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

Digital sections and digital line system – Optical line systems for local and access networks

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40-Gigabit-capable passive optical networks 2 (NG-PON2): Physical media dependent (PMD) layer specification

Recommendation ITU-T G.989.2

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Recommendation ITU-T G.989.2

40-Gigabit-capable passive optical networks 2 (NG-PON2): Physical media dependent (PMD) layer specification

Summary

Recommendation ITU-T G.989.2 specifies the physical media dependent (PMD) layer requirements for a passive optical network (PON) system with a nominal aggregate capacity of 40 Gbit/s in the downstream direction and 10 Gbit/s in the upstream direction, hereinafter referred to as NG-PON2. NG-PON2 is a flexible optical fibre access network capable of supporting the bandwidth requirements of mobile backhaul, business and residential services. Furthermore, this Recommendation describes optional configurations, to extend beyond this nominal capacity, as the ITU-T G.989 series of Recommendations allows for multiple upstream and downstream line rates.

The NG-PON2 wavelength plan is defined to enable the coexistence through wavelength overlay with legacy PON systems (see ITU-T G.989.1). The transmission convergence (TC) layer is based on Recommendation ITU-T G.987.3, with unique modifications for NG-PON2 captured in Recommendation ITU-T G.989.3. The optical network unit (ONU) management and control interface (OMCI) specifications are described in Recommendation ITU-T G.988 for NG-PON2 extensions.

This Recommendation specifies the characteristics of hybrid time and wavelength division multiplexing (TWDM) channels, referred to as TWDM PON. The characteristics of optional, tunable point-to-point wavelength overlay channels are also described, referred to as point-to-point wavelength division multiplexing (PtP WDM) PON.

The TWDM PON described in this Recommendation represents a further development from the systems described in the ITU-T G.984 and ITU-T G.987 series of Recommendations. To the greatest extent possible, this Recommendation retains the requirements of ITU-T G.984.1 and ITU-T G.987.1 to ensure maximal reuse of existing technology and compatibility with deployed optical access systems and optical fibre infrastructure.

History

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FOREWORD

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

Compliance with this Recommendation is voluntary. However, the Recommendation may contain certain mandatory provisions (to ensure, e.g., interoperability or applicability) and compliance with the Recommendation 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 Recommendation is required of any party.

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ITU draws attention to the possibility that the practice or implementation of this Recommendation 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 Recommendation development process.

As of the date of approval of this Recommendation, ITU had received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. 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/.

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Recommendation ITU-T G.989.2

40-Gigabit-capable passive optical networks 2 (NG-PON2): Physical media dependent (PMD) layer specification

1 Scope

This Recommendation pertains to flexible access networks using optical fibre technology. It describes a network supporting multiple services with bandwidth requirements ranging from that of voice to data and video, running at an aggregate reference downstream rate of 40 Gbit/s.

This Recommendation specifies characteristics of the physical media dependent (PMD) layer of a passive optical network (PON) system based on time and wavelength division multiplexing (TWDM) and an optional point-to-point wavelength division multiplexing (PtP WDM) system that can be used in an overlay to TWDM with the capability of bidirectional data transmission between optical line termination **(**OLT) and optical network unit (ONU).

The optical access network (OAN) addressed by this Recommendation enables the network operator to provide a flexible upgrade to meet future customer requirements, in particular, in the area of the optical distribution network (ODN). The legacy ODN infrastructure is based on a point-to-multipoint tree and branch option using power splitter based technology (see [ITU-T G.989.1] for additional details). However, the use of wavelength splitters in the ODN is also allowed.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T G.652] Recommendation ITU-T G.652 (2009), *Characteristics of a single-mode optical fibre and cable*.

[ITU-T G.657] Recommendation ITU-T G.657 (2009), *Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network*.

[ITU-T G.671] Recommendation ITU-T G.671 (2012), *Transmission characteristics of optical components and subsystems*.

[ITU-T G.694.1] Recommendation ITU-T G.694.1 (2002), *Spectral grids for WDM applications: DWDM frequency grid*.

[ITU-T G.698.1] Recommendation ITU-T G.698.1 (2009), *Multichannel DWDM applications with single-channel optical interfaces*.

[ITU-T G.698.3] Recommendation ITU-T G.698.3 (2012), Multichannel seeded *DWDM applications with single-channel optical interfaces*.

[ITU-T G.707] Recommendation ITU-T G.707/Y.1322 (2009), *Network node interface for the synchronous digital hierarchy (SDH)*.

[ITU-T G.709] Recommendation ITU-T G.709/Y.1331 (2012), *Interfaces for the optical transport network.*

[ITU-T G.783] Recommendation ITU-T G.783 (2006), *Characteristics of synchronous digital hierarchy (SDH) equipment functional blocks*.

[ITU-T G.825] Recommendation ITU-T G.825 (2000), *The control of jitter and wander within digital networks which are based on the synchronous digital hierarchy (SDH)*.

[ITU-T G.957] Recommendation ITU-T G.957 (2006), *Optical interfaces for equipments and systems relating to the synchronous digital hierarchy*.

[ITU-T G.959.1] Recommendation ITU-T G.959.1 (2009), *Optical transport network physical layer interfaces*.

[ITU-T G.982] Recommendation ITU-T G.982 (1996), *Optical access networks to support services up to the ISDN primary rate or equivalent bit rates*.

[ITU-T G.983.1] Recommendation ITU-T G.983.1 (2005), *Broadband optical access systems based on Passive Optical Networks (PON)*.

[ITU-T G.984.1] Recommendation ITU-T G.984.1 (2008), *Gigabit-capable passive optical networks (GPON): General characteristics*.

[ITU-T G.984.2] Recommendation ITU-T G.984.2 (2003), *Gigabit-capable Passive Optical Networks (G-PON): Physical Media Dependent (PMD) layer specification*.

[ITU-T G.984.5] Recommendation ITU-T G.984.5 (2007), *Gigabit-capable passive optical networks (G-PON): Enhancement band*.

[ITU-T G.987] Recommendation ITU-T G.987 (2010), *10-Gigabit-capable passive optical network (XG-PON) systems: Definitions, abbreviations and acronyms*.

[ITU-T G.987.1] Recommendation ITU-T G.987.1 (2010), *10 Gigabit-capable passive optical networks (XG-PON): General requirements*.

[ITU-T G.987.2] Recommendation ITU-T G.987.2 (2010), *10-Gigabit-capable passive optical networks (XG-PON): Physical media dependent (PMD) layer specification*.

[ITU-T G.987.3] Recommendation ITU-T G.987.3 (2010), *10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification*.

[ITU-T G.988] Recommendation ITU-T G.988 (2010), *ONU management and control interface (OMCI) specification*.

[ITU-T G.989.1] Recommendation ITU-T G.989.1 (2013), *40-Gigabit-capable passive optical networks (NG-PON2): General requirements*.

[ITU-T J.185] Recommendation ITU-T J.185 (2012), *Transmission equipment for transferring multi-channel television signals over optical access networks by frequency modulation conversion*.

[ITU-T J.186] Recommendation ITU-T J.186 (2008), *Transmission equipment for multi-channel television signals over optical access networks by sub-carrier multiplexing (SCM)*.

[ITU-T L.66] Recommendation ITU-T L.66 (2007), *Optical fibre cable maintenance criteria for in-service fibre testing in access networks*.

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

3.1.1 access network [b-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 (UNI).

3.1.2 Ethernet LAN service (E-LAN) [b-MEF6.1]: An Ethernet service type that is based on a Multipoint-to-Multipoint Ethernet virtual connection.

3.1.3 Ethernet line service (E-Line) [b-MEF6.1]: An Ethernet service type that is based on a point-to-point Ethernet virtual connection.

3.1.4 Ethernet tree service (E-Tree) [b-MEF6.1]: An Ethernet service type that is based on a Rooted-Multipoint Ethernet virtual connection.

3.1.5 Ethernet virtual connection (EVC) [b-MEF6.1]: An association of user-network interfaces (UNIs) to which the exchange of service frames is limited.

3.1.6 jitter (timing jitter) [b-ITU-T G.810]: The short-term variations of the significant instances of a digital signal from their ideal positions in time (where "short-term" implies that these variations are of frequency greater than or equal to 10 Hz).

3.1.7 service node (SN) [b-ITU-T G.902]: A network element that provides access to various switched and/or permanent telecommunication services.

3.1.8 service node interface (SNI) [b-ITU-T G.902]: An interface which provides access to a service node.

3.1.9 user-network interface (UNI) [b-ITU-T I.112]: The interface between the terminal equipment and a network termination at which interface the access protocols apply.

3.1.10 1:1 VLAN [b-BBF TR-101]: A VLAN forwarding paradigm involving a one-to-one mapping between user port and VLAN. The uniqueness of the mapping is maintained in the Access Node and across the Aggregation Network.

3.1.11 N:1 VLAN [b-BBF TR-101]: A VLAN forwarding paradigm involving many-to-one mapping between user ports and VLAN. The user ports may be located in the same or different Access Nodes.

3.2 Terms defined in this Recommendation: Optical access architecture

This Recommendation defines the following optical access architecture terms:

3.2.1 channel group: A set of channel pairs carried over a common fibre.

3.2.2 channel pair: A set of one downstream wavelength channel and one upstream wavelength channel that provides connectivity between an OLT and one or more ONUs.

3.2.3 channel termination: See OLT PtP WDM channel termination, OLT TWDM channel termination.

3.2.4 coexistence element: A bidirectional functional element used to connect PON systems defined in different series of Recommendations to the same ODN.

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

3.2.6 next generation PON (NG-PON): In the context of ITU-T standards development activity, a generic term referencing the PON system evolution beyond G-PON. The concept of NG-PON currently includes NG-PON1 (phase 1), where the ODN is maintained from B-PON and G-PON, and NG-PON2 (phase 2), where a redefinition of the ODN is allowed from that defined in B-PON and G-PON.

3.2.7 NG-PON1: A PON system with a nominal aggregate capacity of 10 Gbit/s in the downstream direction. The NG-PON1 system is referred to as XG-PON, and specified by the ITU T-G.987 series of Recommendations.

3.2.8 NG-PON2: A PON system with a nominal aggregate capacity of 40 Gbit/s in the downstream direction and 10 Gbit/s in the upstream direction, and implementing the suite of protocols specified in the ITU-T G.989 series of Recommendations. An NG-PON2 system is composed of a set of TWDM channels and/or a set of PtP WDM channels.

3.2.9 OLT PtP WDM channel termination: A logical function that resides at the OLT network element and terminates a single PtP WDM channel in a PtP WDM system.

3.2.10 OLT TWDM channel termination: A logical function that resides at the OLT network element and that terminates a single TWDM channel in a TWDM system.

3.2.11 optical access network (OAN): A part of an access network whose network elements are interconnected by optical communication channels. Note: 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 access network.

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

3.2.13 optical distribution segment (ODS): A simple ODN, that is, a point-to-multipoint optical fibre infrastructure that is entirely passive and is represented by a single-rooted tree of optical fibres with splitters, combiners, filters, and possibly other passive optical components.

3.2.14 optical line termination (OLT): A network element in an ODN-based optical access network that terminates the root of at least one ODN and provides an OAN SNI.

3.2.15 optical network terminal (ONT): An ONU supporting a single subscriber.

3.2.16 optical network unit (ONU): A network element in an ODN-based optical access network that terminates a leaf of the ODN and provides an OAN UNI.

3.2.17 optical trunk line (OTL): A passive point-to-point segment of a composite ODN.

3.2.18 passive optical network (PON) system: 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.

3.2.19 PtP WDM channel: In an NG-PON2 system, PtP WDM channel refers to the pair of one downstream wavelength channel and one upstream wavelength channel providing point-to-point connectivity.

3.2.20 PtP WDM PON: A multiple wavelength PON system that enables point-to-point connectivity using a dedicated wavelength channel per ONU for the downstream direction and a dedicated wavelength channel per ONU for the upstream direction.

3.2.21 RF video overlay: A method for video transmission in the downstream direction in a wavelength band between 1550 nm and 1560 nm according to [ITU-T J.185] and [ITU-T J.186].

