.652 fibre in O-band, the minimal chromatic dispersion is −6.35 ps/(nm*km) at 1260 nm, the maximal chromatic dispersion is 5.17 ps/(nm*km) at 1360 nm.

Based on the rate equation model of semiconductor lasers [Agrawal-2] and the parameters shown in [Yamamoto] [Ghelfi], Figure 8-2 shows the simulated eye diagram of 25 Gbit/s and 40 Gbit/s EML laser with NRZ modulation. From the figure, both 25 Gbit/s and 40 Gbit/s have very good eye diagram, which means the EML laser has enough bandwidth to support both 25 Gbit/s and 40 Gbit/s bandwidth.

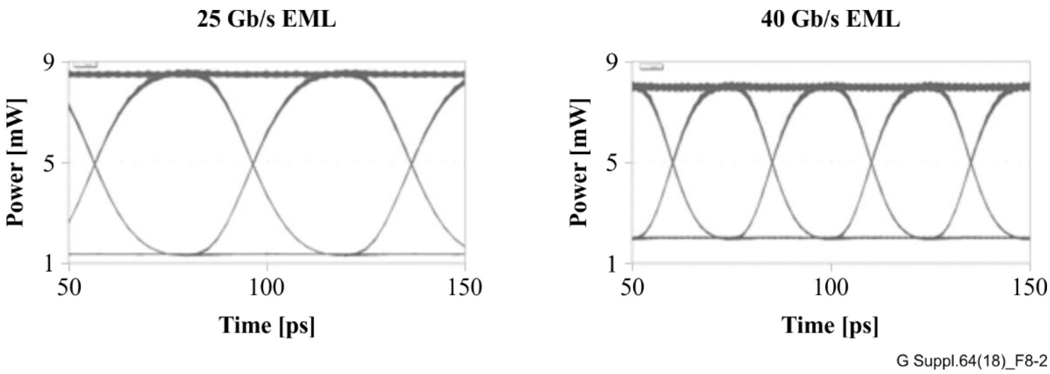
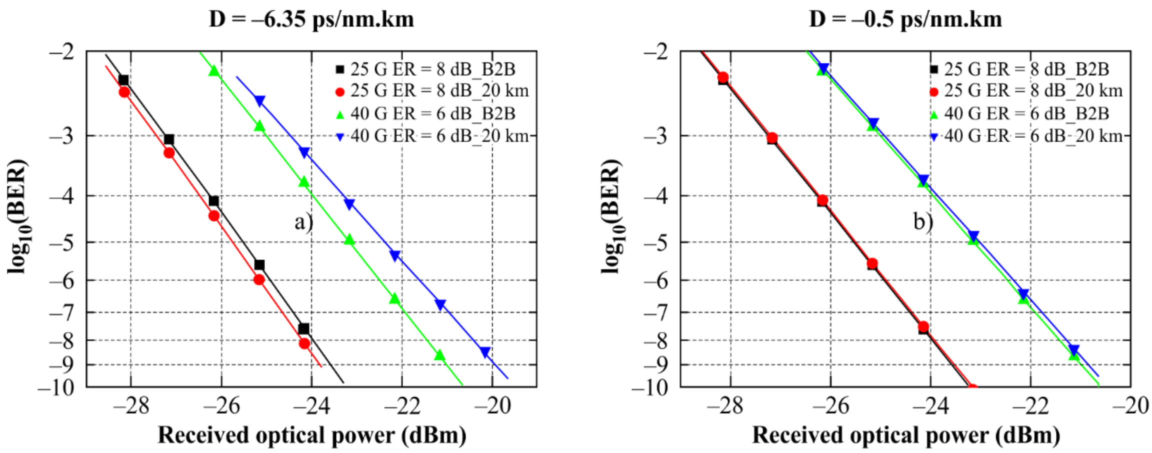
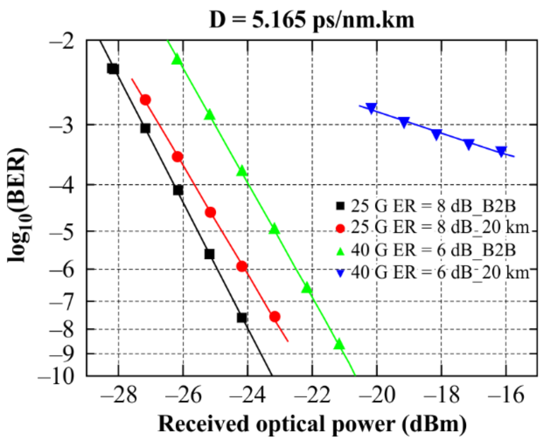


Figure 8-2 – Simulated eye diagram of EML laser with 25 Gbit/s and 40G NRZ modulation

In Figure 8-3, the dispersion penalty after 20 km based on the nonlinear Schrodinger (NLS) equation theory is compared with VPIphotonics fibre optics simulation tool. The chirp factor of EML is assumed as 0.5 [Ghelfi], which is a typical value for EML laser.





Sensitivity@1E-3 (dBm)				
	B2B	20 km		
		D = –6.35 ps/nm*km	D = 0.5 ps/nm*km	D = 5.165 ps/nm*km
25 G EML	–27.2	–27.4	–27.2	–26.7
40 G EML	–25.0	–24.4	–24.9	–19.0

G Suppl.64(18)_F8-3

Figure 8-3 – 25 Gbit/s and 40 Gbit/s EML dispersion penalty comparison after 20 km (a) in O- band, (b) in zero dispersion band and (c) in O+ band

At back to back, there is ~2.2 dB sensitivity difference between 25 Gbit/s and 40 Gbit/s EML. In the O- band, due to the negative chromatic dispersion coefficient, the sensitivity after 20 km is even a bit better compared with B2B for 25 Gbit/s. For 40 Gbit/s as the negative dispersion is too much, so there is a small penalty after 20 km. In a zero dispersion band, the dispersion penalty is negligible for both 25 Gbit/s and 40 Gbit/s. At O+ band, the dispersion penalty is still small, approximately 0.5 dB for 25 Gbit/s, while for 40 Gbit/s EML, the dispersion penalty becomes significant.

Figure 8-4 shows the simulated eye diagram of 25 Gbit/s and 40 Gbit/s DML laser, and Figure 8-5 shows the dispersion penalty after 20 km for 25 G DML lasers. Due to the carrier lifetime and the photon life time limitation, the DFB laser can only support 25 Gbit/s NRZ direct modulation but not 40 Gbit/s NRZ direct modulation. Due to the high chirp of DML, the 25 Gbit/s DML with NRZ modulation can only operate in zero dispersion and O- band without serious dispersion penalty, but in O+ band, the dispersion penalty after 20 km transmission is quite significant even for 25 Gbit/s DML laser.

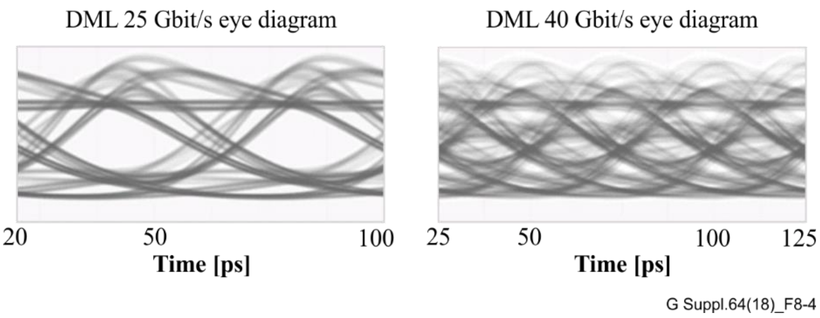


Figure 8-4 – Simulated eye diagram of DML laser with 25 Gbit/s and 40 G NRZ modulation

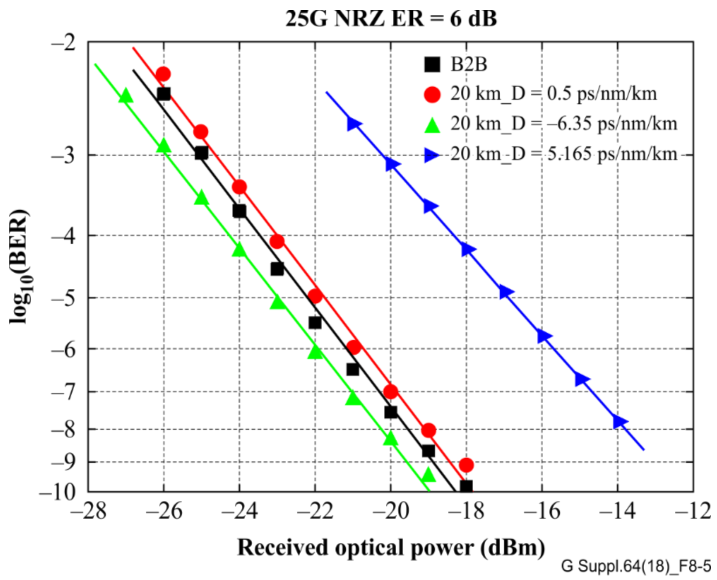


Figure 8-5 – 25 Gbit/s DML dispersion penalty comparison after 20 km

One can extrapolate from 10 Gbit/s the required NRZ receiver (Rx) sensitivity for 25 Gbit/s and 40 Gbit/s, and the corresponding OLT minimum launch powers. For APD receivers, using the mode in [Beijing Univ], [Kazovsky], signal noise ratio (SNR) of APD:

$$SNR = \frac{(MRP_{in})^2}{2qFM^2(MRP_{in} + I_d)\Delta f + 4k_B T\Delta f / R_L} \tag{8-2}$$

where:

P_{in} is the average receiver optical power

Δf = receiver bandwidth

M = multiplication factor

F = excess noise factor

R = response of APD

Assume APD is photocurrent shot noise limited, then if increase the bandwidth Δf by 2.5 times (for 25 Gbit/s NRZ), P_{in} must be increased by at least 2.5 times (4 dB) to maintain the same SNR; similarly , if bandwidth Δf is increased by 4 times (for 40 Gbit/s NRZ), P_{in} must be increased by at least 4 times (6 dB) to maintain the same SNR; whereas when bit rate increases, the M, R, F cannot be the same as 10 Gbit/s, so the sensitivity of APD will increase at an even higher level (less sensitive) when bit rate goes to 40 Gbit/s. Accordingly, the approximate formula in [Yamamoto $P_{in} \propto B^{7/6}$, the sensitivity of 40 Gbit/s APD will be at least 7 dB lower (less sensitive) than 10 Gbit/s APD.

The parameters of XG-PON downstream in [b-ITU-T G.987.2] can be used as a base line extrapolating the ONU sensitivity and OLT transmitter launch power requirement for higher bit rates, which is shown in Table 8-2.

Table 8-2 – Example NRZ power, downstream

NRZ bit rate	Rx sensitivity, downstream	Transmit power min, N1 class
10 Gbit/s	−28 dBm	2 dBm
25 Gbit/s	−24 dBm	6 dBm
40 Gbit/s	−21 dBm	9 dBm
NOTE – Assume OPP maintains same with XG-PON, which is highly wavelength dependent.		

8.1.1.2 NRZ modulation assisted with DSP technology

Digital signal processing (DSP) technology can be used to improve the performance of NRZ transmission via the compensation of inter-symbol interference (ISI), which may be caused by fibre chromatic dispersion and/or bandwidth limitation of the transmitter and the receiver. At 25 Gbit/s, DSP-assisted NRZ is capable of transmission over 20 km in the C-band, which is not the case for the conventional NRZ. On the other hand, if the O-band is chosen for 25-Gbit/s per-wavelength transmission, fibre chromatic dispersion is no longer a concern that requires the use of DSP assistance. DSP-assistance has also been shown to allow the use of 10G-class optics for 25-Gbit/s transmission, thereby lowering the cost of the optics. It remains to be seen if the lowered cost in optics can justify the additional cost associated with the use of DSP, i.e., the cost of the digital signal processor, the analog-to-digital converter (ADC), and/or the digital-to-analog converter (DAC).

The different frequency component of optical signal which has a certain spectral width in optical transmission system has different transmission rate. When data rate goes beyond 10 Gbit/s, it will lead the signal to be broadened and result in serious inter symbol interference (ISI). If the effective bandwidth of the signal is greater than the effective bandwidth of the system, for example, utilizing existing 10G optics to transmit 25 Gbit/s signal, when the signal is transmitted through the system, it will lose a lot of important components and will be distorted. In such case, the optical fibre system can no longer be considered an infinite bandwidth communication channel. In order to overcome the above effects in high-speed optical system, equalization compensation is essential.

The DSP-based equalizer system is to compensate for transmission-channel impairments such as frequency-dependent phase and amplitude distortion. Reasonable clock recovery and equalizer designs, such as feed-forward equalization (FFE), decision feedback equalization (DFE), maximum likelihood sequence equalization (MLSE) etc., make it easy to recover the original signals from distorted signals. According to the different requirements and application scenarios, equalizations with different structures and complexity are proposed.

Figure 8-6 shows an example of a 28 Gbit/s NRZ modulation scheme in a C-band based on a DSP equalization. At the transmitter side, a normal NRZ signal is transmitted by a digital to analogue converter (DAC), then through a band limited optical link, the original NRZ signal is degraded. At the receiver side, an equalization algorithm based on a DSP to compensate the bandwidth limitation and optical dispersion is used to recover the original signal.