3.2.22 TWDM channel: 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.

3.2.23 TWDM PON: 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.

3.2.24 wavelength channel: 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 wavelength multiplexer (WM) tributary port.

3.2.25 wavelength multiplexer (WM): A bidirectional functional element used to multiplex/demultiplex between NG-PON2 wavelength channel pairs and channel groups.

3.2.26 10-gigabit-capable passive optical network (XG-PON): A PON system supporting nominal transmission rates on the order of 10 Gbit/s in at least one direction, and implementing the suite of protocols specified in the ITU-T G.987 series of Recommendations. XG-PON is the realization of NG-PON1.

3.2.27 XG-PON1: A variant of XG-PON system that operates at a nominal line rate of 10 Gbit/s downstream and 2.5 Gbit/s upstream.

3.2.28 XG-PON2: A variant of XG-PON system that operates at a nominal line rate of 10 Gbit/s downstream and upstream.

3.3 Terms defined in this Recommendation: Optical parameters, power and loss budgets[1]

This Recommendation defines the following optical parameters, power and loss budget terms:

3.3.1 attenuation: See **optical path loss**.

3.3.2 channel spacing (CS): The absolute difference between the nominal central frequencies of two adjacent wavelength channels in a given reference grid.

3.3.3 consecutive identical digit (CID) immunity: The longest continuous sequence of identical bits that can be present in a digital signal without causing degradation such that the system specifications are no longer met.

3.3.4 differential fibre distance: The absolute difference between the fibre distances of any two given paths between the R/S and S/R reference point for channel group (S/R-CG) reference points in the same ODN.

3.3.5 differential optical path loss: The absolute difference between the optical losses of any two given paths between the R/S and S/R-CG reference points in the same ODN.

3.3.6 dispersion: A physical phenomenon comprising the dependence of the phase or group velocity of a light wave in the medium on its propagation characteristics such as optical frequency (wavelength) or polarization mode.

3.3.7 dynamic range: An optical receiver characteristic that represents the difference between the worst-case sensitivity (i.e., maximum over the operating conditions) and the worst-case overload (i.e., minimum over the operating conditions), and is usually expressed as a ratio of the former to the latter.

3.3.8 extinction ratio (ER): 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 (A) to the average optical power level at the centre of a binary digit corresponding to the low intensity of light (B):

$$ER = 10 \log_{10} (A/B).$$

[1] For the definition of the NG-PON2 architectural reference points mentioned within this clause, please see clause 5.2. For the definition of the burst mode transmitter enabled/disabled periods and the associated transient times, see clause 5.13.

For the burst mode signal, averaging is performed from the first bit of the preamble to the last bit of the burst, inclusive. For the continuous mode signal, averaging is performed over the entire signal string.

3.3.9 fibre distance: 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.

3.3.10 in-band crosstalk tolerance: the minimum value of signal-to-crosstalk ratio at the S/R-CG (upstream direction) or R/S (downstream direction) reference point that maintains the receiver compliance with the sensitivity requirements.

3.3.11 line code: 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.

3.3.12 mask of transmitter eye diagram: A general method of transmitter pulse shape characterisation that allows the combined specification of rise time, fall time, pulse overshoot/undershoot, ringing and jitter to ensure satisfactory operation with a compliant receiver. Transmitter mask compliance is required at the appropriate reference point (S/R-CG for downstream, R/S for upstream).

3.3.13 mean launch optical power: 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.

3.3.14 nominal central frequency: The specified frequency of a wavelength channel.

3.3.15 nominal line rate: 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.

3.3.16 operating wavelength band: The spectral interval defined by its boundaries λ_{min} and λ_{max} which includes all possible central operating wavelengths for a particular application.

3.3.17 optical path loss: The total relative optical power loss of an optical signal propagating through the ODN. This loss is caused by the fibre, connectors, splices, splitters, wavelength couplers, attenuators and other passive optical components.

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

3.3.19 optical power spectral density when not enabled (WNE-PSD): The optical PSD per transmitter, at any wavelength inside or outside the operating wavelength band, measured when the transmitter is not enabled and the allocated transient time has elapsed, at the appropriate reference point (S/R-CG for downstream direction, R/S for upstream direction). Measurements are averaged over time and are expressed as the total integrated power within a sliding spectral window of known width.

3.3.20 optical return loss (ORL): 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.

3.3.21 overload: A receiver parameter equal to the maximum average received optical power that produces the specified bit error ratio (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.

3.3.22 per channel out-of-band optical power spectral density (OOB-PSD): The optical power spectral density (PSD) outside the operating wavelength band measured at the appropriate reference point (S/R-CG for downstream direction, R/S for upstream direction). Measurements are averaged over the time periods when the transmitter is enabled, or when the transmitter is not enabled but the allocated transient time has not yet elapsed, and are expressed as the total integrated power within a sliding spectral window of known width.

3.3.23 per channel out-of-channel optical power spectral density (OOC-PSD): For a transmitter in a stationary wavelength channel state, the optical PSD outside the spectral interval corresponding to the operating wavelength channel, measured at the appropriate reference point (S/R-CG for downstream direction, R/S for upstream direction). Measurements are averaged over the time periods when the transmitter is enabled, or when the transmitter is not enabled but the allocated transient time has not yet elapsed, and are expressed as the total integrated power within a sliding spectral window of known width.

3.3.24 reflectance: 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.

3.3.25 sensitivity: 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.

3.3.26 side mode suppression ratio (SMSR): 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.

3.3.27 spectral excursion: For a transmitter in a stationary wavelength channel state, the absolute difference between the nominal central frequency of the channel and the –15 dB points of the transmitter spectrum furthest from the nominal central frequency measured at the transmitter output at the appropriate reference point (S/R-CG for downstream direction, R/S for upstream direction).

3.3.28 spectral width: The full width of the largest spectral peak, measured 15 dB down from the maximum amplitude of the peak.

3.3.29 stationary wavelength channel state: An optical transmitter or receiver is said to be in a stationary wavelength channel state, if 1) it is fixed wavelength, or 2) it is wavelength tunable and its transient processes associated with the execution of a wavelength channel tuning control command have completed.

3.3.30 tolerance to reflected optical power: A transmitter parameter that characterizes the maximum admissible ratio of the average reflected optical transmit power incident at the transmitter to the average optical transmit power.

3.3.31 transmitter calibration: An optical transmitter is calibrated with accuracy δ, if given a target transmission frequency f_0 within its tuning range, it is capable of transmitting with the spectral excursion not exceeding δ (in other words, its transmission spectrum between the –15 dB cutoff points lays entirely within the spectral interval ($f_0 - \delta$, $f_0 + \delta$)).

3.3.32 transmitter power wavelength dependency: For a tunable transmitter under wavelength control, the variation of the mean launch optical power when tuning within maximum spectral excursion (MSE).

3.3.33 transmitter disable transient time: For a burst-mode transmitter, the allocated transient time on de-assertion of the TxEnable signal, measured in bit periods with respect to the transmitter nominal line rate.

3.3.34 transmitter enable transient time: For a burst-mode transmitter, the allocated transient time on assertion of the TxEnable signal, measured in bit periods with respect to the transmitter nominal line rate.

3.3.35 tuning granularity: The smallest step by which a tunable device is able to adjust the operating frequency/wavelength within the tuning range of the device. This Recommendation specifies the tuning granularity by its maximum allowable value.

3.3.36 tuning range: The spectral interval either in frequency (f_{min}, f_{max}) or wavelength (λ_{min}, λ_{max}) over which the operating frequency/wavelength of a tunable device can be adjusted by means of tuning control.

3.3.37 tuning time: The elapsed time from the moment the tunable device leaves the source wavelength channel to the moment the tunable device reaches the target wavelength channel.

3.3.38 tuning window: The difference between the highest and lowest operating frequencies/wavelengths of a tunable device, attainable by means of tuning control.

3.3.39 wavelength channel spacing: See channel spacing.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

AMCC	Auxiliary Management and Control Channel
AN	Access Network
AWG	Arrayed Waveguide Grating
BER	Bit Error Ratio
BN	Branching Node
CDR	Clock and Data Recovery
CE	Coexistence Element
CEx	Coexistence Element Type x (x = 1, 2, etc.)
CID	Consecutive Identical Digit
CPRI	Common Public Radio Interface
CS	Channel Spacing
DoP	Degree of Polarization
DSP	Digital Signalling Processing
EDC	Electronic Dispersion Compensation
ER	Extinction Ratio
EVC	Ethernet Virtual Connection
FEC	Forward Error Correction
FFS	For Further Study
FSR	Free Spectral Range
G-PON	Gigabit-capable Passive Optical Network

MAC	Media Access Control
MSE	Maximum Spectral Excursion
MTE	Maximum Tuning Error
NRZ	Non-Return to Zero
OAN	Optical Access Network
ODN	Optical Distribution Network
ODS	Optical Distribution Segment
OLT	Optical Line Terminal
ONU	Optical Network Unit
OOB	Out-Of-Band
OOB-PSD	Out-Of-Band Power Spectral Density
OOC	Out-Of-Channel
OOC-PSD	Out-Of-Channel Power Spectral Density
OPP	Optical Path Penalty
ORL	Optical Return Loss
OTDR	Optical Time Domain Reflectometer
OTL	Optical Trunk Line
PHY	Physical interface
PMD	Physical Media Dependent
PON	Passive Optical Network
PSBd	Downstream Physical Synchronization Block
PSD	Power Spectral Density
PSync	Physical Synchronization sequence
PtP WDM	Point-to-Point Wavelength Division Multiplexing
QAM	Quadrature Amplitude Modulation
RE	Reach Extender
RF	Radio Frequency
Rx	Receiver
SLM	Single Longitudinal Mode
SMSR	Side Mode Suppression Ratio
SN	Service Node
SNI	Service Node Interface
S/R-CG	S/R reference point for Channel Group
S/R-CP	S/R reference point for Channel Pair
SRS	Stimulated Raman Scattering
Tplo	Physical layer overhead time
TWDM	Time and Wavelength Division Multiplexing

Tx	Transmitter
UI	Unit Interval
UNI	User-Network Interface
WDM	Wavelength Division Multiplexing
WNE-PSD	optical Power Spectral Density When Not Enabled
WM	Wavelength Multiplexer
XG-PON	10-Gigabit Passive Optical Network
X/S	Crosstalk-to-Signal Ratio

5 Conventions

5.1 Optical access concepts

This Recommendation uses the optical access network terminology and definitions system adopted by [ITU-T G.987]. An example of an access network architecture satisfying the definition system is shown in Figure 5-1.

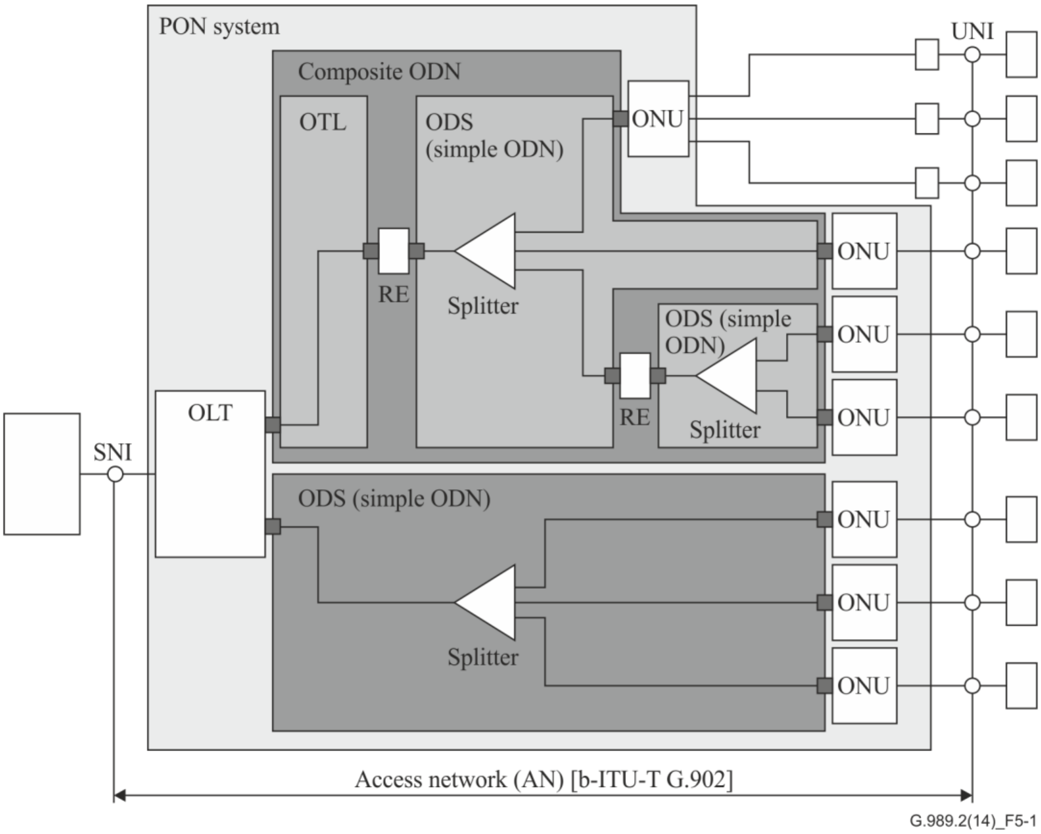


Figure 5-1 – Reference access network architecture

5.2 Multi-wavelength PON system reference points

In a multiple wavelength PON system, such as NG-PON2, the OLT is conceptually composed of multiple OLT channel terminations connected via a wavelength multiplexer (WM). The associated reference logical architecture and its reference points are presented in Figure 5-2.