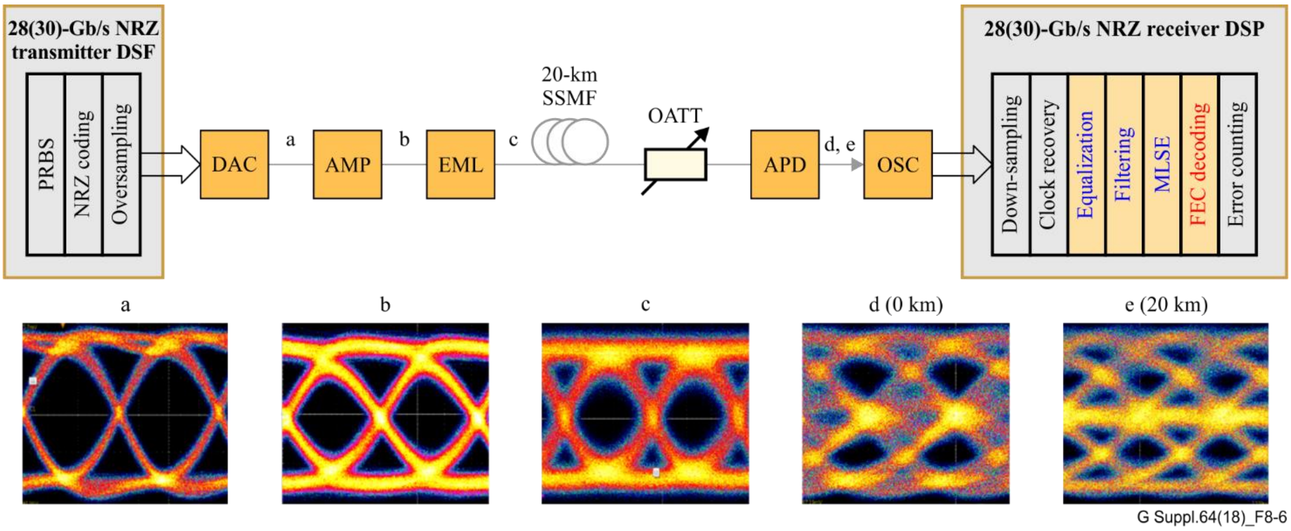


Figure 8-6 – Schematic of the 28-Gbit/s NRZ-DSP equalization experiment set-up. (a-e): measured eye diagrams at different locations in the transmission link

At the transmitter, the pseudo random bit sequence (PRBS) is encoded into NRZ format and two times oversampled, before being converted to an analogue radio frequency (RF) signal by a high-speed DAC with 56 GSa/s. An analogue amplifier is used to adjust the RF signal to an appropriate level. A 10 Gbit/s EML with a center wavelength of ~1550 nm is used to convert the electrical signal to an optical signal. After a 20 km fibre transmission at the receiver side, 10 Gbit/s APD is used to directly detect the optical signal and followed by an ADC device to convert the signal to electrical digital signal. In the DSP function block, down-sampling and clock recovery are first performed. Equalization is then applied to compensate for the bandwidth-limitation induced ISI. Finally, the FEC decoder processes the output from the equalization module and corrects the pre-FEC bit errors.

Another potential benefit of DSP-assisted NRZ is its capability to reliably recover the signal even at a high received bit error ratio (BER), e.g., higher than 10^{-3}. This may allow advanced forward error correction (FEC) to be used to increase the link budget for 25-Gbit/s NRZ transmission. In addition, the use of DSP may ease the implementation of multi-rate burst-mode clock data recovery (CDR), which could be needed for TDM coexistence between 25 Gbit/s and 10 Gbit/s upstream signals.

In summary, DSP-assisted NRZ offers several potential benefits, and its adoption in future PON systems depends on factors such as its associated cost, power consumption and commercial product availability. If DSP is to be adopted, it is likely to be first used in OLTs as the OLT cost can be shared among many ONUs.

8.1.1.3 NRZ modulation with duobinary detection

The electrical duo-binary (EDB) is a three electrical level and higher-order modulation format [Lender], it can be applied either at the transmitter and receiver, or just at the receiver. In both cases, it will improve the dispersion tolerance in the system and reduce the receiver bandwidth requirements. For more details refer to clause 8.1.2 on electrical duo binary. NRZ signal can also be detected on the receiver side based on EDB technology.

At the receiver, the detection of the 3-level signal can be a simple electrical circuit that includes a splitter, two comparators and an XOR gate [Sinsky]. Compared to NRZ, EDB exhibits a reduction in signal spectrum of approximately 60% and improves chromatic dispersion tolerance by approximately a factor of 2.

Applied to a high bit rate PON, the low-pass filter (LPF) function might be best implemented at the optical receiver. In this implementation, the signal is transmitted in conventional NRZ. This allows for an EDB receiver with only 40% of the bandwidth of an NRZ receiver. For example, a conventional high-volume low-cost 10G APD NRZ receiver can be used to implement a 25G duobinary receiver. The performance of the 10G-APD-based 25G duobinary receiver will approximate the performance of a 25G APD receiver. Experimental confirmation has been reported in continuous mode [van Veen] and burst-mode [Yin].

EDB may be an important implementation option to mitigate the risk of potentially low-volume high-cost 25G APDs, for a 25G PON. With regards to standardization, the impact is minimal. NRZ transmission and receiver sensitivity can be specified in the traditional way. The receiver is a black box, allowing vendors to choose their implementation based on their innovation and the evolution of technology. The standard does not commit any vendor to choose a duobinary receiver implementation. (Although in this scenario, where a conventional NRZ receiver implementation is allowed, the superior dispersion tolerance of EDB cannot be taken advantage of). Figure 8-7 is a pictorial view of this scenario, where a single 25G receiver sensitivity at R is specified, followed by a black box receiver with one of three possible receiver implementations.

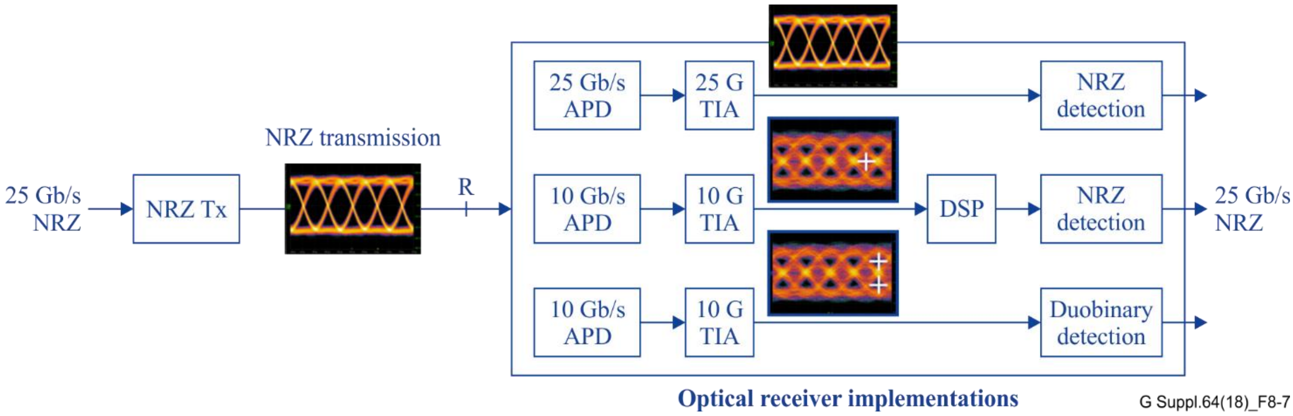


Figure 8-7 – NRZ transmission and multiple receiver implementation options

8.1.2 Electrical duo binary

EDB is one of the associated coding techniques. As compared to NRZ, it is a three electrical level and higher-order modulation format.

In Figure 8-8, the left graph shows the NRZ waveform, the middle graph shows the EDB waveform at the same transmission rate, and the right graph shows the corresponding power spectrum diagram. It is obvious that the frequency spectrum of EDB is half of NRZ except the difference between level two and level three. This will greatly improve the dispersion tolerance ability.

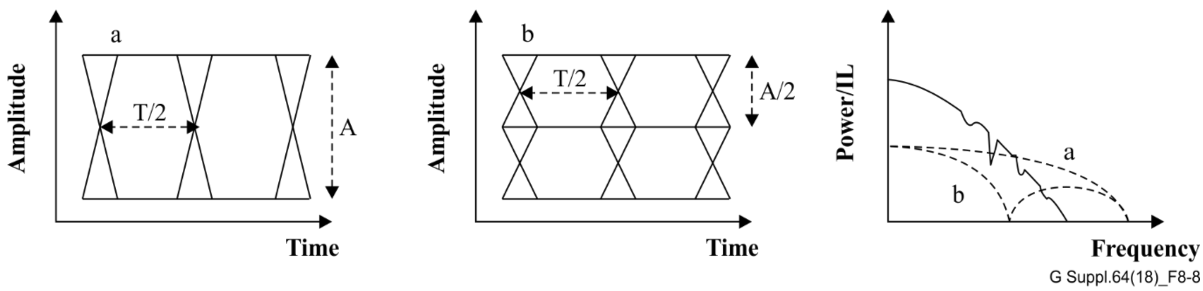


Figure 8-8 – Schematic of NRZ waveform (left), EDB waveform (middle) and the corresponding power spectrum diagram (right)

Electrical duobinary data can be generated by sending NRZ On-Off Keying (NRZ-OOK) data through an electrical "delay-and-add" filter, creating a 3-level signal [Lender]. This filter has a z-transform of $1+z^{-1}$, which can be approximated by a low-pass filter (LPF) in the electrical domain. Duobinary coding is a correlative coding method, so to avoid error propagation, pre-coding of the data at the transmitter is needed [Sinsky].

Figure 8-9 shows the coding and decoding schematic diagram of EDB. In a typical EDB system, there are three parts: Pre-coder (differential encoding), en-coder and de-coder. The pre-coder part mainly completes the input stream differential coding, and the logic is implemented using XOR logic with feedback delay. The encoder part mainly completes coding related functions (the three level output) by logically using the 1 bit time delay and add. At the receiver, a simple example of EDB decoder is an electrical circuit that includes a splitter, two comparators of upper level detection and lower level detection, and an XOR gate.

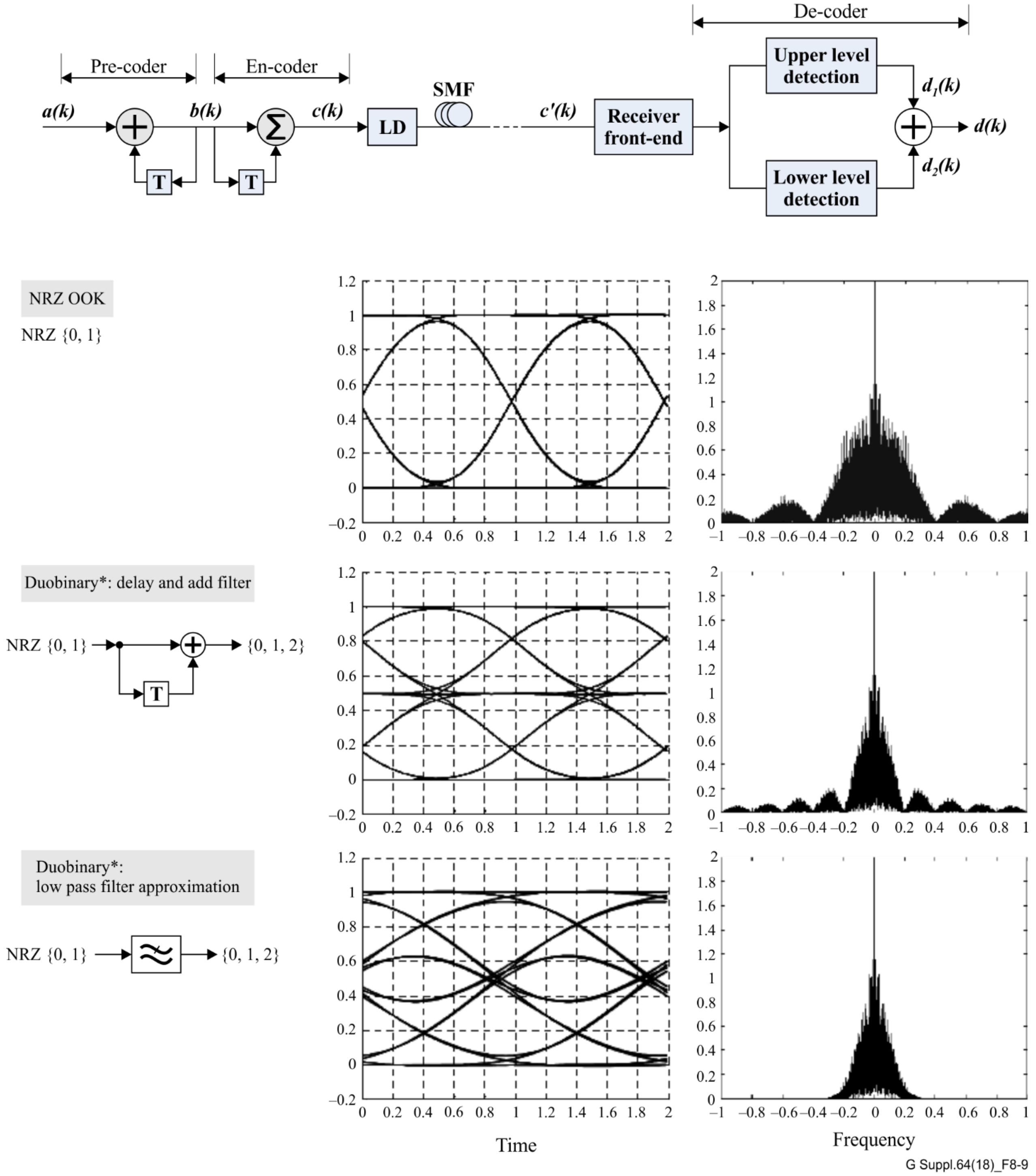


Figure 8-9 – Coding and decoding schematic diagram of EDB

The duobinary LPF encoding can be realized by the bandwidth roll-off of either the transmitter or the receiver. The required bandwidths of the LPF are shown in Table 8-3.

Table 8-3 – Duobinary LPF encoding bandwidths compared to NRZ

	10 Gbit/s	25 Gbit/s	40 Gbit/s
NRZ	7.5 GHz	18.75 GHz	30 GHz
Electrical Duobinary	not in scope	7 GHz	11 GHz

As compared to NRZ, the payoff for EDB is a reduction in signal spectrum and an increase in CD tolerance by approximately a factor of 2. These characteristics of duobinary mitigate the need for higher speed components and increase dispersion tolerance, while the cost is higher for decoding complexity and lower sensitivity (due to the three-level eye diagram). Therefore, the semiconductor optical amplifier (SOA) may be required by EDB to meet the same power budget of NRZ.

To allow for a duobinary implementation, the standard must specify pre-coding (duobinary coding is a correlative coding method, so to avoid error propagation, pre-coding of the data at the transmitter is needed). Pre-coding is a kind of differential coding, and is a simple logical operation (like scrambling). It is implemented with a one-bit delay line and an XOR gate in the electrical domain at the transmitter. When choosing an NRZ receiver implementation, the pre-coding must be decoded. This again is achieved with a simple one-bit delay line and an XOR gate in the electrical domain. See Figure 8-10.

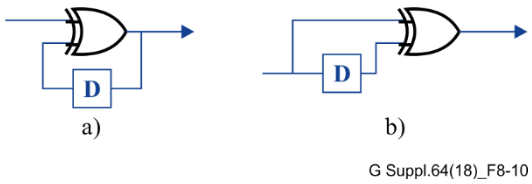


Figure 8-10 – (a) Transmitter pre-coder (b) NRZ receiver decoder

There is an artifact of pre-coding that must be accounted for in NRZ receivers. When there is a single bit error, the error is propagated to the next bit, thereby doubling the pre-FEC bit error rate. This effect is minimized by symbol-based FECs like Reed-Solomon (RS). Analysis has shown that the post-FEC penalty for this error doubling is maximum 0.1 dB in the case of a RS(255,223) FEC, and might even slightly improve the performance of DSP-aided NRZ detection [Houtsma], [Yao] because precoding mitigates burst errors which can also occur due to error propagation in DFE and MLSE based equalization schemes.

To summarize, if pre-coding is adopted in a 25G standard, it enables (but does not require) a duobinary receiver implementation based on high-volume low-cost 10G APDs, as a mitigation in case of an expensive 25G APDs – which may be especially critical for the ONU. The price of this mitigation is maximum 0.1 dB penalty of NRZ receiver implementations (assuming Reed-Solomon (255,223) FEC).

8.1.3 Optical duo binary

For the NRZ system, dispersion has the most influence on the "1,0,1" sequence. The optical pulse phase of NRZ signal modulated by an electroabsorption modulator (EAM) or a Mach-Zehnder modulator (MZM) has the same symbol. When the pulse is broadened by the dispersion, "0" between the "1,0,1" sequence will have a certain optical intensity because of the two "1" pulse edge overlay. Pulse broadening increases when transmission distance increases, the optical intensity of "0" increases, eye opening is reduced because of ISI. Finally the performance of the receiver is heavily decreased.

Optical duo-binary (ODB) has three levels "1,0,−1". Although the two adjacent optical pulses have dispersion, pulse broadening will be offset because they are the opposite symbols. Thus the ISI is reduced, dispersion tolerance is improved greatly. Dispersion characters of NRZ and ODB are shown in Figure 8-11.

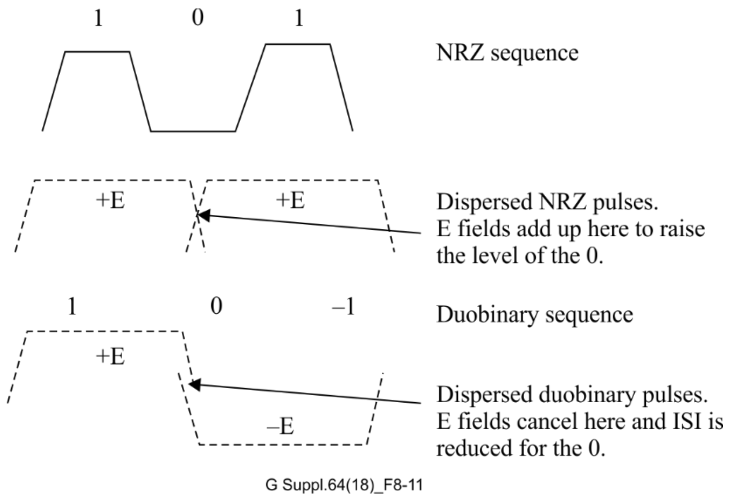


Figure 8-11 – ODB interference offset to avoid ISI

There are three levels "1,0,−1" in DB electrical signal. "0" level should be biased on the NULL point (valley) of the MZM. Thus the optical intensity of level "1" and "−1" coincide, but their phases are opposite. ODB uses phase character in the E/O transition, and the amplitude of the output optical signal is coincident, so the ODB signal can be received by a regular NRZ receiver.

The ODB modulation principle is shown in Figure 8-12. The rectangular coordinate axes in the left bottom subfigure is the electrical signal voltage adding on the modulation RF port [Winzer]. The solid line is the optical intensity modulation curve of MZM. The dash line is the phase modulation curve.

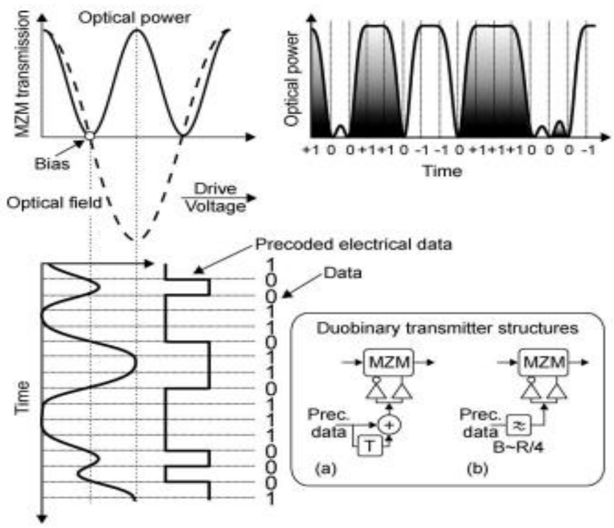


Figure 8-12 – ODB modulation principle

As an example, Figure 8-13 shows the coding and decoding schematic diagram of 25 Gbit/s ODB in C-band. The pre-coder and encoder schematic of ODB is the same as EDB, the low pass filter first transforms the 25 Gbit/s NRZ signal to a three-level duo binary signal. At the transmitter, a phase modulator, such as a 10 Gbit/s MZM at 1550 nm operation wavelength, is used to transform the three levels electrical duo binary signal to an optical duo binary signal. This result is achieved with a MZM biased at its null point. With a "0" input, no light is transmitted, and the "+1" and "−1" inputs are transmitted as +E and –E electric fields, respectively. While this is a three-level signal in terms of the electric field, it is a two-level signal in terms of optical power. This scheme significantly reduces the complexity of the receiver (different with EDB), and increases the chromatic dispersion tolerance. Because the "+1" and "−1" signals have the same amplitude in intensity, the decoder part of ODB can conduct modulo 2 operation, so the ODB detection is quite similar to the NRZ detection.

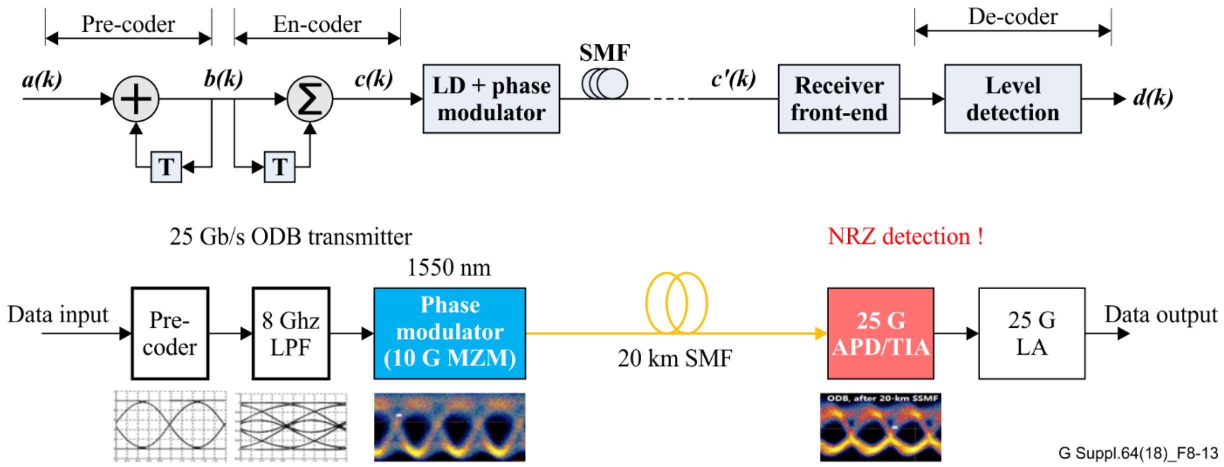


Figure 8-13 – Coding and decoding schematic diagram of 25 Gbit/s ODB

8.1.4 PAM4 modulation

Four-level pulse amplitude modulation (PAM4) is a form of signal modulation where the message information is encoded in the amplitude of four signal pulses. The principle of 25 Gbit/s PAM4 is shown in Figure 8-14. The baud rate of 25 Gbit/s PAM4 signal is only 12.5 GBaud/s. The spectral efficiency is doubled. The dispersion tolerance of 25 Gbit/s PAM4 is four times of 25 Gbit/s NRZ. The transmitter of 25G PAM-4 modulation only needs a 12.5 Gbit/s EML and a 12.5 Gbit/s linear driver, and the receiver is a 12.5G bit/s linear APD ROSA. In order to re-use the existing industry chain, 10 Gbit/s optical devices can be used for 25 Gbit/s PAM4 modulation instead of 12.5G optical components. Electrical compensation algorithms can be adopted to compensate for the bandwidth. PAM-4 coder and decoder chip is necessary for PAM4 modulation.

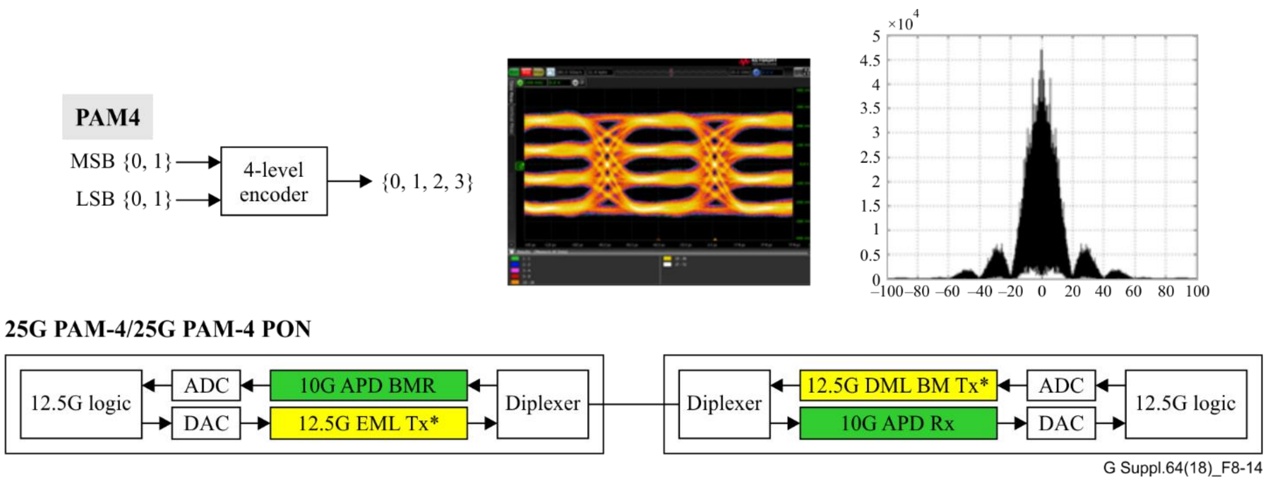


Figure 8-14 – Schematic of PAM4 modulation

8.1.5 DMT modulation

While NRZ, duo-binary and PAM4 can be used for PON transmission above 10G per wavelength, orthogonal frequency division multiplexing modulation (OFDM) can also be utilized to achieve high data rate with low bandwidth optical transceivers. Moreover, deep integration with sophisticated electronic digital signal processing (DSP) introduces strong implementation flexibility and capabilities of compensating various transmission impairments.

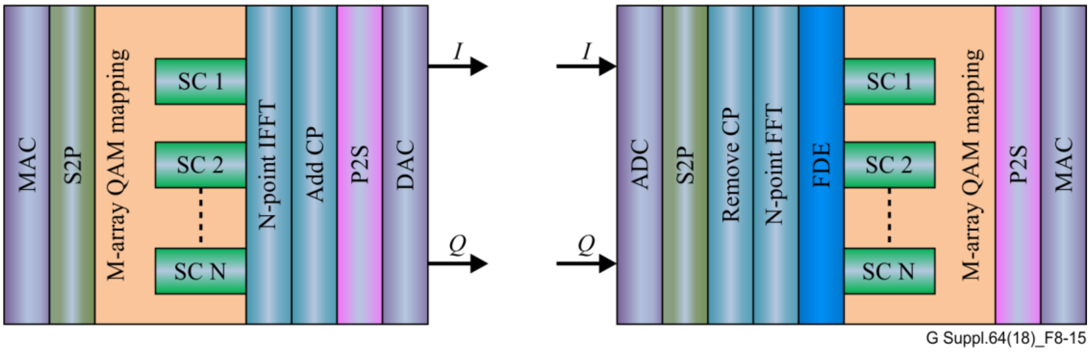


Figure 8-15 – Basic OFDM system architecture

The basic architecture of the electronic OFDM transmitter and receiver are shown in Figure 8-15. In the transmitter, high speed binary data is first parallelized (S/P), and then mapped to M-ary quadrature amplitude modulation (QAM) symbols (e.g., M = 4, 8, 16…), and feed into a N-point inverse fast fourier transform (IFFT) to generate a digital OFDM signal with N orthogonal subcarriers. After cyclic prefix (CP) insertion, the digital output is serialized and applied to a two-channel digital-to-analog converter (DAC). The output of in-phase (I) and quadrature (Q) components of the OFDM signal are then converted into fibre either by optical IQ modulator or direct optical intensity modulation. In the receiver, the I and Q signal components are digitized by a two-channel analog-to-digital converter (ADC), which is followed by serial-to-parallel conversion and cyclic prefix removal. An N-point fast fourier transform (FFT) is used to digitally de-multiplex the N OFDM subcarriers. Single-tap frequency domain equalization (FDE) maybe performed to correct linear impairments (e.g., chromatic dispersion) on each of the N subcarriers, which is followed by M-ary QAM symbol de-mapping. Finally, the received bits are serialized to recover the transmitted data.

One of the major merits of using OFDM is that frequency domain multiplexing can be introduced into the PON network. In a current PON system, the whole PON capacity can be shared among users via both wavelength domain (i.e., WDM) and time domain (i.e., TDM). While in OFDM systems, extra frequency domain can be accessed by means of IFFT/FFT via DSP. One (or more) subcarrier(s) can be assigned either dynamically or statically from the entire OFDM band to different users, as shown in Figure 8-16. In addition, frequency domain multiplexing can also work together with wavelength and time domains multiplexing to achieve flexible bandwidth sharing with multiple granularities.