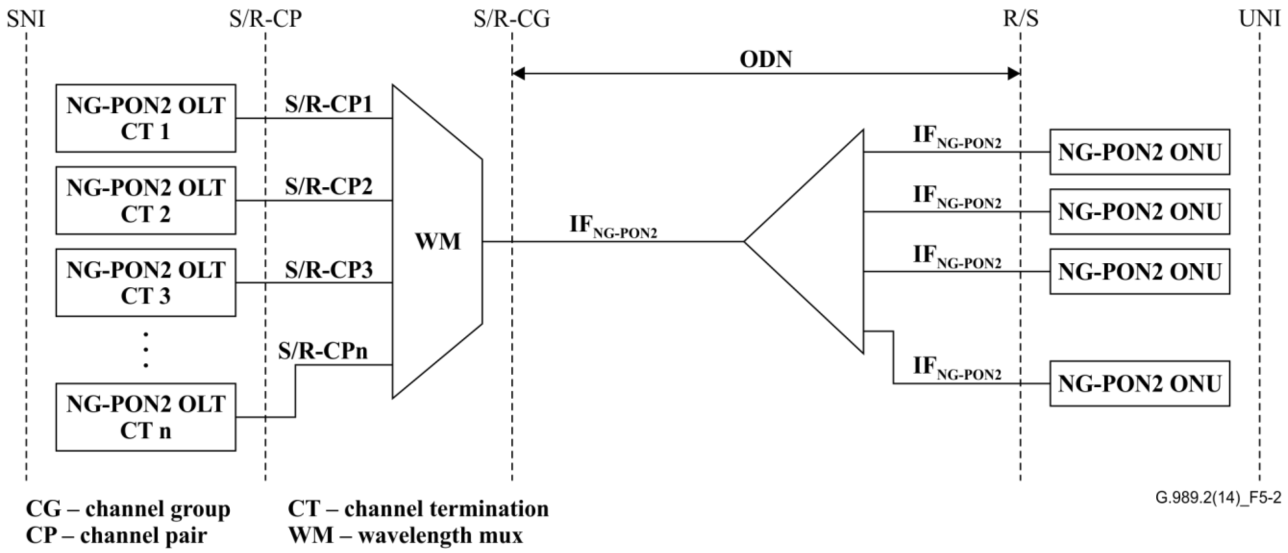


Figure 5-2 – NG-PON2 reference logical architecture

5.3 Power and loss budget parameters

The relationship between power and loss budget parameters is captured in Figure 5-3.

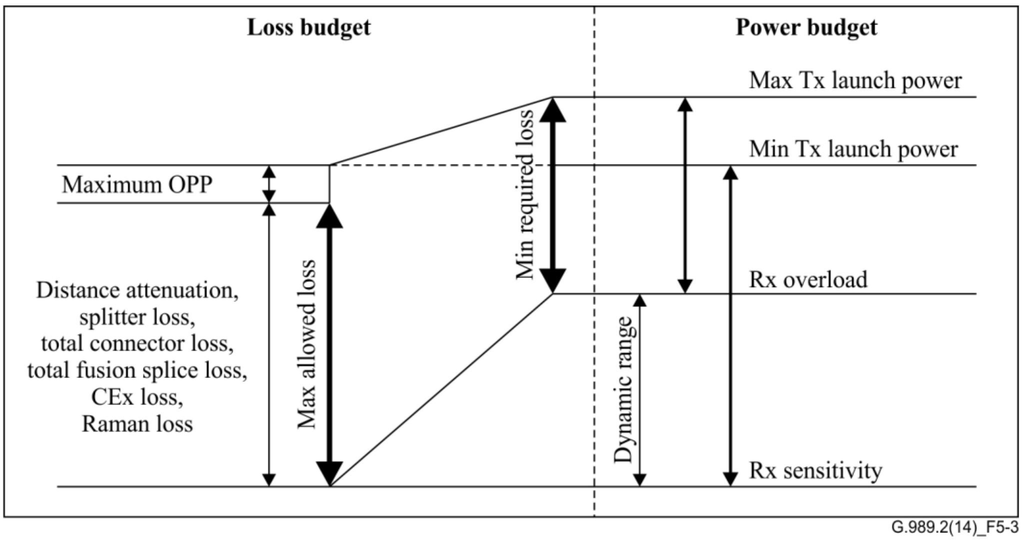


Figure 5-3 – Relationship between the power and loss budget parameters

5.4 Dynamic range, sensitivity and overload

The concept of the dynamic range definition is illustrated in Figure 5-4. The receiver sensitivity and overload are generally understood, respectively, as the minimum and maximum average received optical power at which the bit error ratio (BER) at the receiver output remains at the specified reference level. The observed values of receiver sensitivity and overload may vary as the operating temperature and signal quality change, and the system ages. The signal quality characteristics that affect receiver sensitivity and overload may include the transmitter extinction ratio (ER), parameters of the eye diagram and in-band crosstalk. In the present series of Recommendations, receiver sensitivity and receiver overload are formally specified by their respective worst-case values, i.e., maximum sensitivity and minimum overload over the range of operating temperature and signal quality parameters, and under the end-of-life conditions.

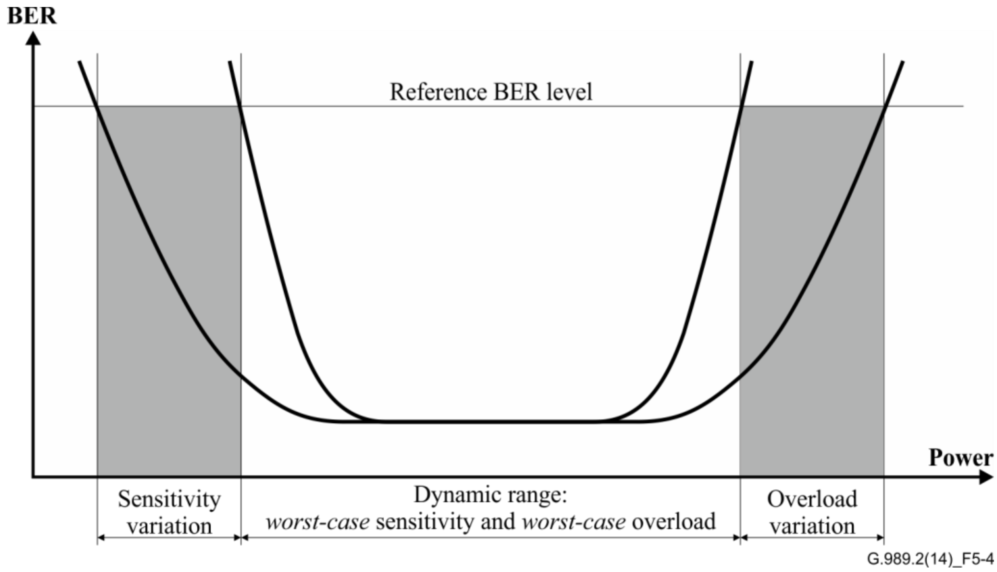


Figure 5-4 – Receiver output BER as a function of received optical power and the definition of dynamic range

5.5 Sensitivity and overload in the presence of forward error correction (FEC)

To simplify TWDM PON optical component verification, this Recommendation, as well as [ITU T G.987.2] prior to it, specifies the sensitivity and overload at the reference BER level, which corresponds to the receiver output and the forward error correction (FEC) decoder input. It is assumed that the FEC algorithms specified, respectively, for continuous mode downstream and burst mode upstream transmission are sufficiently strong to achieve the BER level of 10^{-12} or better at the FEC decoder output. See [b-ITU-T G.sup39] for further discussion.

5.6 Reach and distance

See clause 5.4 of [ITU-T G.987], which is applicable in the NG-PON2 context as well.

5.7 Use of the term passive optical network (PON)

See clause 5.5 of [ITU-T G.987], which is applicable in the NG-PON2 context as well.

5.8 Use of the term optical distribution network (ODN)

See clause 5.6 of [ITU-T G.987], which is applicable in the NG-PON2 context as well.

5.9 Use of the terms optical network unit (ONU) and optical network termination (ONT)

See clause 5.7 of [ITU-T G.987], which is applicable in the NG-PON2 context as well.

5.10 Use of the terms T-CONT and Alloc-ID

The terms transmission container (T-CONT) and allocation identifier (Alloc-ID) are used for consistency with the ITU-T G.989 series of Recommendations, but are not used in this Recommendation.

5.11 Use of the terms bandwidth assignment and bandwidth allocation

These terms are used for consistency with the ITU-T G.989 series of Recommendations, but are not used in this Recommendation.

5.12 Use of the terms band and range

When used in the context of optical spectrum, the terms band and range generally denote a spectral interval in terms of frequency (f_{min}, f_{max}) or wavelength (λ_{min}, λ_{max}). Within the NG-PON2 context, the term band applies specifically to a spectral interval which covers all wavelength channels of a specific application (e.g., TWDM PON upstream band, narrowband option, shared spectrum band, G-PON downstream band), whereas the term range usually applies to a spectral interval corresponding to a single wavelength channel.

The operating bands are specified in wavelength terms as a matter of convenience for classification and reference purposes. The actual minimum and maximum wavelengths for an operating band of each application should be calculated from the maximum and minimum frequencies of the two outmost wavelength channels defined for that application.

5.13 Transmitter enable control and associated transient times

Conceptually, TxEnable is a binary signal that controls a burst-mode ONU transmitter. The TxEnable signal must be asserted (active) for the ONU to transmit an assigned burst. The TxEnable signal is expected to be de-asserted (inactive) whenever no burst is assigned to the ONU. The transmitter enable transient time and transmitter disable transient time are the allocated time intervals which serve to accommodate any transient physical processes that may be associated, respectively, with assertion and de-assertion of the TxEnable signal. The maximum number of bits allocated for transmitter enable transient time and transmitter disable transient time are specified in Tables 11-6 and 11-7 for 2.48832 Gbit/s and 9.95328 Gbit/s, respectively. Figure 5-5 shows the relationship between the level of the TxEnable signal (without loss of generality, active-high logic is assumed) and the associated transient times of the burst-mode transmitter. Within the scope of this Recommendation, the definitions of the optical-power-related physical media dependent (PMD) parameters applicable to the burst-mode transmitters (mean launch optical power, ER, out-of-channel power spectral density (OOC-PSD), optical power spectral density when not enabled (WNE-PSD)) are referenced to the corresponding averaging intervals which are specified in terms of transmitter's enabled/disabled periods and the associated transient times.