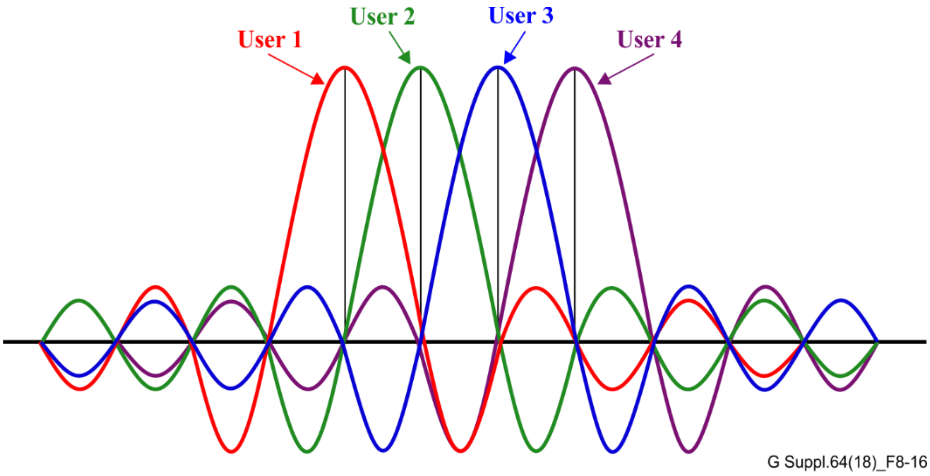


Figure 8-16 – Frequency-domain OFDM subcarrier multiplexing for multi-user access

For 10G above per wavelength PON systems, OFDM is expected to generate high-speed signals by low bandwidth transceivers, for example, 25G or 40G data rate can be supported by using 10G directly modulated DFB lasers (DMLs) or external modulated lasers (EMLs), and 10G APD/PIN detectors. In order to avoid complex optical I/Q modulator, conjugate symmetry can be exploited for simple implementation by using single-channel DAC/ADC instead of analogue I/Q modulator/demodulators, known as discrete multi-tone (DMT). Figure 8-17 shows the example architecture with DMT modulation.

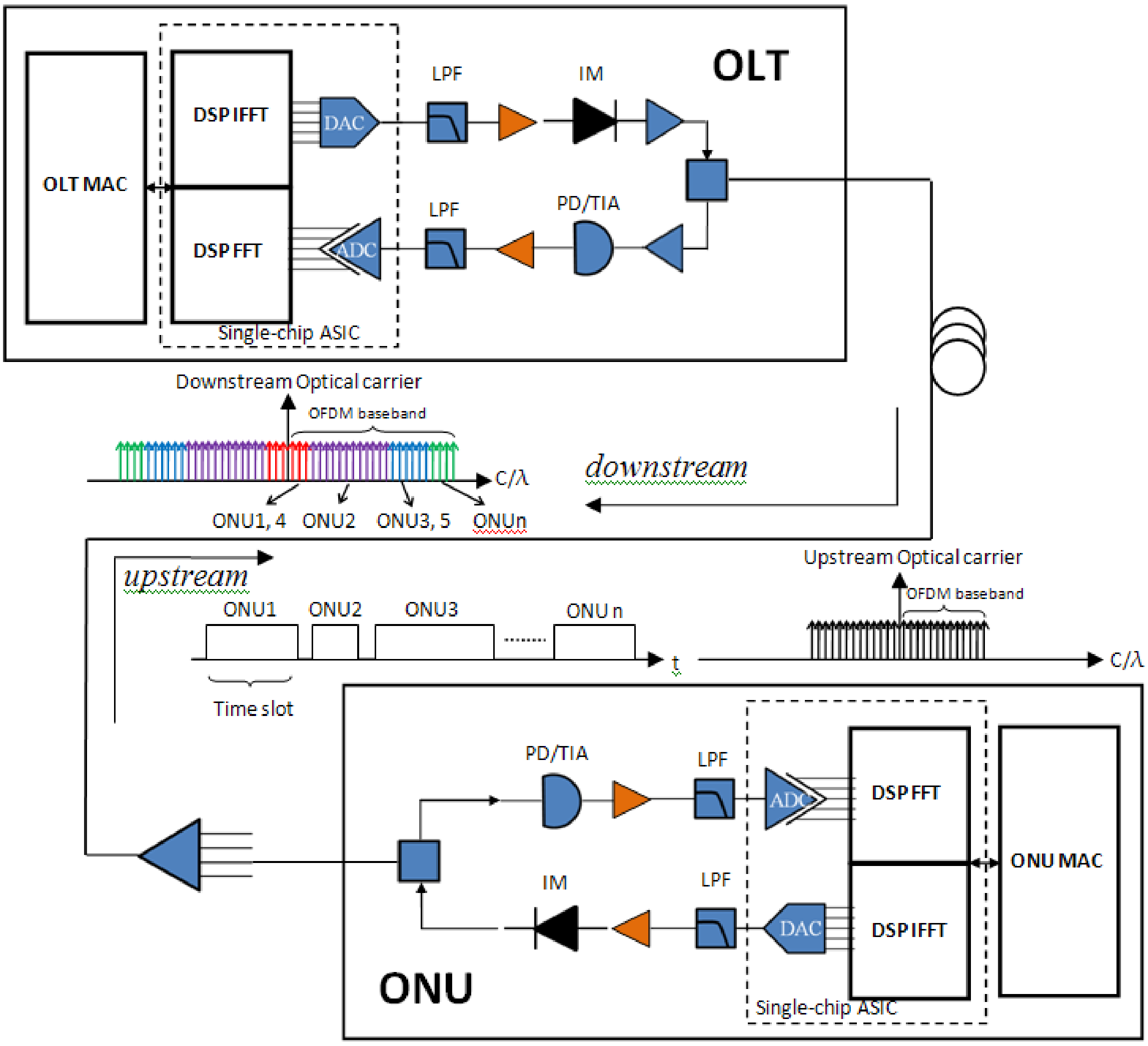


Figure 8-17 – Example architecture of DMT modulation

At the OLT transmit in the downstream direction, the digital baseband signal is generated by the DMT modulator based on a DSP with QAM mapping and IFFT, then, it is converted to an analogue signal using a single channel DAC. An intensity modulator (IM) is used to convert the baseband signal to optical intensity for downstream transmission. At the ONU reception, the downstream signal is directly detected by a linear optical PIN or APD receiver, and then sampled by ADC. Then FFT and QAM de-mapping are processed by DSP, so the downstream data is re-generated. Downstream multiplexing can be conducted with different granularities. A group of ONUs may be assigned by one or more sub-carriers in the frequency domain. The available bandwidth of each sub-carrier or sub-carrier group can be further divided among ONUs in the time domain.

As shown in Figure 8-17, the time domain multiple access (TDMA) with the DMT modulation can be used in the upstream direction. At the ONU transmit side, a DMT digital baseband signal is generated by DSP, and then converted into optical intensity using DAC and IM modulator and transmitted in dedicated time slot assigned to each ONU by the OLT. At the OLT receive side, the upstream signal in each time slot is directly detected by a burst mode receiver and digitized by ADC, and then DSP fulfils the burst clock recovery and completes the DMT demodulation. Frequency domain multiple access (FDMA) can also be supported in upstream, but necessitates more accurate frequency control mechanisms.

8.1.6 Bandwidth, dispersion limitation and equalization analysis

In this clause, the achievable performance is evaluated for the following modulation formats: NRZ (PAM-2), PAM-4, EDB (Electrical DuoBinary), ODB (Optical DuoBinary), including the impact of RX equalization, transmitter/receiver (TX/RX) frequency response and chromatic dispersion.

The evaluation [b-Torres-Ferrera] is based on computer simulations for: signal generation at TX, adaptive equalization at RX, fibre propagation (mainly chromatic dispersion), noise sources and bandwidth limitations. Figure 8-18 shows the adopted simulation model.

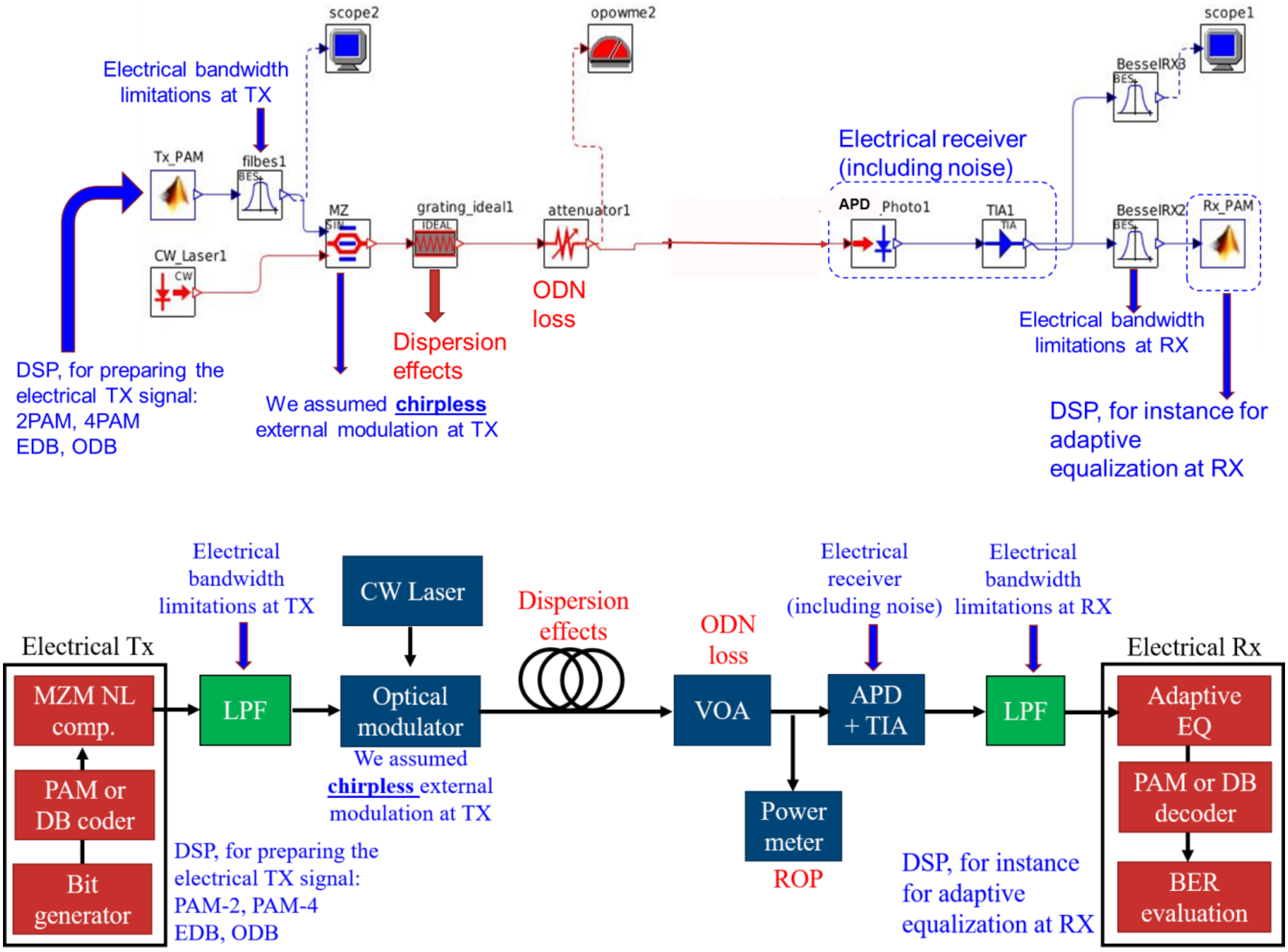


Figure 8-18 – Adopted computer simulation model

The following assumptions have been made:

- Bit rate: 25 Gbit/s, corresponding to 12.5 Gbaud for PAM-4 modulation and 25 Gbaud for the other modulation formats (PAM-2, EDB, ODB)
- External modulation: chirpless MZM with non-linear compensation
- APD-based receiver (G=25 (14 dB), F=10.5 dB, R=0.8, IRND=32 pA/$\sqrt{Hz}$)
- Adaptive equalization at the receiver:
  - 20-tap feed-forward equalizer (FFE)
  - Least mean square adaptation algorithm
  - Decision threshold optimization

- Same frequency response at both TX and RX, both modelled with either a Butterworth or super Gaussian (S-Gaussian) filter response, characterized by the 3 dB bandwidth (B_{3dB}) and the 20 dB bandwidth (B_{20dB})
- Reference BER = 1E-3

In the following, the normalized bandwidth is defined as: $B_{3dB}\% = \frac{B_{3dB}}{bit\ rate} \cdot 100$ and similarly for $B_{20dB}\%$.

8.1.6.1 Effect of bandwidth limitation and equalization

First, a comparison of back-to-back performance for the different modulation formats and for the ideal condition of infinite extinction ratio (ER) is given in Figure 8-19 versus the 3dB TX/RX bandwidth, showing the performance advantage obtained with equalizer versus the cases without equalizer and respectively with or without threshold optimization. Both the TX and RX have been modelled here with a single pole Butterworth transfer function. The vertical dashed line in the graphs represents the 3 dB bandwidth of a 10G TX/RX device, assumed to be 7 GHz.

The benefit of using an equalizer is quite evident and its use is assumed in the following analysis.

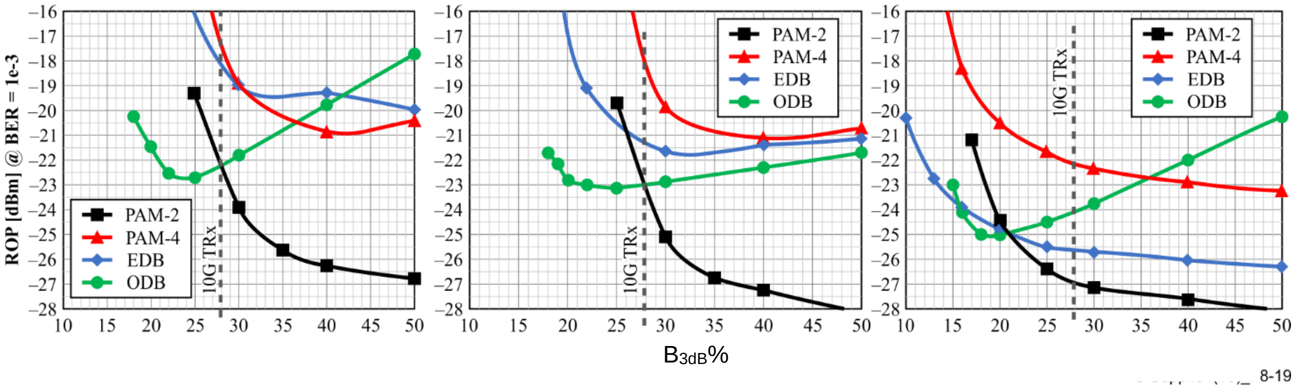


Figure 8-19 – back-to-back performance, ER = ∞, a) without equalizer, fixed threshold; b) without equalizer, optimized threshold; c) with equalizer, optimized threshold

8.1.6.2 Effect of TX/RX frequency response

To analyse the impact of the TX/RX frequency response on performance, this response has been modelled using a Butterworth or S-Gaussian filter with a fixed 3 dB bandwidth of 7 GHz and a varying 20 dB bandwidth, as shown in Figure 8-20. The advantage of the S-Gaussian model is that it allows to easily set any value for the 20 dB bandwidth, by varying the order, whereas the Butterworth model is constrained to have an integer number of poles.

The graphs in Figures 8-21 to 8-23 show the effect of a reduced 20 dB bandwidth, where it is evident that:

- all modulation formats have a rapidly increasing penalty when B_{20dB} decreases below about 25 GHz for PAM-2 and about 15 GHz for the other formats
- ODB is the most sensitive to in-band filter shaping (the increased penalty shown with the S-Gaussian filter is attributed to the reduced in-band power that this filter collects with respect to the Butterworth filter, compared in Figure 8-20 and Figure 8-22), but it gives the best performance if a small bandwidth (12 < B_{20dB} < 17 GHz) TX/RX combination is used
- EDB has > 2.5 dB advantage over PAM-4 for B_{20dB} > 18 GHz and is less sensitive than ODB to the particular filter shape

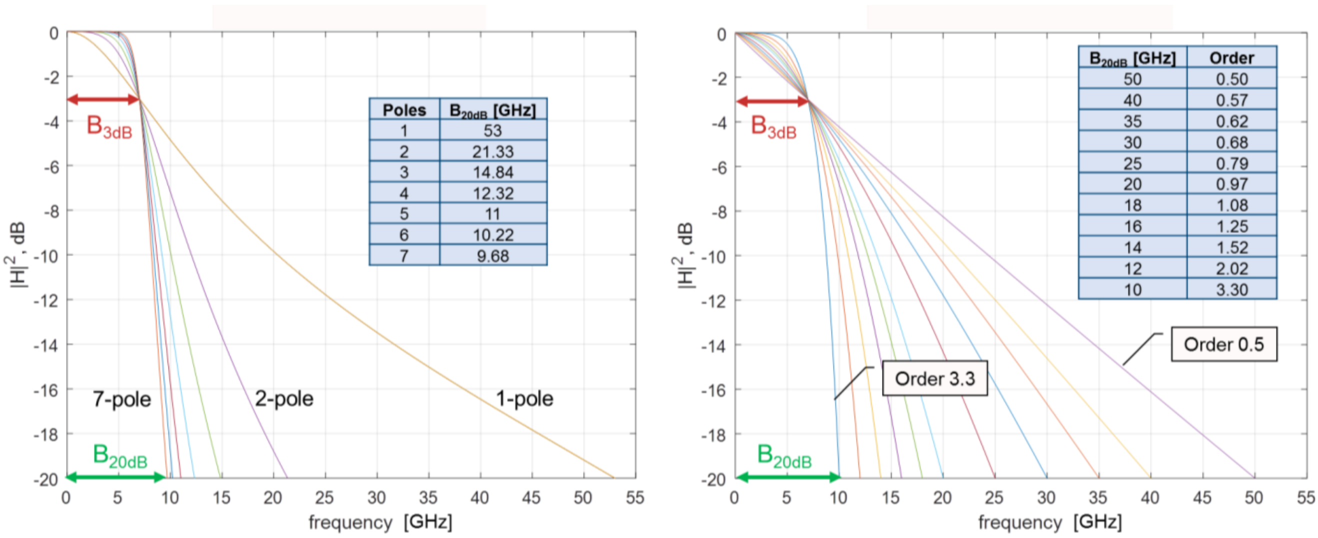


Figure 8-20 – 3 dB and 20 dB bandwidths for Butterworth (left) and S-Gaussian (right) filters

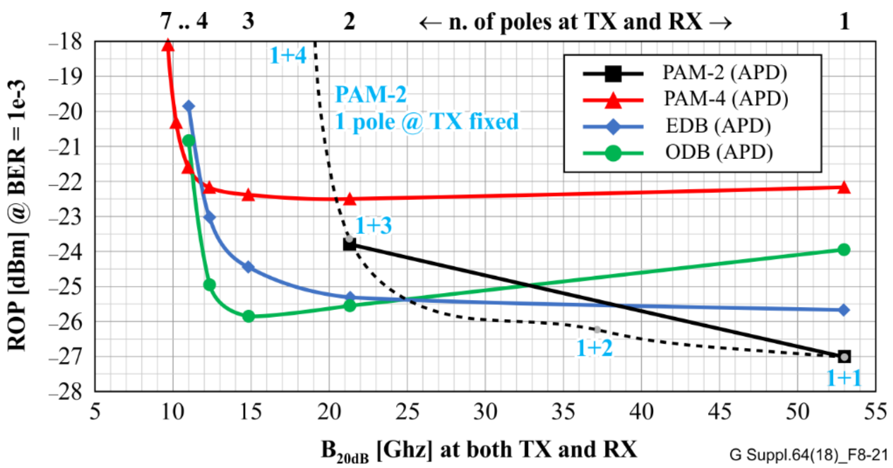


Figure 8-21 – Effect of TX/RX frequency response, Butterworth filter model, varying B_{20dB} (number of poles); the dashed line represents the case with a single-pole TX and a varying number of poles at RX

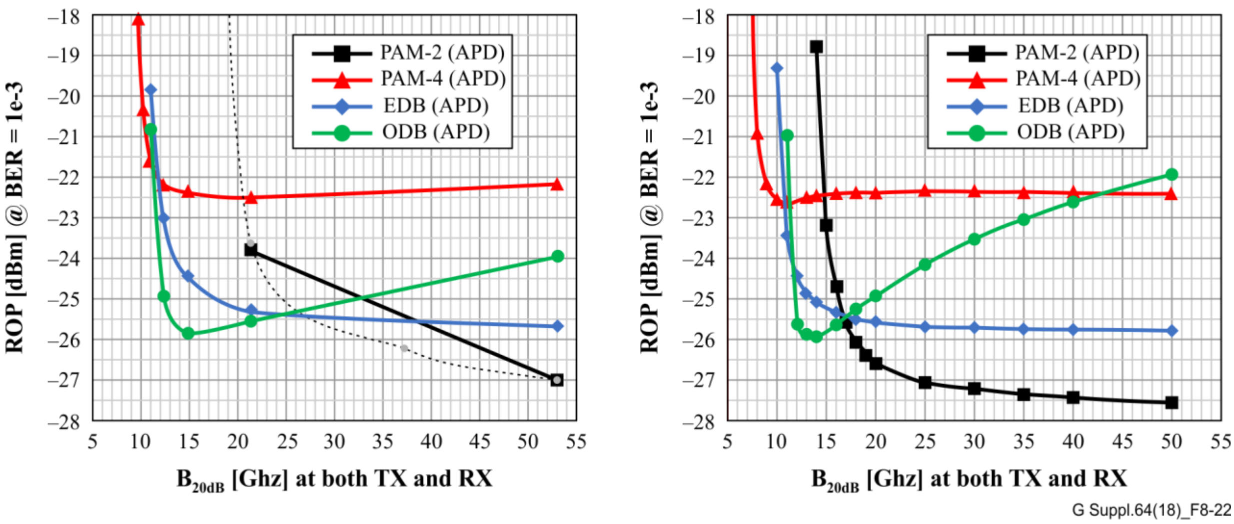


Figure 8-22 – Effect of TX/RX frequency response, comparison of Butterworth (left) and S-Gaussian (right) filter models, varying B_{20dB}

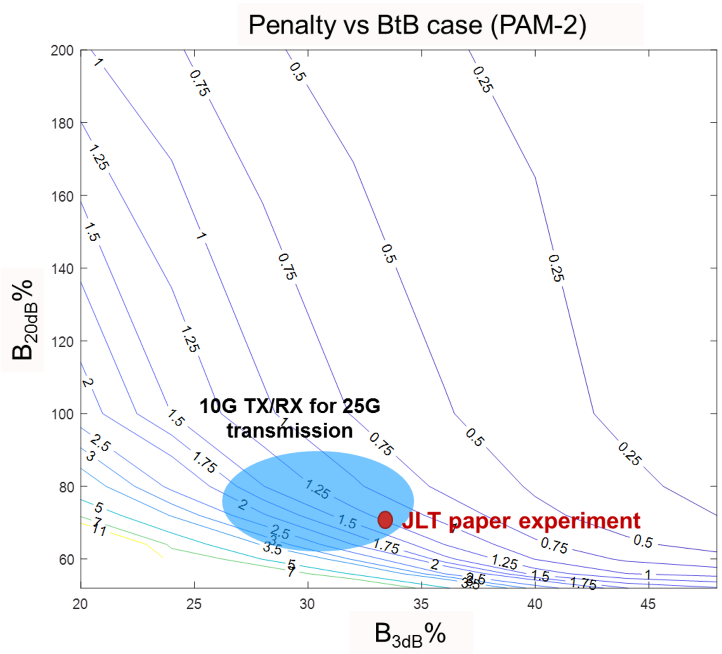


Figure 8-23 – Penalty for PAM-2 transmission versus TX/RX 3dB and 20dB bandwidths; the red dot corresponds to the case analysed in the JLT paper

The representation in Figure 8-23 shows the penalty for varying 3 dB and 20 dB bandwidths with respect to back-to-back performance for PAM-2 and gives an immediate perception of performance sensitivity to TX/RX bandwidth limitations. The coloured area represents the expected positioning of a commercial 10G transceiver and the red dot represents one experimental case, addressed in the paper "A Study of Options for High-Speed TDM-PON Beyond 10G" by V. Houtsma, D. van Veen (JLT vol.34 n.4). The comparison between the filter model applied to this case and the experimental data is shown in Figure 8-24.

Attention should be paid particularly in the area of the graph where the lines are denser, as in this area performance is quite sensitive to the 3 dB and 20 dB bandwidths of the optical device.

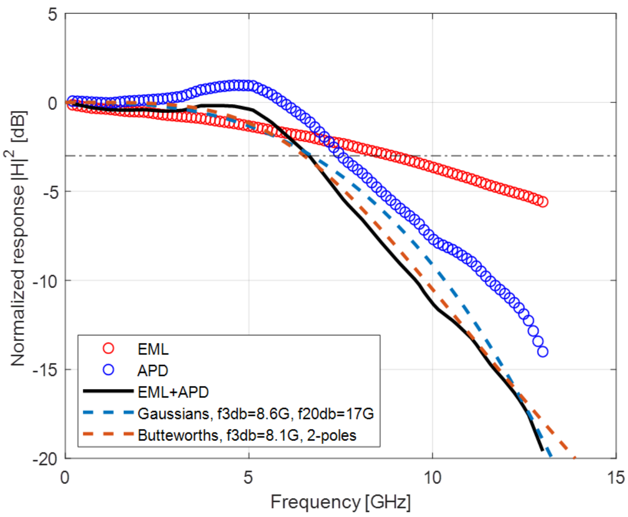


Figure 8-24 – Comparison between the filter model and the experimental data from the JLT paper mentioned in the text

8.1.6.3 Combined effect of TX/RX frequency response and chromatic dispersion

The effect of chromatic dispersion is evaluated in the different spectral regions of interest that are characterized by the following accumulated dispersion values over a 20 km span (using ITU-T G.652 Recommendation formula and fibre dispersion values)[1]:

- O-band (1260÷1360nm): $0.0 < |D| < 6.4$ ps/(nm.km) $\Rightarrow 0 < |D_{20km}| < 128$ ps/nm
- C-band (1530÷1565nm): $15.5 < |D| < 18.9$ ps/(nm.km) $\Rightarrow 310 < |D_{20km}| < 378$ ps/nm
- L-band (1565÷1625nm): $17.6 < |D| < 22.1$ ps/(nm.km) $\Rightarrow 352 < |D_{20km}| < 442$ ps/nm

The impact on performance caused by chromatic dispersion is shown in the graph of Figure 8-24 for the four different modulation formats and for both TX and RX modelled using a two-pole Butterworth filter response with a 3 dB bandwidth of 7 GHz. PAM-2 is the most affected format by dispersion and can only work in the O band, in a region close to the zero dispersion region. The other modulation formats are less sensitive to dispersion with PAM-4 being the most robust even for very high dispersion values. However PAM-4 suffers from approximately 3 dB penalty compared to EDB and ODB. ODB is the best format for an operation in C and L bands.

The combined dependence on dispersion and TX/RX frequency response is shown for three different reference dispersion values and for the Butterworth and S-Gaussian models respectively in the graphs of Figures 8-25 and 8-26.