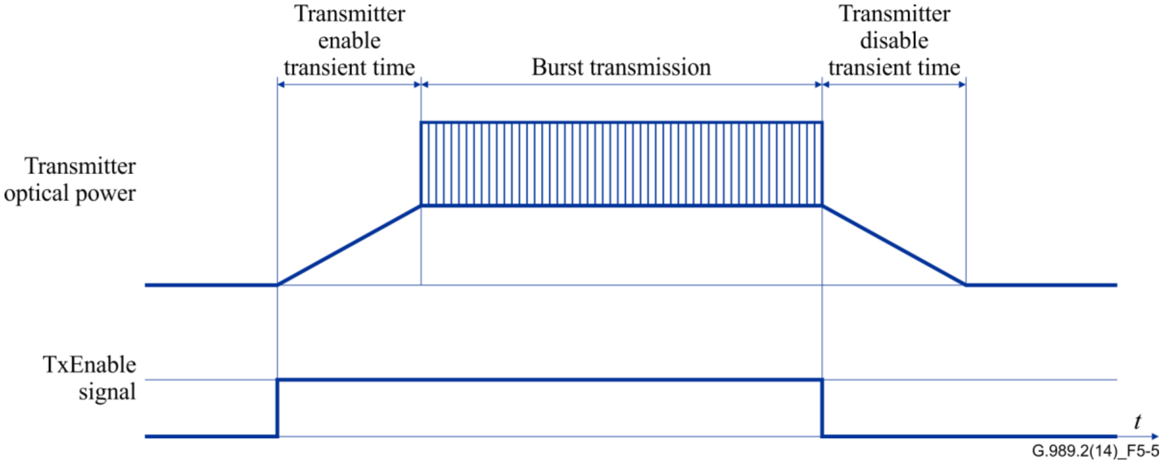


Figure 5-5 – The TxEnable signal and the associated transient times of a burst-mode transmitter

6 Architecture of the optical access network

Figure 6-1 represents the reference logical architecture for the multi-wavelength NG-PON2 system. A multi-system OAN architecture for NG-PON2 coexistence with legacy systems is represented in Figure 5-1 of [ITU-T G.989.1]. During coexistence, mitigation techniques may be necessary to avoid inter-system impairments, e.g., see Appendix VI and Appendix IX for Raman crosstalk considerations. This architecture allows both point-to-multipoint connectivity (i.e., TWDM PON) and virtual point-to-point connectivity (i.e., PtP WDM PON).

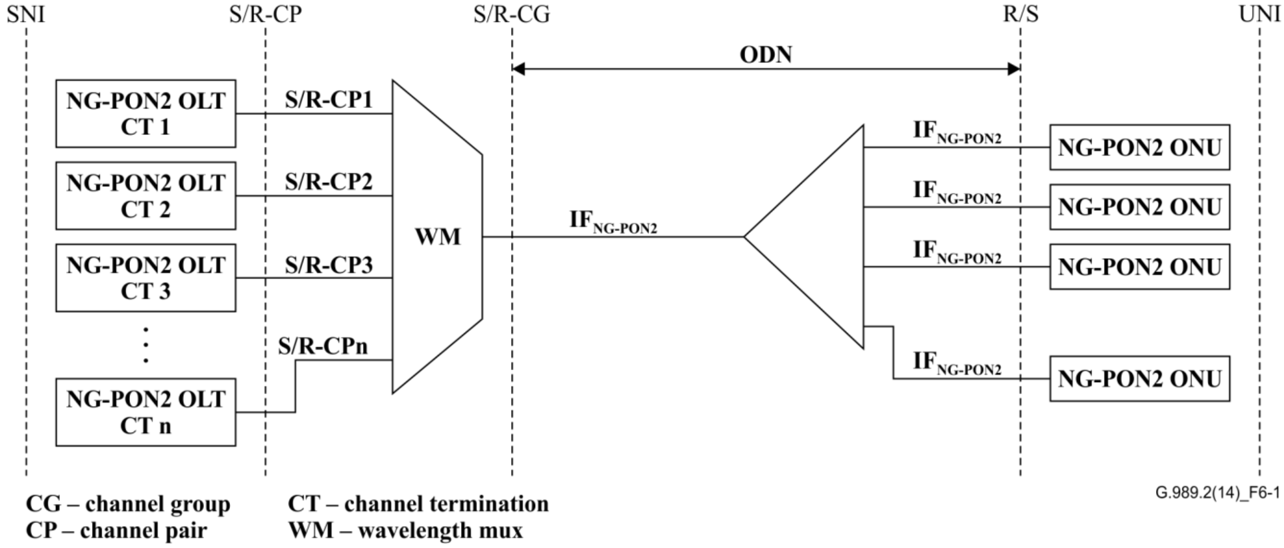


Figure 6-1 – NG-PON2 reference logical architecture

The following reference points from Figure 6-1 are defined below:

- S: The sending interface to the network.
- R: The receiving interface from the network.
- S/R, R/S: Combination of points S and R existing simultaneously in a single fibre, when operating in bidirectional mode. The S/R point is referenced to the OLT side, the R/S point is referenced to the ONU side.

The two directions for optical transmission in the ODN are identified as follows:

- downstream direction for signals travelling from the OLT to the ONU(s); and
- upstream direction for signals travelling from the ONU(s) to the OLT.

Transmission in downstream and upstream directions takes place in the ODN through the same fibre and components (duplex/diplex configuration).

Optical power is specified at the S/R reference point for channel group (S/R-CG) reference point of Figure 6-1 for the individual wavelength channels in the associated optical interface parameters tables. Additionally, examples of WM loss values are provided in Appendix VIII. The optical power for the individual S/R reference point for channel pairs (S/R-CPs) is not specified in this standard and can be derived from the S/R-CG and WM loss values.

Each ONU in Figure 6-1 is equipped with a tunable transmitter and a tunable receiver. The tunable ONU transmitter must be able to adjust to the allocated upstream TWDM or PtP WDM wavelength channels within the bands specified in Table 9-1. The tunable ONU receiver must be able to adjust to the allocated downstream TWDM or PtP WDM wavelength channels within the bands specified in Table 9-1.

This Recommendation specifies a minimum of four, with extension up to eight, TWDM channels. A minimum of four PtP WDM channels is supported with a maximum not specified. The number of wavelength channels supported by a given equipment implementation or network instance is not specified; however the optical parameter tables should be consulted for the specific assumptions made for the parameters given.

The architecture can be extended to support multiple OLTs on a common ODN for other purposes such as pay-as-you-grow deployment and spectral flexibility.

6.1 Physical grouping of logical functions

The logical functions identified in Figure 6-1 for NG-PON2 could be considered to be individual physical items, or fully integrated into a single device.

6.2 ODN optical path loss classes

ODN optical path loss classes (ODN classes) are specified in Table 6-1.

The optical path loss for each class is specified at $IF_{NG-PON2}$ of one side of the ODN and at $IF_{NG-PON2}$ of the other side of the ODN in each direction. It takes into account a 15 dB differential optical path loss and optical path penalty (OPPs).

Table 6-1 – ODN optical path loss classes (ODN classes)[2]

	Class N1	Class N2	Class E1	Class E2
Minimum optical path loss	14 dB	16 dB	18 dB	20 dB
Maximum optical path loss	29 dB	31 dB	33 dB	35 dB
Maximum differential optical path loss	15 dB			

ODNs including gain elements, wavelength couplers or low split ratio power splitters may have optical path losses less than the stated minimum loss values above. In such a case, the ODN must contain measures (e.g., optical attenuators) to guarantee the minimum optical path loss for the given class to prevent BER degradation and/or potential damage to receivers.

6.3 Fibre distance classes

Fibre distance classes are specified in Table 6-2.

Table 6-2 – ODN fibre distance classes

Fibre distance class	Minimum fibre distance (km)	Maximum fibre distance (km)
DD20	0	20
DD40	0	40

7 Services

See clause 7 of [ITU-T G.989.1] for services to be carried by NG-PON2.

8 User network interface and service node interface

See clause 7 of [ITU-T G.989.1].

2 The ODN optical path loss classes are consistent with those specified for XG-PON1 [ITU-T G.987.2].

9 Common optical network requirements

9.1 Layered structure of optical network

The layered structure of the NG-PON2 optical network can generally be represented by a structure in which the data plane and the auxiliary management and control plane are mounted on top of the common physical medium, represented by the NG-PON2 ODN.

9.2 Wavelength plans for NG-PON2

Table 9-1 specifies the wavelength plans for both TWDM PON and PtP WDM PON. The NG-PON2 wavelength plan is specified to enable the coexistence through wavelength overlay with legacy PON systems (see [ITU-T G.989.1]).

Shared spectrum allows full coexistence with G-PON, XG-PON1, radio frequency (RF) video overlay and TWDM. The expanded spectrum option of PtP WDM PON supports spectral flexibility as described in clause 9.2 of [ITU-T G.989.1]. Expanded spectrum can be used in the absence of any one of these coexistence systems.

Table 9-1 – NG-PON2 wavelength bands

Wavelength compatible systems	TWDM PON		PtP WDM PON
	Downstream	Upstream	Upstream/downstream
GPON, RF video, XG-PON1	1596-1603 nm	Wideband option 1524-1544 nm Reduced band option 1528-1540 nm Narrow band option 1532-1540 nm	Expanded spectrum 1524-1625 nm (Note 1) Shared spectrum 1603-1625 nm (Note 2)
NOTE 1 – This Recommendation specifies PtP WDM PON anywhere in the spectrum identified in Table 9-1, subject to spectrum otherwise being used. Whenever a particular subset of the spectrum in either band is unused by TWDM PON and/or legacy systems, PtP WDM PON is permitted to make use of that particular sub-band in upstream and/or downstream direction. However, the isolation requirements to the TWDM PON and/or legacy systems must be considered when determining the expanded spectrum wavelengths to be occupied by PtP WDM PON. NOTE 2 – When TWDM PON and PtP WDM PON are both present, wavelength channels of both technologies may occupy adjacent wavelength bands; however, TWDM and PtP WDM channels must not be interleaved. The required guard band between TWDM PON and PtP WDM PON is a minimum of 3 nm when using separate mux/demux devices. In the shared spectrum case, the PtP WDM PON upstream channels use the shorter wavelengths in the shared spectrum. When a single device is used to multiplex PtP WDM PON and TWDM PON, the required guard band is a minimum of 100 GHz.			

The selection of the operating band option in the PtP WDM PON sub-bands depends on the coexistence requirements. In the expanded spectrum case, DWDM grids as specified in [ITU-T G.694.1] or [ITU-T G.698.3] can be used. See Appendix VII for some example channel plans; however other plans are conceivable and permitted.

9.3 Physical media dependent layer requirements

This clause contains the PMD layer specifications that are common to both TWDM PON and PtP WDM PON. Unique specifications for TWDM PON and PtP WDM PON are contained in respective clauses and annexes of this Recommendation.

9.3.1 Physical media and transmission method

9.3.1.1 Transmission medium

This Recommendation is based on the fibre described in [ITU-T G.652]. Other fibre types compatible with this Recommendation, e.g., [ITU-T G.657], may be used for indoor cabling and/or drop section.

9.3.1.2 Transmission direction

Signals are transmitted both upstream and downstream through the optical transmission medium of the ODN.

9.3.1.3 Transmission method

Bidirectional transmission is accomplished by use of a WDM technique on a single fibre.

9.3.2 Minimum extinction ratio

The minimum ER is specified in logarithmic form and is expressed in decibels as a positive number. To satisfy the requirement, a component or device must meet or exceed the specified ratio.

To measure signal ER at a single-channel reference point (S/R-CP or R/S) the configuration shown in Figure B.1 of [ITU-T G.957] can be used directly. In the case of measurements at the multichannel reference point (S/R-CG), channel isolation is performed with a reference optical bandpass filter (as described in [ITU-T G.959.1], Annex B) before applying this filter output to the configuration shown in Figure B.1 of [ITU-T G.957].

9.3.3 Maximum reflectance of equipment, measured at the transmitter wavelength

The maximum reflectance of equipment, measured at the transmitter wavelength, is specified as a ratio less than one and is expressed in decibels. To satisfy the requirement, a component/device must not exceed the specified ratio.

9.3.4 Tolerance to reflected optical power

The tolerance to reflected optical power is specified as a ratio less than one and is expressed in decibels. To satisfy the requirement, the transmitter must operate without performance degradation in the presence of the optical reflections at or below the specified tolerance level.