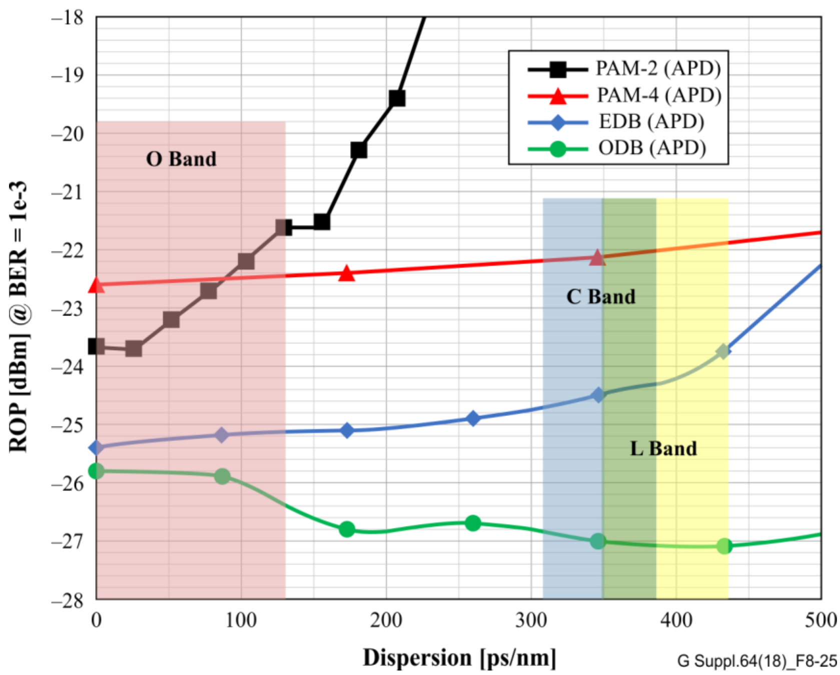


Figure 8-25 – Effect of chromatic dispersion, two-pole Butterworth TX/RX response, B_{3dB}=7 GHz

[1] The maximum absolute values are used here because of the assumption of a chirpless transmitter

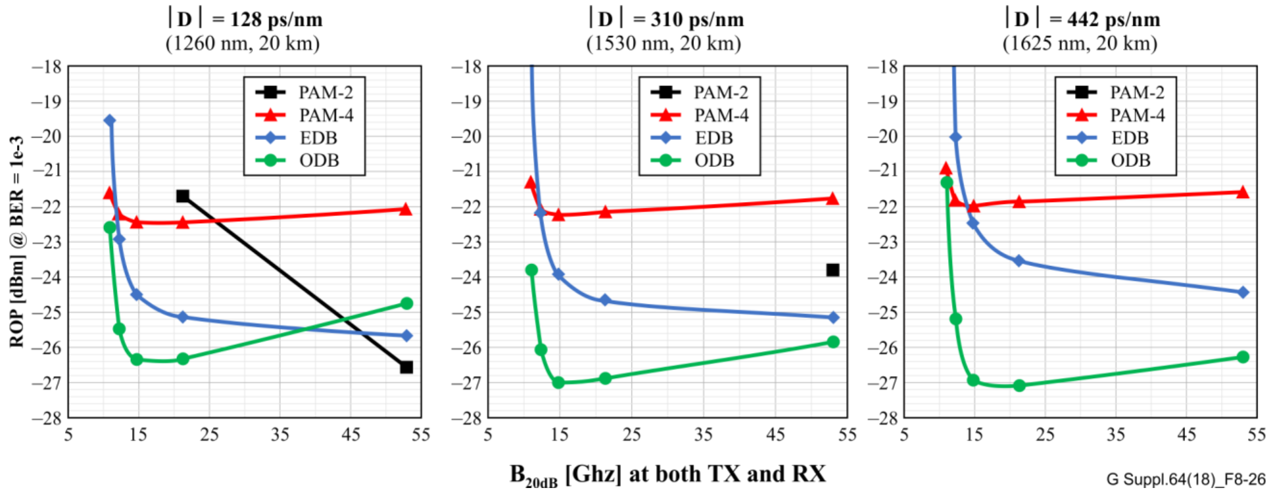


Figure 8-26 – Effect of dispersion and TX/RX frequency response, Butterworth filter model, B_{3dB}=7 GHz, varying B_{20dB} and |D|

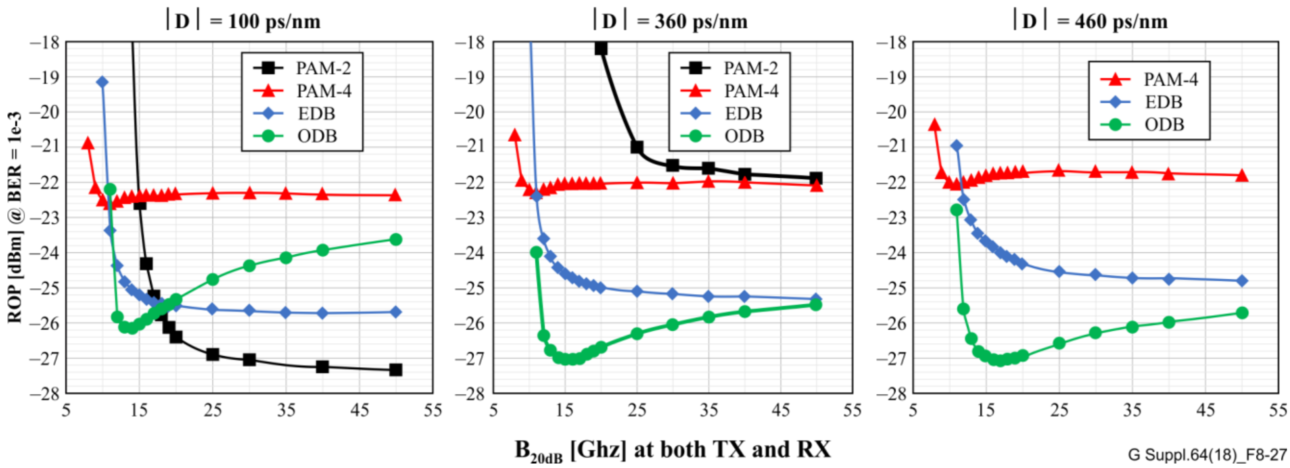


Figure 8-27 – Effect of dispersion and TX/RX frequency response, S-Gaussian filter model, B_{3dB}=7 GHz, varying B_{20dB} and |D| (note: |D| values are not the same of Figure 8-25)

When the overall frequency response of TX and RX is taken into account, the following considerations can be made:

- PAM-2 can only work in the low dispersion region of the O band and only if the TX and RX 20 dB bandwidth is high enough (at least 20÷30 GHz)
- ODB is the best choice for operation in the C or L band
- PAM-4 is less sensitive to TX/RX frequency response, but it is outperformed by EDB and ODB if the 20 dB bandwidth is > 15 GHz

The previous analysis and figures relate to simulations based on optimistic assumptions, a complimentary view is provided in Figure 8-28 [Houtsma-2], [van Veen] and is based on assumptions closer to real equipment and experimental results [Nada et al].

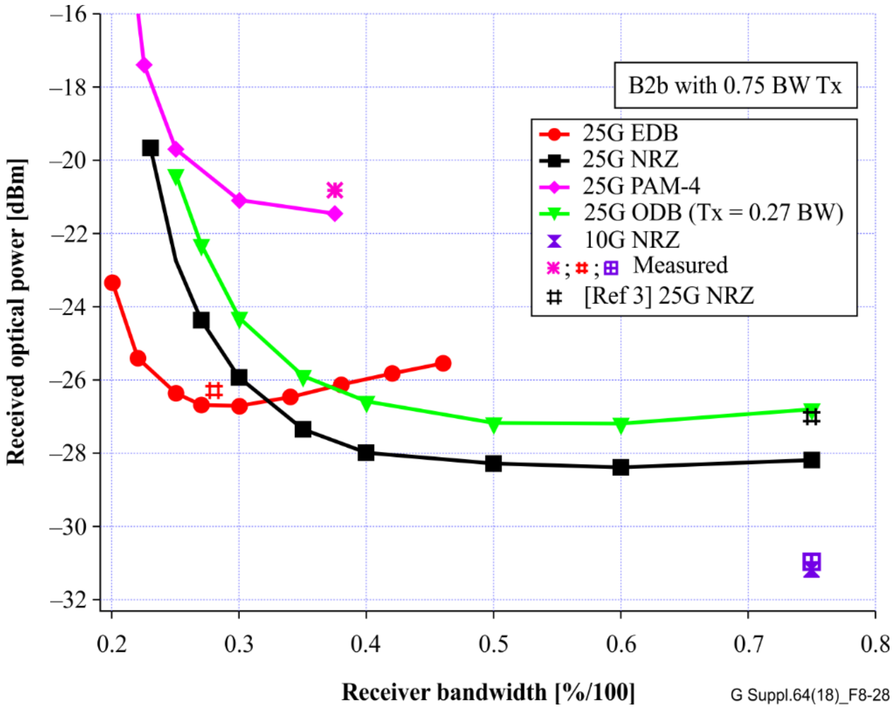


Figure 8-28 – Back-to-back experiment results, ER = 13 dB (5.5 dB PAM-4). TX filter response −3 dB point at 0.75 x bit rate for NRZ and EDB, 0.27 × bitrate for ODB, 0.75 × baud rate (0.375 × bit rate) for PAM-4

Summary:

The main conclusions that can be drawn from the previous analysis about the obtainable performance of using 10G optical devices for 25G operation, based on the assumptions made at the beginning, are summarized in the following points:

- Equalization gives a great advantage and is therefore envisaged
- TX/RX overall frequency response (not just the 3 dB bandwidth) may have a big impact on performance and must therefore be taken into account
- PAM-2 can only work in the low dispersion region of the O band and only if the TX and RX 20 dB bandwidth is high enough (at least 20÷30 GHz); in these conditions it offers the best performance
- EDB is well suited for operation in higher dispersion regions of the O band
- PAM-4 is less sensitive to TX/RX frequency response, but it is out performed by EDB and ODB if the 20 dB bandwidth is > 15 GHz
- ODB is the best choice, from the performance point of view, for operation in the C or L band, but EDB can also be considered depending on a complexity/cost vs performance trade off; note in particular that ODB requires a MZM which is more expensive than an EAM

8.1.7 Modulation technologies comparison

Generally speaking, different modulation technologies have different advantages and disadvantages, different modulation technologies can meet different requirements in different scenarios. The coexistence requirement, line rate and power budget requirement will have a big impact on modulation technology selection. Considering the following reasons:

1) the main high bandwidth optic industry chain above 10G are in O-band,

2) re-using the existing ODN is the general basic requirement,

3) 25 Gbit/s and 50 Gbit/s are the main feasible line rates per wavelength in this stage.

In this clause, the advantages and disadvantages at 25 Gbit/s and 50 Gbit/s line rates are compared in the O-band, with the assumption that achieving at least 29 dB power budget is a basic requirement.

1) Overall comparison

Attributes	NRZ	EDB		ODB	PAM-4	OFDM
		@ Tx&Rx	@Rx Only			
Required optical component bandwidth at Tx	~0.9 B0 (B0 is the bit rate)	~1/3 B0 (B0 is the bit rate)	~0.9 B0 (B0 is the bit rate)	~1/3 B0 (B0 is the bit rate)	>0.45 B0 (B0 is the bit rate)	<<B0
Required optical component bandwidth at Rx	0.75 B0	~3/8 B0	~1/3 B0	0.75 B0 (B0 is the bit rate)	>3/8 B0	<<B0
Approx. back-to-back Rx sensitivity penalty compared to NRZ (dB)	0	~2	~1-2	~1	~3.0	>4
Dispersion tolerance	+	++	++	+++	+++	++++
Transmitter linearity required	no	no	no	no	yes	YES (high linearity requirement)
Receiver linearity required	no	quasi-linearity needed	quasi-linearity needed	no	yes	YES (high linearity requirement)
Complexity At transmitter	+	+	+	+++ phase modulator needed, MZM	++	++++++++ (DSP needed at Tx)
Electronics complexity At receiver	+	++ (EDB decoder)	++ (EDB decoder)	+ (detection same as NRZ)	++++ (PAM4 encoder and decoder)	++++++++ (DSP needed at Rx)

Generally speaking, NRZ has the best simplicity and highest receiver sensitivity, but it also requires the highest bandwidth on optics and has the lowest dispersion tolerance. Duo binary and PAM4 can decrease the bandwidth requirement of optics and better dispersion tolerance but with the cost of lower receiver sensitivity and higher electronics complexity. OFDM has the lowest bandwidth requirement on optics, but it requires high linearity on optics, complicated electronic process and loses lot of receiver sensitivity. Between EDB and ODB, generally speaking, ODB needs a more complicated modulator in the transmitter side but simplifies the receiver (similar to NRZ receiver).

2) Comparison at 25 Gbit/s

Attributes at 25 Gbit/s	NRZ	EDB		ODB	PAM-4	OFDM/DMT
		@ Tx&Rx	@ Rx only			
OLT Transmitter	25G EML/DML	10G EML	25G EML/DML	10G MZM	12.5G EML	10G linear DFB + DSP needed
Receiver	25G APD	12.5G APD	10G APD	25G APD	12.5G APD	10G linear APD
ONU Electronics	25G TIA ,LDD	quasi-linear 12.5G TIA; EDB decoder	quasi-linear 10G TIA; EDB decoder	25G TIA	PAM4 Decoder	25G DSP
Dispersion sustainability	Medium/Good	Good	Good	Good	Good	Very Good
Challenges to meet 29dB power budget	Low	Low/Medium	Low/Medium	Low/Medium	medium	high

For 25 Gbit/s in O-band, due to the low fibre dispersion coefficient and wide availability of 25 Gbit/s optics, the NRZ modulation without dispersion compensation seems to be the best solution due to its simplicity and high receiver sensitivity.

3) Comparison at 50 Gbit/s

Attributes at 50 Gbit/s	NRZ	EDB		ODB	PAM-4	OFDM/DMT
		@ Tx&Rx	@Rx Only			
OLT Transmitter	50G EML	25G EML	50G EML/DML	20G MZM	25G EML	10G linear DFB + DSP needed
Receiver	50G APD	25G APD	25G APD	50G APD	25G APD	10G linear APD
ONU Electronics	50G TIA, LDD	quasi-linear 25G TIA; EDB decoder	quasi-linear 25G TIA; EDB decoder	50G TIA	25G PAM4 Decoder	50G DSP
Dispersion Sustainability	Poor	Medium	Medium	Medium	Medium	Good
Challenges to meet 29dB power budget	Medium	Medium/High	Medium/High	Medium/High	High	Very high!!!

At 50 Gbit/s line rate, the high bandwidth requirement on optics for NRZ will become a big issue. In the current industry chain, only very few 40 Gbit/s or 50 Gbit/s commercial EML TOSA or MZM TOSA are available with very high cost. There are not any commercial 50 Gbit/s APD products in the market by far. So advanced modulation technologies, such as PAM4 or EDB, seem to be more practical solutions for 50 Gbit/s line rate per wavelength. Of course, the challenge for 50 Gbit/s is how to meet at least a 29 dB power budget requirement. Take the 25 Gbaud/s PAM4 as an example, the sensitivity of 25 Gbaud/s PAM4 is at least 4.8 dB worse than 25 Gbit/s NRZ due to the eye

openness that PAM4 is only 1/3 of that in NRZ, how to migrate this sensitivity gap and achieve the same power budget with 25 Gbit/s is the key issue for 50 Gbit/s per wavelength.

8.2 Transmitter and receiver technologies

The following achievements are assumed for the discussion of the receiver technologies.

- Higher bitrate (25G to 40 Gbit/s) with keeping standard optical budgets (N1, N2, E1, E2).
- Per-lambda upgrade of NG-PON2, i.e., TDM/TDMA-based shared access.

Figure 8-29 illustrates the system configuration. Because the ONU receiver is likely to be based on direct detection (DD), we focus on the OLT receiver to receive the upstream burst mode PON signals.

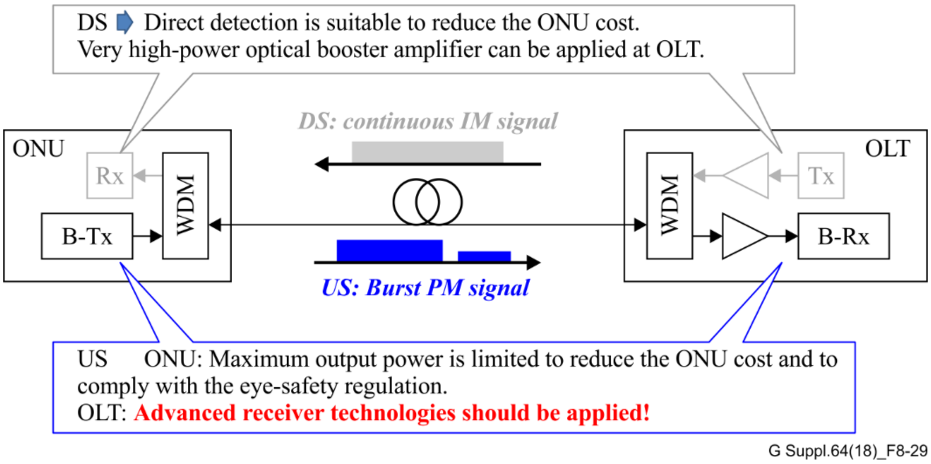


Figure 8-29 – System configuration assumed in this study

Figure 8-30 illustrates schematics of two receiver technologies discussed before; one is the intensity modulation (IM) – DD based optically pre-amplified receiver and the other is the digital-coherent receiver. For the IM-DD based optically pre-amplified receiver, Non return to zero (NRZ) signals are assumed as a modulation format. We assume that the ONU transmitter consists of B Gbaud EA-DFB transmitter. For the digital-coherent receiver, single polarization BPSK and QPSK are assumed as a modulation format. ONU consists of B Gbaud phase modulator for BPSK, or B/2 Gbaud IQ modulator for QPSK.

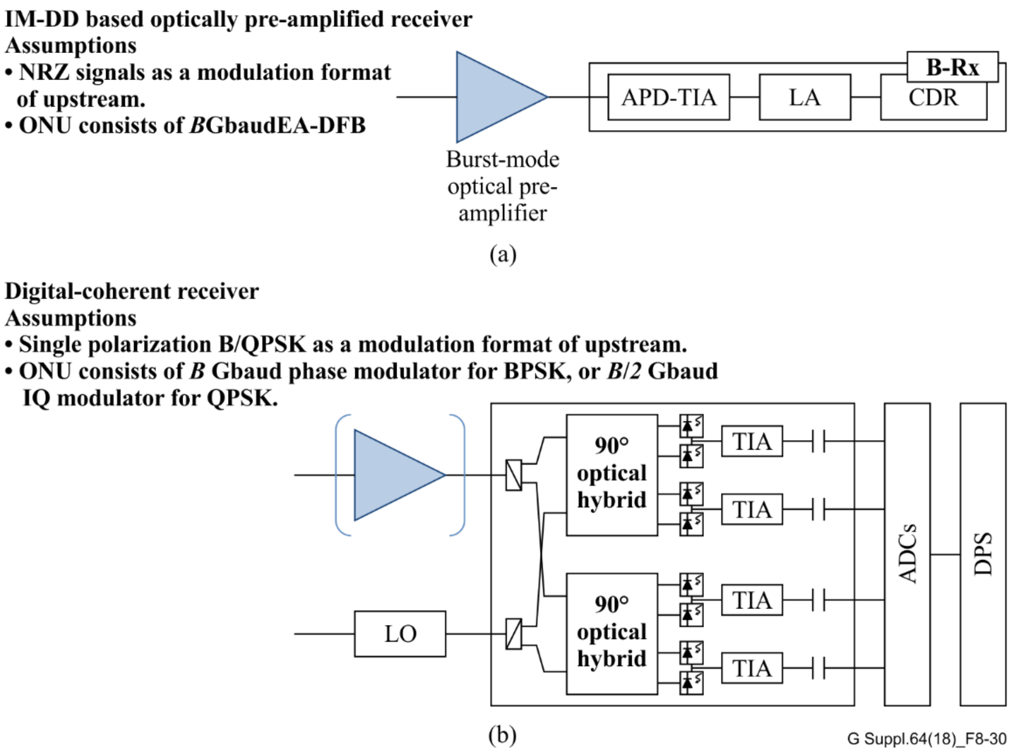


Figure 8-30 – Receiver technologies

Calculation and observation

Figure 8-30 show the achievable power budget calculated for the cases of 25 Gbit/s and 40 Gbit/s, respectively. Excess loss of filters (Co-existence filter, Mux/Demux, etc.) was not considered. Effect of fibre dispersion was not considered, either.

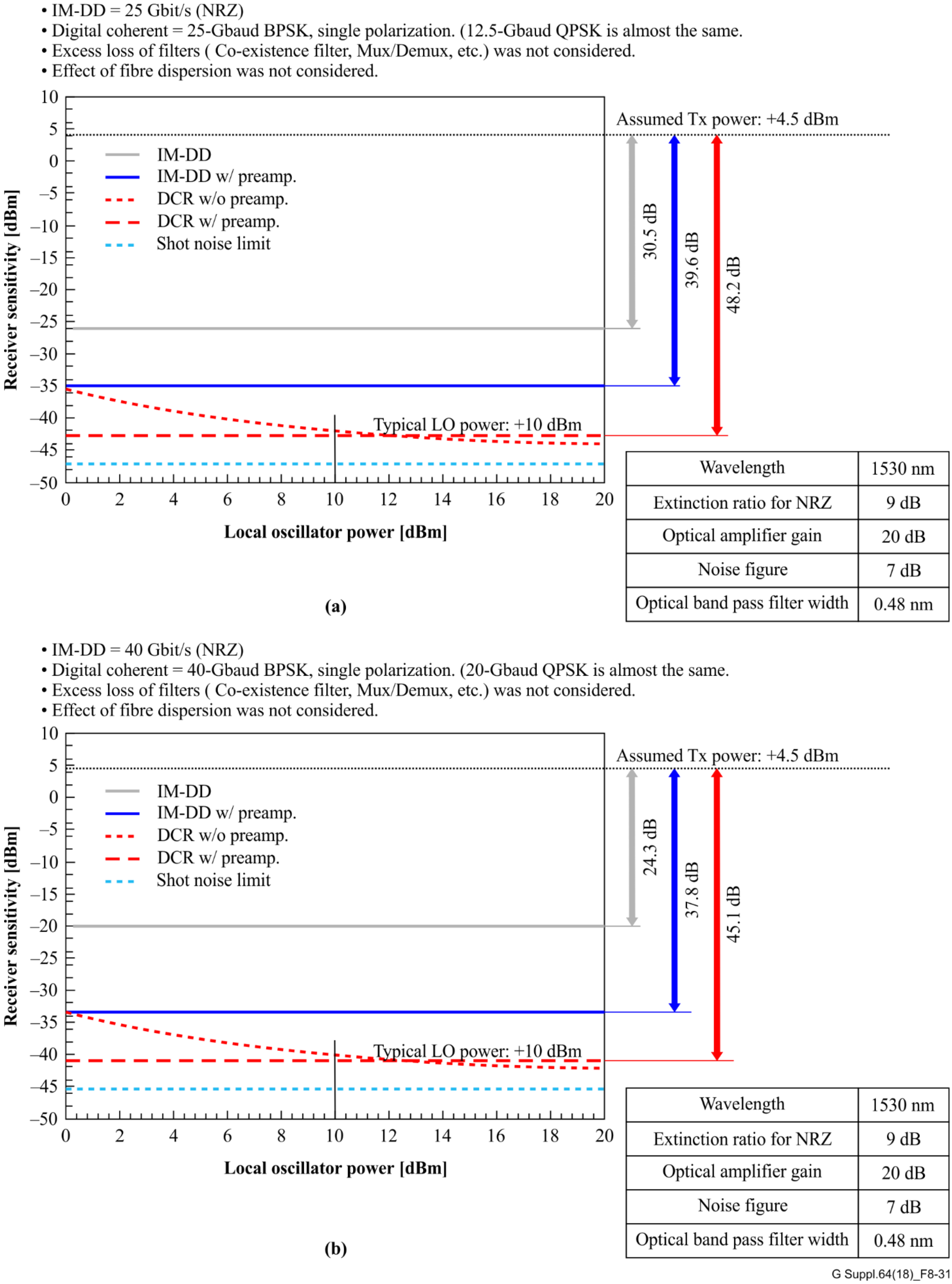


Figure 8-31 – Achievable power budget

For the IM-DD based optically pre-amplified receiver, the following is observed:

- E2 class (maximum budget: 35 dB) can be barely supported at both 25G and 40 Gbit/s.

- Considering the optical path penalties (optical dispersion, Raman depletion, etc.) and excess losses of optical components (Mux/Demux, coupling loss, etc.), it might not meet the requirements.
- Optical/electrical chromatic dispersion compensations are mandatory.

For the digital-coherent receiver, we observe the following:

- E2 class can be supported with a sufficient margin even for 40 Gbit/s.
- Chromatic dispersion is compensated by the aid of digital signal processing, without any compensations in the optical domain (such as chirp-managed laser, dispersion shift fibre, etc.).

It is expected to further expand the reach (i.e. >>40 km) and the speed (i.e. >>40 Gbit/s/wavelength).

8.3 Optical amplifier technologies

When bit rate goes to above 10 Gbit/s, generally speaking, the sensitivity of the receiver goes to a higher number (less sensitive) compared with 10 Gbit/s, due to 1) higher band width and consequently more noise power and 2) smaller chip area which will result in lower responsivity. On the other hand, the chip area of transmitter also needs to go even smaller to achieve higher bandwidth, it will be more challenging to achieve the same launch power for the transmitter. In multiple wavelength system architecture, the extra insertion loss of mux/demux also needs to be considered. In order to achieve the same power budget and reuse the legacy ODN, optical amplifiers may be need in systems based on 10 Gbit/s above line rates. This clause shows the optical amplifier technologies which can be used for 10 Gbit/s above systems.

8.3.1 Erbium-doped optical fibre amplifier

The erbium-doped fibre amplifier (EDFA) is an optical amplifier that use an erbium doped optical fibre as a gain medium to amplify an optical signal. The signal to be amplified and a pump laser are multiplexed into the erbium doped fibre, and the signal is amplified through interaction with the doping erbium ions. EDFA is the most deployed fibre amplifier as its amplification window coincides with the third transmission window of silica-based optical fibre. It has the advantage of high gain, low noise figure and low polarization dependence. It is very widely used in DWDM fibre transmission system.

Currently, two bands EDFA have been developed in the third transmission window commercially – C-band (from approximately 1525 nm-1565 nm) and the L-band (from approximately 1570 nm to 1610 nm). If the wavelengths are defined in C-band or L-band, EDFA will be a good option to provide high gain and help to meet the required power budget. It can be used both in the transmitter side as a boost amplifier and the receiver side as pre-amplifier.

The disadvantage of EDFA amplifier is its high footprint and high cost. Generally speaking, it is more economical to be used in a multiple wavelength system, where the multiple channels can share the same amplifier and cost.

If the wavelengths are in the S-band (1490 nm region) or the O-band (1300 nm region), it needs thulium or praseodymium doped fibre amplifiers, but such doped fibre amplifiers have not been developed in any commercial system by far.

8.3.2 Semiconductor optical amplifier

Semiconductor optical amplifiers (SOAs) are amplifiers which use a semiconductor to provide the gain medium. Compared with EDFA, SOA can only provide medium gain and has higher noise figure, but SOA is small in size, electrically pumped and much less expensive than EDFA. SOA can also be integrated with semiconductor lasers, modulators, detectors, etc. SOA is available in every semiconductor laser operating wavelength band, such as in the O-band, S-band, C-band, L-band, etc.

In the transmitter side, the SOA can be used to boost the launch power. The most straight forward way is integrating an SOA with the transmitter chip. Figure 8-32 shows the schematic of a 10 Gbit/s EML transmitter integrated with an SOA on the laser chip. The middle Figure of 8-32 shows the DFB+EML packaged BOSA integrated with an SOA inside. Such BOSA can be assembled in a XFP module. The launch power with SOA integrated can be 8~10dBm. If we want to enhance the power budget of the downstream, integrating an SOA in the OLT transmitter will be the most suitable way, due to it only increases a small cost in the OLT transmitter side, is able to maintain same OLT ports density, does not need extra space in OLT and still keeps the ONU with low challenge and low cost.