This parameter is shown in [ITU-T G.984.2] as "Tolerance to the transmitter incident light power".

9.3.5 Optical path between S/R and R/S

9.3.5.1 Attenuation range

The optical power parameters are specified for four distinct ODN optical path loss classes in clause 6.2. Each class is specified by its respective minimum and maximum optical path loss between the S/R-CG and R/S reference points. The attenuation range is the difference between the maximum and minimum optical path loss in each class.

9.3.5.2 Minimum optical return loss

The minimum optical return loss (ORL) is specified as a ratio greater than one and is expressed in decibels. To satisfy the requirement, a component/device must meet or exceed the specified ratio.

9.3.5.3 Maximum discrete reflectance between points S and R

The maximum discrete reflectance is the maximum value of reflectance of any single discrete element in the ODN. The value specified in this Recommendation is lower than –35 dB, also see [ITU-T G.982].

9.3.5.4 Dispersion

Maximum values of dispersion (ps/nm) are specified in Tables 11-4 to 11-7 for TWDM PON, and Tables A.2 to A.7 for PtP WDM PON. These values are consistent with the maximum OPPs specified. They take into account the worst-case fibre dispersion coefficient over the operating wavelength band.

9.3.6 Receiver at reference point R

All parameters are specified as follows, in accordance with Tables 11-4 to 11-7 for TWDM PON, and Tables A.2 to A.7 for PtP WDM PON.

9.3.6.1 Receiver sensitivity

The receiver sensitivity is specified as a power level and is expressed in decibels relative to 1 mW. To satisfy the requirement, a component or device must be qualified at or below the specified power level.

9.3.6.2 Receiver overload

The receiver overload is specified as a power level and is expressed in decibels relative to 1 mW. To satisfy the requirement, a component/device must be qualified at or above the specified power level.

9.3.6.3 Maximum optical path penalty

The optical path penalty is specified as a ratio greater than one and is expressed in decibels. The optical link budget for a particular ODN optical loss class is satisfied, only if the difference between the minimum transmitter mean launch optical power (in decibels relative to 1 mW) and the receiver sensitivity (in decibels relative to 1 mW) is equal to or exceeds the sum of the maximum OPP (in decibels) and the maximum optical path loss (in decibels) specified for the given ODN optical loss class.

9.3.6.4 Maximum reflectance measured at the receiver wavelength

The reflectance at S/R-CG or R/S reference point, measured at the receiver wavelength, is specified as a ratio less than one and is expressed in decibels. To satisfy the requirement, a component/device must not exceed the specified ratio.

9.3.6.5 Clock extraction capability

Conventional clock extraction applies for continuous data transmission i.e., as used for TWDM PON downstream and PtP WDM PON in both directions.

For TDMA burst mode transmission, the clock of the upstream transmission signal is extracted rapidly from several alternating bits in the preamble. The clock extracted from the preamble is maintained at least during reception of the signal from the delimiter through the end of the upstream assigned burst, or is continuously extracted from the signal after the preamble during reception of the assigned burst.

9.3.6.6 Consecutive identical digit immunity

The consecutive identical digit (CID) immunity is specified as a bit pattern length. To satisfy the requirement, the system must meet or exceed the specified length.

9.3.6.7 Transmission quality and error performance

The bit error ratio reference level describes the quality of the transmission system. The BER reference level is specified for performing measurements of the receiver sensitivity and overload. A compliant system provides BER equal to or better than the specified value.

9.3.7 Tunable characteristics for transmitter and receiver

A key feature of NG-PON2 is the ability to tune the ONU transmitter and receiver. In the OLT to ONU downstream direction, a tunable ONU receiver is required to select the proper wavelength channel. In the ONU to OLT upstream direction, the ONU transmitter is tuned to emit at the desired wavelength channel. There are two characteristics of tunable transmitter/receiver; channel control and wavelength control. For wavelength control, two types of mechanisms are allowed; one requires OLT and ONU interaction to manage the wavelength, the other requires the ONU to be in complete control of the wavelength.

The mechanisms of the tuning process are outside the scope of this Recommendation. Note that the specifications in the optical interface parameter tables in clause 11 and Annex A must be met throughout the tuning process to avoid any rogue behaviour.

The central frequency, spectral excursion, channel spacing (CS), and tuning characteristics are specified in the respective clauses and annexes of this Recommendation. This Recommendation classifies the wavelength channel tuning time of a receiver or transmitter into three classes. These classes may enable different use cases, but the definition of the use cases are outside the scope of this Recommendation.

Table 9-2 – Classes of transmitter/receiver wavelength channel tuning times

Class 1	< 10 µs
Class 2	10 µs to 25 ms
Class 3	25 ms to 1 s

9.3.8 Minimum side mode suppression ratio

The minimum side mode suppression ratio (SMSR) is specified in logarithmic form and is expressed in decibels as a positive number. To satisfy the requirement, the component/device must meet or exceed the specified ratio.

SMSR is measured on the laser output, before any filtering. This prevents a significant mode partition noise penalty. Other limitations on out-of-band (OOB)/out-of-channel (OOC) power still apply to the equipment interface.

9.3.9 Out-of-channel power spectral density mask

The OOC-PSD must not exceed certain levels that depend on the optical frequency offset from the nominal channel central frequency (f_0). These limits are depicted in Figure 9-1, in terms of the specified CS, and the specified maximum spectral excursion (MSE). OOC2 is the limit within the ± MSE interval of each channel, and OOC1 is the limit in between those intervals. A transmitter must comply with the mask when it is tuned anywhere within its MSE.

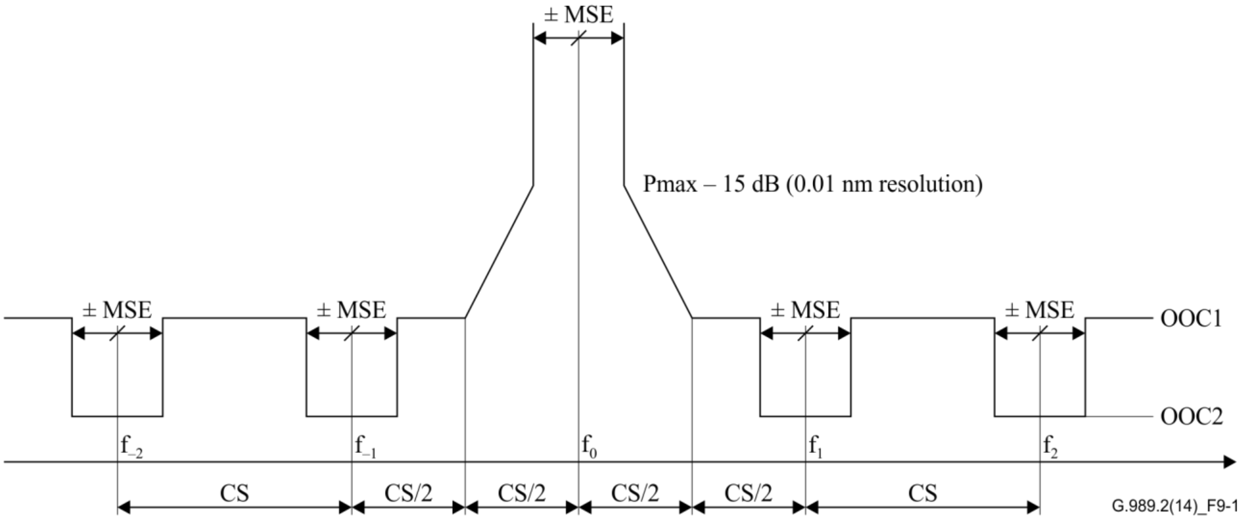


Figure 9-1 – OOC-PSD mask definition

10 Crosstalk-to-signal ratio tolerance for NG-PON2

In the previously specified PON systems, the crosstalk-to-signal ratio (X/S) tolerance characteristics have applied only to the ONU. However, NG-PON2 is a multi-wavelength architecture and as such, the NG-PON2 wavelength channels not intended for a particular receiver (either at the ONU or at the OLT) can be considered interfering signals. This clause specifies X/S characteristics for both the ONU and the OLT. It is anticipated that the ONU will provide X/S filtering directly at the ONU's receiver; whereas X/S filtering at the OLT will likely be external to the OLT receiver, or in combination with the receiver. In any case, this Recommendation specifies only the X/S filtering needed and leaves the method of obtaining that X/S to the implementers of this Recommendation.

As NG-PON2 is a multi-wavelength system, interfering signals may derive from other NG-PON2 wavelength channels. In the case of the ONU, interfering signals may also derive from coexisting legacy systems such as G-PON, XG-PON1, RF video overlay and maintenance wavelengths from optical time domain reflectometer (OTDR). To minimize the effect of interfering signals, NG-PON2 receivers need to reject them using an appropriate wavelength filtering. This Recommendation does not specify the isolation characteristics of the wavelength filtering directly, but specifies the X/S tolerance of the NG-PON2 receiver[3]. Here, S is the optical power of an individual wavelength channel within an aggregate NG-PON2 signal, and X is that of the aggregated interfering signals, consisting of legacy signals and other NG-PON2 wavelength channels. Both are measured at the receiver reference point R, corresponding to the IF reference points specified in Figure 6-1.

The interfering signal format for measuring X/S tolerance is a non-return to zero (NRZ) pseudo-random code with the same line rate as the target NG-PON2 signal. In the case of both TWDM PON and PtP WDM PON, eight channels are considered the worst-case configuration.

The wavelength filtering is divided into two parts: a wideband X/S, based on legacy system considerations, and a narrowband X/S based on the NG-PON2 wavelength channels.

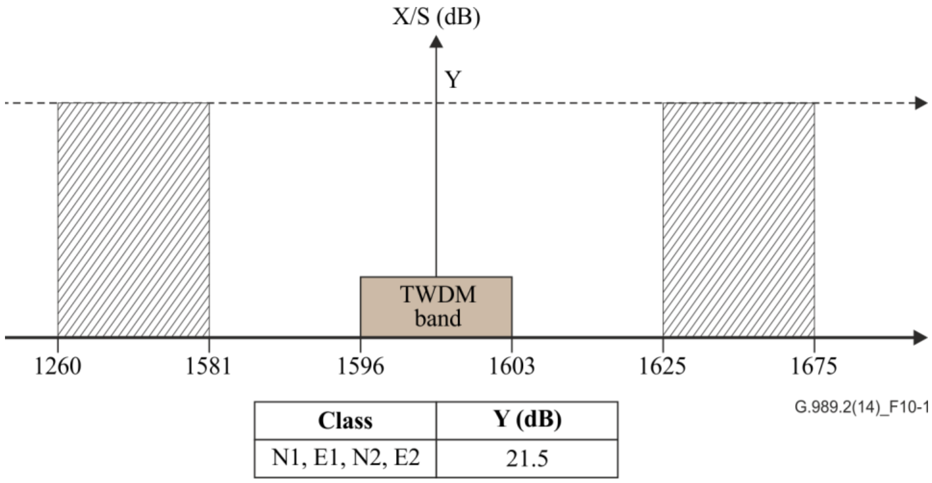
[3] The X/S definition is intended to capture the worst-case difference in interfering signal levels (X) relative to the intended data signal (S). In order to derive the actual isolation value, the X/S value is added to the required level of isolation from the interfering signal to obtain a stated degradation of "x" dB to the data signal.

10.1 Wideband X/S tolerance mask definition

This clause describes the generic X/S tolerance of NG-PON2 devices. It makes no assumption about additional services using the wavelength band specified in this Recommendation.

10.1.1 Wideband ONU X/S tolerance

Figure 10-1 shows the generic PON X/S tolerance mask that allows the NG-PON2 ONU receiver to meet its sensitivity requirements in the presence of legacy systems. Implementers need to specify the isolation characteristics of the wavelength filters to obtain enough isolation of the interfering signal(s). The wavelengths and total optical power of all additional services must fall beneath the mask of Figure 10-1 to allow coexistence with NG-PON2 ONUs.



Class	Y (dB)
N1, E1, N2, E2	21.5

Figure 10-1 – X/S tolerance mask for TWDM PON ONU

S: Received optical power for target channel in TWDM PON downstream band.