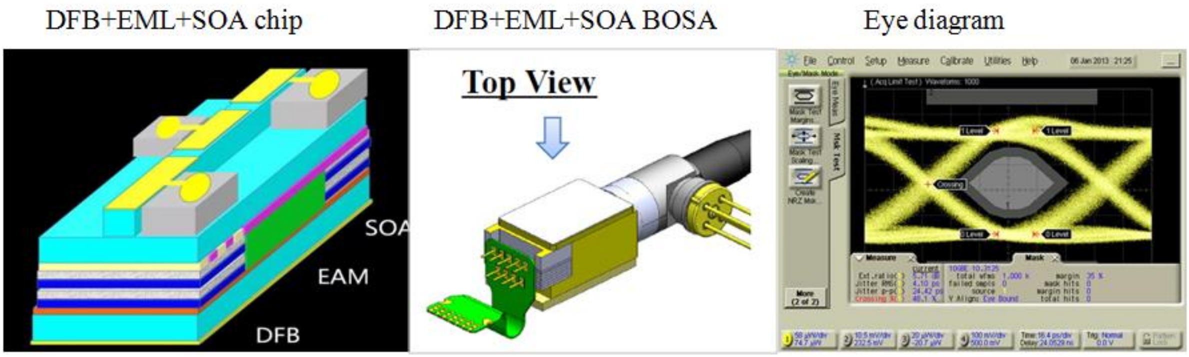


Figure 8-32 – Schematic of EML transmitter with SOA integrated on the laser chip

The SOA can also be used in the receiver side as pre-amplifier. Due to the relative high noise figure of SOA, a lot of ASE noise will be introduced after the signal passes through the SOA pre-amplifier. A narrow pass band filter can be used to improve the signal noise ratio distinctly after the SOA. Figure 8-33 shows the spectrums when different narrow band pass filters are applied after the SOA pre-amplifier. From the Figure 8-33, the narrow band filter can eliminate the ASE noise into the detector by a big extent, consequently can enhance the sensitivity of the receiver. Of course, there will be some tradeoff between the channel width and the gain performance of the pre-amplifier.

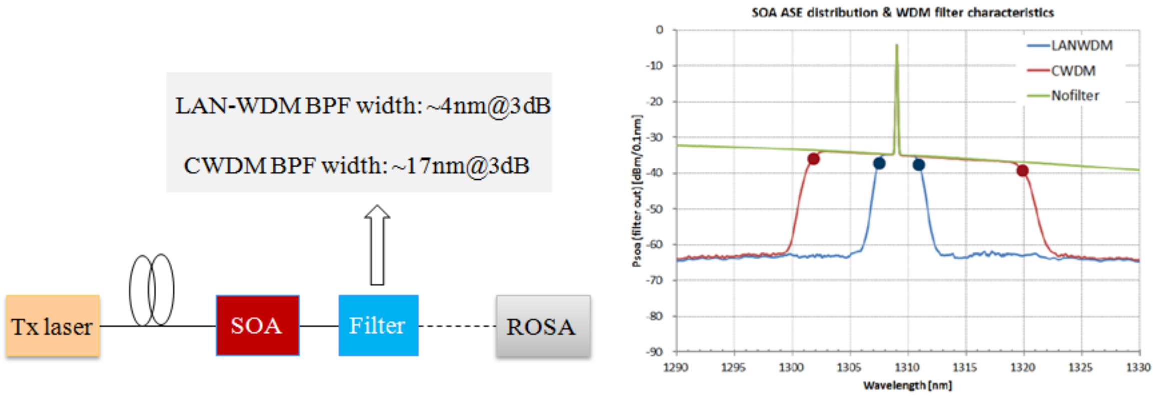
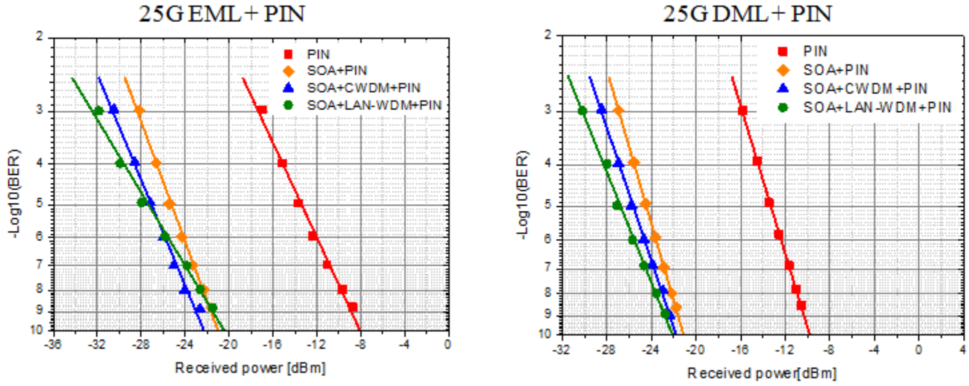


Figure 8-33 – SOA spectrum after narrow band pass filters

Generally speaking, there can be two configurations – SOA+PIN and SOA+APD. Figure 8-33 shows some experiment results on the performance of SOA+25 Gbit/s PIN receiver. The set-up of the experiment is displayed on the left side of Figure 8-33, a 25 Gbit/s EML or a 25 Gbit/s DML with NRZ modulation is used as the transmitter, the 25 Gbit/s signal through a variable optical attenuator goes in to the SOA preamplifier. A CWDM band pass filter (with ~17 nm 3 dB pass band width) and a LAN-WDM band pass filter (with ~4 nm 3 dB pass band width) are applied before the 25G PIN receiver. The small signal gain of the SOA at 25°C is round about 20 dB, and noise figure is round 8 dB. The extinction ratio of 25G EML is ~10 dB, and the extinction of 25G DML is ~5.6 dB.

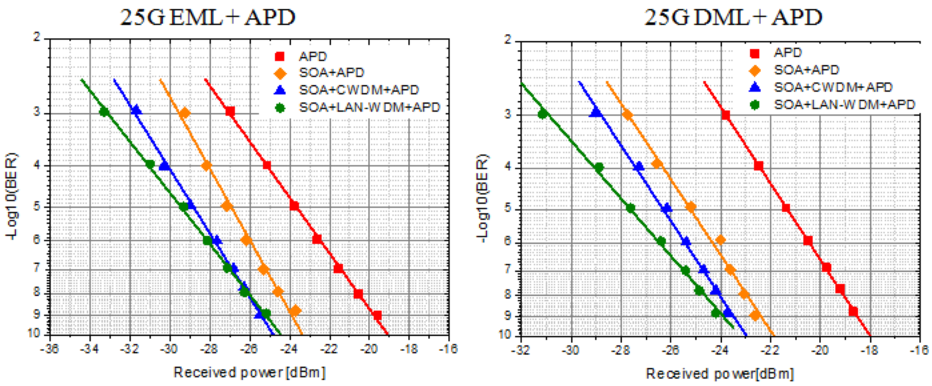
Figure 8-34 shows that the SOA can provide more than 14dB sensitive gain for the 25 Gbit/s EML signal and 25 Gbit/s DML, if a narrow LAN WDM-filter is applied before the PIN detector.



	25G PIN+SOA Receiver sensitivity @BER=1E-3			
	25G PIN	PIN+SOA No filter	PIN+SOA With CWDM filter	PIN+SOA with LAN-WDM filter
EML transmitter	-17 dBm	-28.2 dBm	-30.4 dBm	-31.8 dBm
DML transmitter	-15.8 dBm	-27.0 dBm	-28.5 dBm	-30.2 dBm

Figure 8-34 – 25 Gbit/s PIN+SOA receiver performance on EML and DML signal

Figure 8-35 shows the experiment results on the performance of SOA+25 Gbit/s APD receiver with the same conditions as in Figure 8-33. As depicted in the figure, for the 25G APD receiver, the SOA can provide an additional 6~7 dB sensitivity gain for EML and DML signal when a narrow LAN-WDM filter is applied between the APD and SOA.



	25G APD+SOA Receiver sensitivity @BER=1E-3			
	25G APD	APD+SOA No filter	APD+SOA With CWDM filter	APD+SOA with LAN-WDM filter
EML transmitter	-27 dBm	-29.2 dBm	-31.6 dBm	-33.1 dBm
DML transmitter	-23.8 dBm	-27.7 dBm	-29.0 dBm	-31.0 dBm

Figure 8-35 – 25 Gbit/s APD+SOA receiver performance on EML and DML signal

Based on the comparison of Figures 8-34 and 8-35, SOA+APD can only provide extra ~1dB gain compared with SOA+PIN. If the sensitivity is not that insufficient, the PIN+SOA receiver will have the advantage of smaller footprint and lower cost, compared with APD+SOA.

8.4 Wavelength allocation options

For further study

8.5 Alternative wavelength options for future 25G and 50G PON

For further study

8.6 Forward error correction options for high-speed PON

Optical path loss is one of the key requirements for a high-speed PON system. FEC technology can improve optical power budget at a relative lower cost, comparing enhanced optical components. Different FEC methods provide corresponding margin increase for optical power budget. Besides, enabling FEC brings extra overhead and latency in the system. The FEC coding gain owns higher priority among many factors when selecting a dedicated FEC method. Given the different types of optical components used in the upstream direction and downstream direction, FEC methods can be different. Candidate FEC codes are RS code, BCH and LDPC. In addition, commonality on FEC code mechanism among various high speed PONs is desirable.

1) Reed-Solomon code

Reed-Solomon codes are block-based error correcting codes with a wide range of applications in digital communications and storage.

The Reed-Solomon encoder takes a block of digital data and adds extra "redundant" bits. Errors occur during transmission for a number of reasons (for example noise or interference). The Reed-Solomon decoder processes each block and attempts to correct errors and recover the original data. The number and type of errors that can be corrected depends on the characteristics of the Reed-Solomon code. Reed Solomon codes are linear block codes. A Reed-Solomon code is specified as RS(n,k) with s-bit symbols. This means that the encoder takes k data symbols of s bits each and adds parity symbols to make an n symbol code word. There are n-k parity symbols of s bits each. A Reed-Solomon decoder can correct up to t symbols that contain errors in a code word, where $2t = n-k$. Today, Reed–Solomon codes are widely implemented in digital storage devices and digital communication standards, though they are being slowly replaced by more modern low-density parity-check (LDPC) codes or turbo codes.

The following example shows a typical Reed-Solomon code word:

A popular Reed-Solomon code is RS(255,223) with 8-bit symbols. Each code word contains 255 code word bytes, of which 223 bytes are data and 32 bytes are parity, where $n = 255$, $k = 223$, $s = 8$ and $2t = 32$, $t = 16$. The decoder can correct any 16-symbol errors in the code word, i.e. errors in up to 16 bytes anywhere in the code word can be automatically corrected.

2) BCH code

BCH codes (Bose–Chaudhuri–Hocquenghem) codes are binary codes that are constructed using polynomials over a finite field. One of the key features of BCH codes is that during code design, there is a precise control over the number of symbol errors correctable by the code. In particular, it is possible to design binary BCH codes that can correct multiple bit errors. Another advantage of BCH codes is the ease with which they can be decoded, namely, via an algebraic method known as syndrome decoding. This simplifies the design of the decoder for these codes, using small low-power electronic hardware.

A primitive BCH code is a BCH code defined using a primitive element α. If α is a primitive element of GF(qm), then the blocklength is $n = qm - 1$. This is the maximum possible block length for decoder alphabet GF(qm). A narrow-sense BCH code is a BCH code with $b = 1$. Some decoding formulas simplify when $b = 1$. But $b \neq 1$ is usually used.

3) LDPC code

Low-density parity-check (LDPC) codes are a class of recently re-discovered highly efficient linear block codes made from many single parity check (SPC) codes. They can provide performance very close to the channel capacity (the theoretical maximum) using an iterated soft-decision decoding approach, at linear time complexity in terms of their block length. Practical implementations rely heavily on decoding the constituent SPC codes in parallel. LDPC codes are also used for 10GBase-T Ethernet, which sends data at 10 gigabits per second over twisted-pair cables. As of 2009, LDPC codes are also part of the Wi-Fi 802.11 standard as an optional part of 802.11n and 802.11ac, in the high throughput (HT) PHY specification.

4) Comparisons

Table 8-4 shows comparisons of coding gain between different code words and different lengths [Laubach] [Powell].

Table 8-4 – Coding gain for different code words and lengths

FEC code	Length(bit)	Code rate	Input BER	Electrical coding gain (dBe) @e-12
RS (255, 223)	2040	0.88	1.1e-3	7.1
RS(1023,847)	10230	0.83	4.2e-3	8.5
RS(2047,1739)	22517	0.85	4.1e-3	8.5
BCH(4095,3501)	4095	0.85	4e-3	8.5
LDPC(16000,13952)	16000	0.87	5.8e-3	8.9
LDPC(19200,16000)	19200	0.83	1e-2	9.6

Based on the comparison, LDPC FEC has the advantage that it can provide high coding gain and still keep good output code rate. IEEE P802.3ca task force has decided to adopt LDPC as the FEC code, high speed PON systems can reuse the same LDPC FEC code with that task force from industry convergence consideration.

Bibliography

[b-ITU-T G.987] Recommendation ITU-T G.987 (2012), *10-Gigabit-capable passive optical network (XG-PON) systems: Definitions, abbreviations and acronyms*.

[b-Torres-Ferrera] Torres-Ferrera, P., et al. *Impact of the Overall Electrical Filter Shaping in Next-Generation 25G and 50G PON*, http://arxiv.org/abs/1801.08584

SERIES OF ITU-T RECOMMENDATIONS

Series A	Organization of the work of ITU-T
Series D	Tariff and accounting principles and international telecommunication/ICT economic and policy issues
Series E	Overall network operation, telephone service, service operation and human factors
Series F	Non-telephone telecommunication services
Series G	**Transmission systems and media, digital systems and networks**
Series H	Audiovisual and multimedia systems
Series I	Integrated services digital network
Series J	Cable networks and transmission of television, sound programme and other multimedia signals
Series K	Protection against interference
Series L	Environment and ICTs, climate change, e-waste, energy efficiency; construction, installation and protection of cables and other elements of outside plant
Series M	Telecommunication management, including TMN and network maintenance
Series N	Maintenance: international sound programme and television transmission circuits
Series O	Specifications of measuring equipment
Series P	Telephone transmission quality, telephone installations, local line networks
Series Q	Switching and signalling, and associated measurements and tests
Series R	Telegraph transmission
Series S	Telegraph services terminal equipment
Series T	Terminals for telematic services
Series U	Telegraph switching
Series V	Data communication over the telephone network
Series X	Data networks, open system communications and security
Series Y	Global information infrastructure, Internet protocol aspects, next-generation networks, Internet of Things and smart cities
Series Z	Languages and general software aspects for telecommunication systems

Printed in Switzerland
Geneva, 2018