X: Maximum total power of other optical signals received in the blocking wavelength band.

X/S: The value in the mask (hatched area) allows the NG-PON2 receiver to meet its sensitivity requirements

The wideband ONU X/S tolerance mask of PtP WDM PON can be derived by analogy with the TWDM PON X/S tolerance mask above. The specific values are for further study (FFS).

10.1.2 Wideband OLT X/S tolerance

The separation of legacy system wavelengths from the NG-PON2 wavelengths is accomplished by the coexistence element (CE), as defined in [ITU-T G.984.5]. This device must have sufficient isolation to allow the OLT to operate within specifications. As the CE is not part of the OLT equipment, there are no requirements on the OLT equipment for wideband X/S tolerance.

10.2 Narrowband TWDM PON X/S tolerance mask

The narrowband TWDM PON X/S mask is shown in Figure 10-2, using the particular value tables as given below. The TWDM-PON self-interference configuration is common to both the ONU and OLT. This configuration of one desired wavelength and 14 potentially interfering wavelengths is devised to approximate the worst-case crosstalk situation. Of the 14 interference locations, only seven contiguous points will be populated at any one time. That is to say, if the central frequency is on channel C (C being of the value one through eight), the shortest wavelength interferer would be at channel one, and the longest wavelength interferer would be on channel eight. The receiver is required to have its specified sensitivity for the desired signal over the wavelength band λ_{S-} to λ_{S+}, despite the fact that the seven interferers are present with power level X and modulated with a TWDM PON signal format of the same rate as the signal channel.

10.2.1 Narrowband ONU X/S tolerance mask

In addition to the TWDM interferers, there are an assumed eight PtP WDM interferers, both downstream and upstream. These are assumed to be at the channel assignments as given in Appendix VII, Table VII-3. The upstream interference channels (which result from the potential for a 32 dB ORL in the ODN) have a power level Y and modulated with an NRZ signal at a similar data rate as the signal channel. The downstream interference channels have a power level Z and are modulated with an NRZ signal at the similar data rate as the signal channel.

The parameters of the downstream mask are given in Table 10-1.

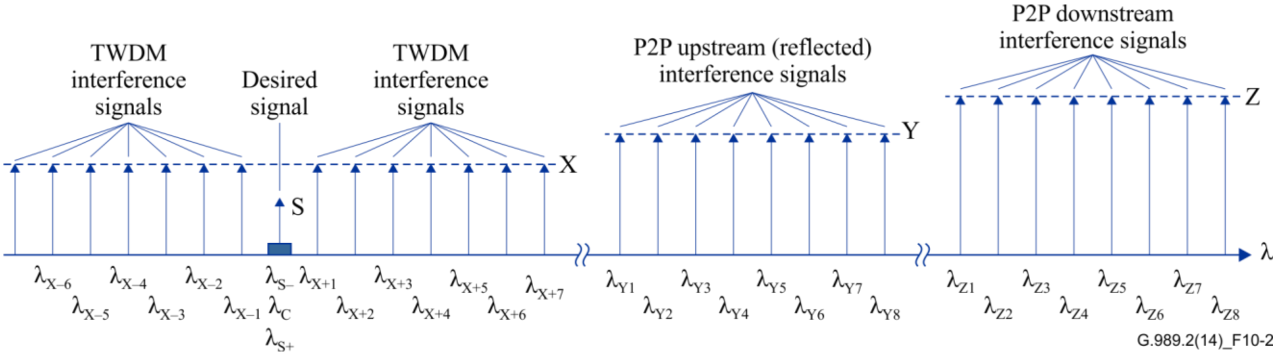


Figure 10-2 – X/S tolerance mask for TWDM PON

Table 10-1 – TWDM PON downstream (ONU receive) X/S parameters

Parameter	Value
λ_{X-7}	λ_C + MSE – 7*CS
λ_{X-6}	λ_C + MSE – 6*CS
λ_{X-5}	λ_C + MSE – 5*CS
λ_{X-4}	λ_C + MSE – 4*CS
λ_{X-3}	λ_C + MSE – 3*CS
λ_{X-2}	λ_C + MSE – 2*CS
λ_{X-1}	λ_C + MSE – CS
λ_{S-}	λ_C – MSE
λ_C	Central frequency of ONU filter
λ_{S+}	λ_C + MSE
λ_{X+1}	λ_C – MSE + CS
λ_{X+2}	λ_C – MSE + 2*CS
λ_{X+3}	λ_C – MSE + 3*CS
λ_{X+4}	λ_C – MSE + 4*CS
λ_{X+5}	λ_C – MSE + 5*CS
λ_{X+6}	λ_C – MSE + 6*CS

Table 10-1 – TWDM PON downstream (ONU receive) X/S parameters

Parameter	Value
λ_{X+7}	λ_C – MSE + 7*CS
S	Receiver sensitivity
X	S + 4 dB (Note 1)
λ_{Y1}	See Table VII.3, column M-13
λ_{Y2}	
λ_{Y3}	
λ_{Y4}	
λ_{Y5}	
λ_{Y6}	
λ_{Y7}	
λ_{Y8}	
Y	S+6 dB (Note 2)
λ_{Z1}	See Table VII.3, column M-14
λ_{Z2}	
λ_{Z3}	
λ_{Z4}	
λ_{Z5}	
λ_{Z6}	
λ_{Z7}	
λ_{Z8}	
Z	2.48832 Gbit/s: S+6 dB (Note 3) 9.95328 Gbit/s: S+8 dB

NOTE 1 – 4 dB is the worst-case OLT transmitter power differential.

NOTE 2 – 6 dB is the maximum PtP WDM ONU transmitter power (+8 dBm) less the ORL (32 dB) less the TWDM OLT receiver sensitivity (–30 dBm).

NOTE 3 – The 2.48832 Gbit/s value (6 dB) is the PtP WDM OLT receiver sensitivity (–28 dBm) plus the PtP WDM OLT transmitter differential (4 dB) less the TWDM OLT receiver sensitivity (–30 dBm). The 9.95328 Gbit/s value (8 dB) is the PtP WDM OLT receiver sensitivity (–23.5 dBm) plus the PtP WDM OLT transmitter differential (3.5 dB) less the TWDM OLT receiver sensitivity (–28 dBm).

10.2.2 Narrowband OLT X/S tolerance mask

The parameters of the OLT X/S mask are given in Table 10-2. Note that for the TWDM PON upstream, the PtP WDM channels are located so far away in wavelength that they are assumed to be filtered effectively by the TWDM PON diplexer.

Table 10-2 – TWDM PON upstream (OLT receive) X/S parameters

Parameter	Value
λ_{X-7}	λ_C + MSE – 7*CS
λ_{X-6}	λ_C + MSE – 6*CS
λ_{X-5}	λ_C + MSE – 5*CS
λ_{X-4}	λ_C + MSE – 4*CS
λ_{X-3}	λ_C + MSE – 3*CS
λ_{X-2}	λ_C + MSE – 2*CS
λ_{X-1}	λ_C + MSE – CS
λ_{S-}	λ_C – MSE
λ_C	Central frequency of OLT filter
λ_{S+}	λ_C + MSE
λ_{X+1}	λ_C – MSE + CS
λ_{X+2}	λ_C – MSE + 2*CS
λ_{X+3}	λ_C – MSE + 3*CS
λ_{X+4}	λ_C – MSE + 4*CS
λ_{X+5}	λ_C – MSE + 5*CS
λ_{X+6}	λ_C – MSE + 6*CS
λ_{X+7}	λ_C – MSE + 7*CS
S	Receiver sensitivity
X	S + 20 dB (Note)
NOTE – 20 dB is the worst-case TWDM ONU transmitter power differential (5 dB) plus the differential optical path loss (15 dB).	

The narrowband X/S tolerance of PtP WDM PON can be derived by analogy with the TWDM PON X/S tolerance above.

11 TWDM PON PMD layer requirements

11.1 PMD layer requirements

The TWDM PON system must support a minimum of four TWDM channels. It may also support an optional extension up to eight TWDM channels.

All parameters are specified as follows, and are in accordance with Tables 11-4 to 11-7.

All parameter values specified are met under the worst-case operating conditions such as temperature and humidity, and include ageing effects, as specified in [ITU-T G.989.1]. The parameters are specified relative to a BER Reference level not worse than the values specified in Tables 11-4 to 11-7, for the worst-case optical path loss (see Table 6-1) and fibre chromatic dispersion.

11.1.1 Nominal Line rate and clock accuracy

The transmission line rate is a multiple of 8 kHz.

Parameters to be specified are categorized by downstream and upstream nominal line rates, and downstream/upstream rate combinations as shown in Table 11-1. Each TWDM channel in the channel group on a TWDM PON can use any of the line rate options specified in Table 11-1.

Table 11-1 – Relation between TWDM PON line rate options and optical parameter tables

	Nominal line rate, downstream/upstream (Gbit/s)	Reference table, downstream/upstream
Basic rate	9.95328/2.48832	Table 11-5/Table 11-6
Rate option 1	9.95328/9.95328	Table 11-5/Table 11-7
Rate option 2	2.48832/2.48832	Table 11-4/Table 11-6

11.1.1.1 Downstream clock accuracy

When the OLT and the end office (the facility of the OLT and synchronization source) are in their normal operating state, the OLT is typically traceable to a Stratum-1 reference (accuracy of 1×10^{-11}). When the OLT is in its free running mode, the accuracy of the downstream signal is at least that of a Stratum-4 clock (3.2×10^{-5}). OLTs intended for timing-critical applications such as mobile backhaul may require Stratum-3 quality in free-running mode.

NOTE – The OLT may derive its timing from either a dedicated timing signal source or from a synchronous data interface (line timing). A packet-based timing source may also be used.

11.1.1.2 Upstream clock accuracy

When in one of its operating states and granted an allocation, the ONU transmits its signal with frequency accuracy equal to that of the received downstream signal.

11.1.2 Line code

The convention used for optical logic levels is:

- high level of light emission for a binary ONE;
- low level of light emission for a binary ZERO.

11.1.2.1 Downstream

Downstream line coding for 9.95328Gbit/s: scrambled NRZ.

Downstream line coding for 2.48832Gbit/s: scrambled NRZ.

In addition to the schemes described in Appendix VI, two line code schemes are described in Appendix IX that are intended to offer mitigation of Raman crosstalk impairments on RF video overlay.

11.1.2.2 Upstream

Upstream line coding for 2.48832 Gbit/s: scrambled NRZ.

Upstream line coding for 9.95328 Gbit/s: scrambled NRZ for 20 km reach, FFS for 40 km reach.

11.1.2.3 Electronic dispersion compensation

Electronic dispersion compensation (EDC) may be used in the OLT (ONU) transmitter to achieve the OPP specified in the optical interface parameter tables. At the ONU (OLT) receiver, EDC may also be used. The use of EDC is outside the scope of this Recommendation.

11.1.3 Operating wavelength

The operating wavelength bands for TWDM PON are specified in clause 9.2.

The downstream frequency is described in Table 11-2.

Table 11-2 – TWDM channel downstream frequency plan

Channel	Central frequency (THz)	Wavelength (nm)
1	187.8	1596.34
2	187.7	1597.19
3	187.6	1598.04
4	187.5	1598.89
5	187.4	1599.75
6	187.3	1600.60
7	187.2	1601.46
8	187.1	1602.31
NOTE – Channels 1-4 are assigned to TWDM with four downstream wavelengths. Channels 5-8 are optionally assigned to TWDM and may be used by PtP WDM or other systems if not reserved for TWDM expansion. The frequency values in this table are normative, while the wavelength values are for information only.		

11.1.4 PMD parameters

11.1.4.1 Compatible optical distribution network

TWDM PON operates over an ODN whose parameters are described by Table 11-3.

Table 11-3 – Physical parameters of a simple ODN

Item	Unit	Specification
Fibre type (Note 1)	–	[ITU-T G.652], or compatible
Attenuation range (as defined in clause 9.3.5.1)	dB	See Table 6-1
Maximum fibre distance between S/R-CG and R/S points (as specified in Table 6-2) (Note 2)	km	DD20: 20 DD40: 40
Minimum fibre distance between S/R-CG and R/S points (as specified in Table 6-2)	km	0
Maximum differential optical path loss	dB	15
Bidirectional transmission	–	1-fibre WDM
Maintenance wavelength	nm	See [ITU-T L.66]
NOTE 1 – See clause 9.3.1.1. NOTE 2 – Support of 60 km fibre distance may require reach extenders (REs).		

11.1.4.2 Optical interface parameters of downstream direction

The following downstream optical interface tables are applicable for 20 and 40 km fibre length, and one to four TWDM channels. Complete specifications for eight TWDM channels are FFS.

Table 11-4 – Optical interface parameters of 2.48832 Gbit/s downstream direction

Item	Unit	Value			
OLT transmitter (optical interface S)					
Nominal line rate	Gbit/s	2.48832 (Note 1)			
Operating wavelength band	nm	1596-1603			
Operating central frequency	THz	Table 11-2			
Operating CS	GHz	100 (Note 2)			
Maximum spectral excursion	GHz	±20			
Line code	–	Scrambled NRZ (Note 1)			
Mask of the transmitter eye diagram	–	See clause 11.1.5.3			
Maximum reflectance at S/R-CG, measured at transmitter wavelength	dB	NA			
Minimum ORL of ODN at S/R-CG	dB	32			
ODN class		N1	N2	E1	E2
Mean channel launch power minimum (at S/R-CG)	dBm	+0.0	+2.0	+4.0	+6.0
Mean channel launch power maximum (at S/R-CG)	dBm	+4.0	+6.0	+8.0	+ 10
Maximum downstream WNE-PSD	dBm (15 GHz)	FFS			
Minimum ER (Note 3)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range	ps/nm	0-420 (DD20) 0-840 (DD40)			
Minimum SMSR (at S/R-CP)	dB	30			
Maximum downstream per channel OOB power spectral density (OOB-PSD) (Note 4)	dBm (15 GHz)	–49.1			
Maximum downstream per channel OOC-PSD (Note 5)	dBm (15 GHz)	–38.7			
Jitter generation	–	See clause 11.1.5.4.3			
ONU receiver (optical interface R)					
Maximum OPP (Note 6)	dB	1.0			
Maximum reflectance at R/S, measured at receiver wavelength	dB	–20			
Bit error ratio reference level	–	10^{-4} (Note 7)			
Receiver wavelength channel tuning time		See Table 9-2			
Maximum tuning granularity	GHz	5			
ODN class		N1	N2	E1	E2

Table 11-4 – Optical interface parameters of 2.48832 Gbit/s downstream direction

Item	Unit	Value			
Sensitivity (at R/S)	dBm	–30.0	–30.0	–30.0	–30.0
Overload (at R/S)	dBm	–10.0	–10.0	–10.0	–10.0
In-band crosstalk tolerance	dB (15 GHz)	32.3			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	see clause 11.1.5.4.2			

NOTE 1 –Two additional line codes that have been developed to facilitate support of the RF video overlay are covered in Appendix IX.

NOTE 2 – Minor deviations from the nominal 100 GHz spacing are allowed in order to accommodate a combined wavelength mux/demux device, see Table 11-2. See Appendix VII for information.

NOTE 3 – A lower ER is allowed but must be compensated by a larger transmitter launch power within the limits of the "mean launch power maximum" value. However, the impact of reduced ER on OOB/OOC power must be considered.

NOTE 4 – This value is based on the following assumptions: OOB impact from TWDM PON on PtP WDM PON can be controlled through appropriate filtering, 0.1 dB penalty, PtP WDM PON operates without FEC, and four interfering TWDM channels.

NOTE 5 – This value is based on the following assumptions: OOC in downstream can be controlled through filtering from WM, 0.1 dB penalty, TWDM PON operates with FEC, and four TWDM channels (three interferers).

NOTE 6 – The specified OPP is valid up to a 40 km optical link distance. If the actual OPP is worse than the specified value, it must be compensated by the transmitter launch power increase up to the limits of the mean launch power maximum.

NOTE 7 – See [b-ITU-T G.Sup39], clause 9.4.1 for additional details.

Table 11-5 – Optical interface parameters of 9.95328 Gbit/s downstream direction

Item	Unit	Value			
OLT transmitter (optical interface S)					
Nominal line rate	Gbit/s	9.95328 (Note 1)			
Operating wavelength band	nm	1596-1603			
Operating central frequency	THz	Table 11-2			
Operating CS	GHz	100 (Note 2)			
Maximum spectral excursion	GHz	±20			
Line code	–	Scrambled NRZ (Note 1)			
Mask of the transmitter eye diagram	–	see clause 11.1.5.3			
Maximum reflectance at S/R-CG, measured at transmitter wavelength	dB	NA			
Minimum ORL of ODN at S/R-CG	dB	32			
ODN class		N1	N2	E1	E2
Mean channel launch power minimum (at S/R-CG)	dBm	+3.0	+5.0	+7.0	+9.0

Table 11-5 – Optical interface parameters of 9.95328 Gbit/s downstream direction

Item	Unit	Value			
Mean channel launch power maximum (at S/R-CG)	dBm	+7.0	+9.0	+11.0	+11.0
Maximum downstream WNE-PSD	dBm (15 GHz)	FFS			
Minimum ER (Note 3)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range	ps/nm	0-420 (DD20) 0-840 (DD40)			
Minimum SMSR (at S/R-CP)	dB	30			
Maximum downstream per channel OOB-PSD (Note 4)	dBm (15 GHz)	–49.1			
Maximum downstream per channel OOC-PSD (Note 5)	dBm (15 GHz)	–38.7			
Jitter generation	–	see clause 11.1.5.4.3			
ONU receiver (optical interface R)					
Maximum OPP (Note 6)	dB	2.0			
Maximum reflectance at R/S, measured at receiver wavelength	dB	–20			
Bit error ratio reference level	–	10^{-3} (Note 7)			
Receiver wavelength channel tuning time		See Table 9-2			
Maximum tuning granularity	GHz	5			
ODN class		N1	N2	E1	E2
Sensitivity (at R/S)	dBm	–28.0	–28.0	–28.0	–28.0
Overload (at R/S)	dBm	–7.0	–7.0	–7.0	–9.0
In-band crosstalk tolerance	dB (15 GHz)	35.3			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	see clause 11.1.5.4.2			

NOTE 1 – Two additional line codes that have been developed to facilitate support of the RF video overlay are covered in Appendix IX.

NOTE 2 – Minor deviations from the nominal 100 GHz spacing are allowed in order to accommodate a combined wavelength mux/demux, see Table 11-2. See Appendix VII for information.

NOTE 3 – A lower ER is allowed but must be compensated by a larger transmitter launch power within the limits of the "Mean launch power maximum" value. However the impact of reduced ER on OOB/OOC power must be considered.

NOTE 4 – This value is based on the following assumptions: OOB impact from TWDM PON on PtP WDM PON can be controlled through appropriate filtering, 0.1 dB penalty, PtP WDM PON operates without FEC, and four interfering TWDM channels.

NOTE 5 – This value is based on the following assumptions: OOC in downstream can be controlled through filtering from WM, 0.1 dB penalty, TWDM PON operates with FEC, and four TWDM channels (three interferers).

Table 11-5 – Optical interface parameters of 9.95328 Gbit/s downstream direction

Item	Unit	Value
NOTE 6 – The specified OPP is valid up to a 40 km optical link distance. If the actual OPP is worse than the specified value, it must be compensated by the transmitter launch power increase up to the limits of the Mean launch power maximum. NOTE 7 – See [b-ITU-T G.Sup39], clause 9.4.1 for additional details.		

11.1.4.3 Optical interface parameters of upstream direction

The following upstream optical interface parameter tables are applicable to up 20 and 40 km fibre length, and one to four TWDM channels. Complete specifications for eight TWDM channels are FFS.

Table 11-6 – Optical interface parameters of 2.48832 Gbit/s upstream direction

Item	Unit	Value			
ONU transmitter (optical interface S)					
Nominal line rate	Gbit/s	2.48832			
Operating wavelength band	nm	1524-1544 (wideband option), 1528-1540 (reduced band option) 1532-1540 (narrowband option)			
Minimum Operating CS	GHz	50			
Maximum Operating CS	GHz	200			
Maximum spectral excursion (over one OLT-ONU tuning cycle) (Note 1)	GHz	±12.5 (for 50 GHz CS) ±20 (for 100 GHz CS) ±25 (for 200 GHz CS)			
Transmitter power wavelength dependency	dB	FFS			
Minimum tuning window (Note 2) When using cyclic channel grid (see Appendix VII) When not using cyclic channel grid	GHz	(N+1)*CS (N-1)*CS+2*MSE			
Maximum tuning granularity	GHz	CS/20			
Transmitter wavelength channel tuning time		See Table 9-2			
Line code	–	Scrambled NRZ			
Mask of the transmitter eye diagram	–	see clause 11.1.5.3.2			
Maximum reflectance at R/S, measured at transmitter wavelength	dB	–6			
Minimum ORL of ODN at R/S	dB	32			
ODN class		N1	N2	E1	E2
Mean channel launch power minimum (at R/S)					
– Type A link (Note 3)	dBm	+4	+4	+4	+4
– Type B link (Note 4)	dBm	0	0	0	0
Mean channel launch power maximum (at R/S)					
– Type A link (Note 3)	dBm	+9	+9	+9	+9
– Type B link (Note 4)	dBm	+5	+5	+5	+5
Maximum transmitter enable transient time	bits	32			

Table 11-6 – Optical interface parameters of 2.48832 Gbit/s upstream direction

Item	Unit	Value			
Maximum transmitter disable transient time	bits	32			
Minimum ER (Note 5)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range	ps/nm	0 to 355 (DD20) 0 to 710 (DD40)			
Minimum SMSR (Note 6)	dB	30			
Maximum upstream OOB-PSD (Note 7)	dBm (15 GHz)	–61.6			
Maximum upstream OOC-PSD – OOC1 (Note 8)	dBm (15 GHz)	–36.7 for 50 GHz CS –40.5 for 100 GHz CS –44.4 for 200 GHz CS			
Maximum upstream OOC-PSD – OOC2 (Note 8)	dBm (15 GHz)	–45.7			
Maximum upstream WNE-PSD (Note 9)	dBm (15 GHz)	–68.5			
Jitter transfer	–	see clause 11.1.5.4.1			
Jitter generation	–	see clause 11.1.5.4.3			
OLT receiver (optical interface R)					
ODN class		N1	N2	E1	E2
Maximum OPP (Note 10) – with Raman effects (DD20, four channel) – with Raman effects (DD40, four channel) – with Raman effects (DD20,eight channel) – with Raman effects (DD40,eight channel)	dB	 1.0 1.5 1.0 2.0	 1.0 1.5 1.5 2.5	 1.5 2.0 2.0 3.5	 1.5 2.0 2.0 3.5
Maximum reflectance at S/R-CG, measured at receiver wavelength	dB	–20			
Bit error ratio reference level	–	10^{-4} (Note 11)			
ODN class		N1	N2	E1	E2
Sensitivity (at S/R-CG, based on DD20, four wavelength) (Note 12)					
– Type A link (Note 3)	dBm	–26	–28	–30.5	–32.5
– Type B link (Note 4)	dBm	–30	–32	–34.5	–36.5
Overload (at S/R-CG)					
– Type A link (Note 3)	dBm	–5	–7	–9	–11
– Type B link (Note 4)	dBm	–9	–11	–13	–15
In-band crosstalk tolerance	dB (15 GHz)	30.0 (Type A link) 26.0 (Type B link)			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	see clause 11.1.5.4.2			
NOTE 1 – MSE values of other CS can be interpolated from the three given values.					

Table 11-6 – Optical interface parameters of 2.48832 Gbit/s upstream direction

Item	Unit	Value
NOTE 2 – N is the channel count. When using cyclic channel grid, if CS is 100 GHz, the minimum tuning windows are 500 GHz and 900 GHz for four and eight channel TWDM PONs, respectively. When using cyclic channel grid, if CS is 50 GHz, the minimum tuning windows are 250 GHz and 450 GHz for four and eight channel TWDM PONs, respectively. When not using cyclic channel grid, if CS is 100 GHz, its minimum tuning windows are 340 GHz and 740 GHz for four and eight channel TWDM PONs, respectively. When not using cyclic channel grid, if CS is 50 GHz, the minimum tuning windows are 175 GHz and 375 GHz for four and eight channel TWDM PONs, respectively. NOTE 3 – Type A link values assume an unamplified OLT receiver. However, an amplified OLT receiver is not precluded. NOTE 4 – Type B link values assume an amplified OLT receiver with the amplifier at the S/R-CG reference point. However, other amplifier approaches, including an unamplified OLT receiver are not precluded. NOTE 5 – A lower ER is allowed but must be compensated by a larger transmitter launch power within the limits of the "Mean launch power maximum" value. However the impact of reduced ER on OOB/OCC power must be considered. NOTE 6 – SMSR is measured on the laser output, before any filtering. This prevents a significant mode partition noise penalty. Other limitations on OOB and OOC PSD still apply to the R/S reference point. NOTE 7 – This value is based on the following assumptions: OOB impact from TWDM PON on PtP WDM PON can be controlled through appropriate filtering, 0.1 dB penalty, PtP WDM PON operates without FEC, and four interfering TWDM channels. NOTE 8 – See OOC-PSD mask in clause 9.3.9. These values are based on the following assumptions: 1 dB upstream OOC penalty, TWDM PON operates with FEC, and four TWDM channels (three interferers). In some implementations, this requirement may be achieved by more tightly regulating the transmitter output power (lowering the maximum level while maintaining the minimum level). NOTE 9 – This value is based on the following assumptions: 0.1 dB penalty, TWDM PON operates with FEC, and 64 TWDM PON ONUs in one channel (63 interferers). NOTE 10 – The specified penalty takes into account the class-specific transmitter power, distance, and number of wavelengths. The maximum OPP values assume no SR-/CG located splitters and low optical fibre loss, resulting in the worst-case Raman effect. ODNs that include high loss elements near the OLT or higher loss optical cable will exhibit lower penalties. NOTE 11 – See [b-ITU-T G.Sup39], clause 9.4.1 for additional details. NOTE 12 – See clause 11.1.4.3.1 for an approach to accommodate the case of 40 km and eight wavelengths.		

Table 11-7 – Optical interface parameters of 9.95328 Gbit/s upstream direction

Item	Unit	Value			
ONU transmitter (optical interface S)					
Nominal line rate	Gbit/s	9.95328			
Operating wavelength band	nm	1524-1544 (wideband option), 1528-1540 (reduced band option) 1532-1540 (narrowband option)			
Minimum Operating CS	GHz	50			
Maximum Operating CS	GHz	200			
Maximum spectral excursion (Note 1) (over one OLT-ONU tuning cycle)	GHz	±12.5 (for 50 GHz CS) ±20 (for 100 GHz CS) ±25 (for 200 GHz CS)			
Transmitter power wavelength dependency	dB	FFS			
Minimum tuning window (Note 2) When using cyclic channel grid (see Appendix VII) When not using cyclic channel grid	GHz	(N+1)*CS (N-1)*CS+2*MSE			
Maximum tuning granularity	GHz	CS/20			
Transmitter wavelength channel tuning time		See Table 9-2			
Line code	–	Scrambled NRZ (20 km) FFS (40 km)			
Mask of the transmitter eye diagram	–	see clause 11.1.5.3.2			
Maximum reflectance at R/S, measured at transmitter wavelength	dB	–6			
Minimum ORL of ODN at R/S	dB	32			
ODN class		N1	N2	E1	E2
Mean channel launch power minimum (at R/S)					
– Type A link (Note 3)	dBm	+4.0	+4.0	+4.0	NA
– Type B link (Note 4)	dBm	+2.0	+2.0	+2.0	+4.0
Mean channel launch power maximum (at R/S)					
– Type A link (Note 3)	dBm	+9.0	+9.0	+9.0	NA
– Type B link (Note 4)	dBm	+7.0	+7.0	+7.0	+9.0
Maximum transmitter enable transient time	bits	128			
Maximum transmitter disable transient time	bits	128			
Minimum ER (Note 5)	dB	6.0			
Tolerance to reflected optical power	dB	–15			
Dispersion range	ps/nm	0 to 355 (DD20)			
Minimum SMSR (Note 6)	dB	30			

Table 11-7 – Optical interface parameters of 9.95328 Gbit/s upstream direction

Item	Unit	Value			
Maximum upstream OOB-PSD (Note 7)	dBm (15 GHz)	–61.6			
Maximum upstream OOC-PSD – OOC1 (Note 8)	dBm (15 GHz)	–36.7 for 50 GHz CS –40.5 for 100 GHz CS –44.4 for 200 GHz CS			
Maximum upstream OOC-PSD – OOC2 (Note 8)	dBm (15 GHz)	–45.7			
Maximum upstream WNE-PSD (Note 9)	dBm (15 GHz)	–68.5			
Jitter transfer	–	see clause 11.1.5.4.1			
Jitter generation	–	see clause 11.1.5.4.3			
OLT receiver (optical interface R)					
ODN class		N1	N2	E1	E2
Maximum OPP (Note 10) – with Raman effects (DD20, four channel) – with Raman effects (DD40, four channel) – with Raman effects (DD20, eight channel) – with Raman effects (DD40, eight channel)	dB	 1.5 FFS FFS FFS	 1.5 FFS FFS FFS	 2.0 FFS FFS FFS	 2.0 FFS FFS FFS
Maximum reflectance at S/R-CG, measured at receiver wavelength	dB	less than −20			
Bit error ratio reference level	–	10^{-3} (Note 11)			
ODN class		N1	N2	E1	E2
Sensitivity (at S/R-CG), based on DD20, four wavelength) (Note 12)					
– Type A link (Note 3)	dBm	–26.5	–28.5	–31.0	NA
– Type B link (Note 4)	dBm	–28.5	–30.5	–33.0	–33.0
Overload (at S/R-CG)					
– Type A link (Note 3)	dBm	–5.0	–7.0	–9.0	NA
– Type B link (Note 4)	dBm	–7.0	–9.0	–11.0	–11.0
In-band crosstalk tolerance	dB (15 GHz)	30.0 (Type A link) 28.0 (Type B link)			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	see clause 11.1.5.4.2			

NOTE 1 – MSE values of other CS can be interpolated from the three given values.

NOTE 2 – N is the channel count. When using cyclic channel grid, if CS is 100 GHz, the minimum tuning windows are 500 GHz and 900 GHz for four and eight channel TWDM PONs, respectively. When using cyclic channel grid, if CS is 50 GHz, the minimum tuning windows are 250 GHz and 450 GHz for four and eight channel TWDM PONs, respectively. When not using cyclic channel grid, if CS is 100 GHz, its minimum tuning windows are 340 GHz and 740 GHz for four and eight channel TWDM PONs, respectively. When not using cyclic channel grid, if CS is 50 GHz, the minimum tuning windows are 175 GHz and 375 GHz for four and eight channel TWDM PONs, respectively.

Table 11-7 – Optical interface parameters of 9.95328 Gbit/s upstream direction

Item	Unit	Value
NOTE 3 – Type A link values assume an unamplified OLT receiver. However, an amplified OLT receiver is not precluded. NOTE 4 – Type B link values assume an amplified OLT receiver with the amplifier at the S/R-CG reference point. However, other amplifier approaches, including an unamplified OLT receiver are not precluded. NOTE 5 – A lower ER is allowed but must be compensated by a larger transmitter launch power within the limits of the "Mean launch power maximum" value. However the impact of reduced ER on OOB/OCC power must be considered. NOTE 6 – SMSR is measured on the laser output, before any filtering. This prevents a significant mode partition noise penalty. Other limitations on OOB and OOC PSD still apply to the R/S reference point. NOTE 7 – This value is based on the following assumptions: OOB impact from TWDM PON on PtP WDM PON can be controlled through appropriate filtering, 0.1 dB penalty, PtP WDM PON operates without FEC, and four interfering TWDM channels. NOTE 8 – See OOC-PSD mask in clause 9.3.9. These values are based on the following assumptions: 1 dB upstream OOC penalty, TWDM PON operates with FEC, and four TWDM channels (three interferers). In some implementations, this requirement may be achieved by more tightly regulating the transmitter output power (lowering the maximum level while maintaining the minimum level). NOTE 9 – This value is based on the following assumptions: 0.1 dB penalty, TWDM PON operates with FEC, and 64 TWDM PON ONUs in one channel (63 interferers). NOTE 10 – The specified penalty takes into account the class-specific transmitter power, distance, and number of wavelengths. The maximum OPP values assume no SR-/CG located based splitters and low optical fibre loss, resulting in the worst-case Raman effect. ODNs that include high loss elements near the OLT or higher loss optical cable will exhibit lower penalties. Suggested maximum OPP values with Raman effects for DD20 and eight channels are 1.5 dB, 2.0 dB, 2.5 dB, and 2.5 dB for N1, N2, E1, and E2 classes, respectively. NOTE 11 – See [b-ITU-T G.Sup39], clause 9.4.1 for additional details. NOTE 12 – See clause 11.1.4.3.1 for an approach to accommodate the case of 40 km and eight wavelengths.		

11.1.4.3.1 Example of upstream OPP and receiver substitution

The upstream tables specify the OLT receiver sensitivity for the base case of 20 km and four TWDM channels. As noted in the tables above, if a different application is used, then the OPPs will be different and potentially impact the optical link budget. The case of the 40 km and eight wavelengths can be accommodated by selecting the OLT receiver specified for the next available ODN class. For example, in Table 11-6, N2 class with 40 km and eight wavelengths needs an additional 1.5 dB of optical link budget. Selecting the E1 class OLT provides a 2.0 dB improvement and thereby meets the budget requirement.

11.1.5 Transmitter at reference point S

All parameters are defined as follows, and are in accordance with Table 11-4 to Table 11-7.

11.1.5.1 Source type

Considering the attenuation/dispersion characteristics of the target fibre channel, suitable transmitter devices include only single longitudinal mode (SLM) lasers. The indication of a nominal source type in this Recommendation is not a requirement though it is also expected that only SLM lasers meet all the distance and line rate requirements of both the downstream and upstream links.

11.1.5.2 Spectral characteristics

For SLM lasers, the laser is specified by its fibre dispersion range, the range over which the laser characteristics and fibre dispersion result in a defined penalty at a specified fibre distance, under standard operating conditions. Additionally, for control of mode partition noise in SLM systems, a minimum value for the laser SMSR is specified. The actual spectral characteristics are limited by the maximum amount of OPP produced with the worst-case optical dispersion in the data signal.

11.1.5.2.1 Operating wavelength band

Operating wavelength band specification options are summarized in Table 9-1.

11.1.5.2.2 Nominal central frequency

The central frequencies are based on the frequency grid given in [ITU-T G.694.1]. The downstream central frequencies are specified in Table 11-2. Examples of TWDM upstream channel grid are in Clause VIII.4.

Note that the value of "c" (speed of light in a vacuum) that is used for converting between frequency and wavelength is 2.99792458×10^8 m/s.

11.1.5.2.3 Operating channel spacing

The specified value of the operating CS is used to parameterize the spectral properties of a laser.

11.1.5.2.4 Maximum spectral excursion

The MSE is specified as a one-sided deviation from the nominal central wavelength and is expressed in gigahertz. The maximum spectral excursion requirement applies to fixed wavelength transmitters as well as tunable wavelength transmitters. For tunable wavelength transmitters, it only applies while they are in a stationary wavelength channel state.

Among the tunable transmitters, the maximum spectral excursion requirement applies to both tunable transmitters, which are under fine wavelength control of the OLT, and tunable transmitters, which are not under fine wavelength control of the OLT.

In the application to NG-PON2, MSE is the total allowable excursion due to:

- spectral width, tuning granularity, short-term wavelength drift (over one OLT-ONU tuning cycle) and tuning control errors, when tunable ONU transmitters under fine OLT control are used;
- spectral width, tuning granularity and tuning accuracy, when tunable ONU transmitters not under fine OLT control are used.

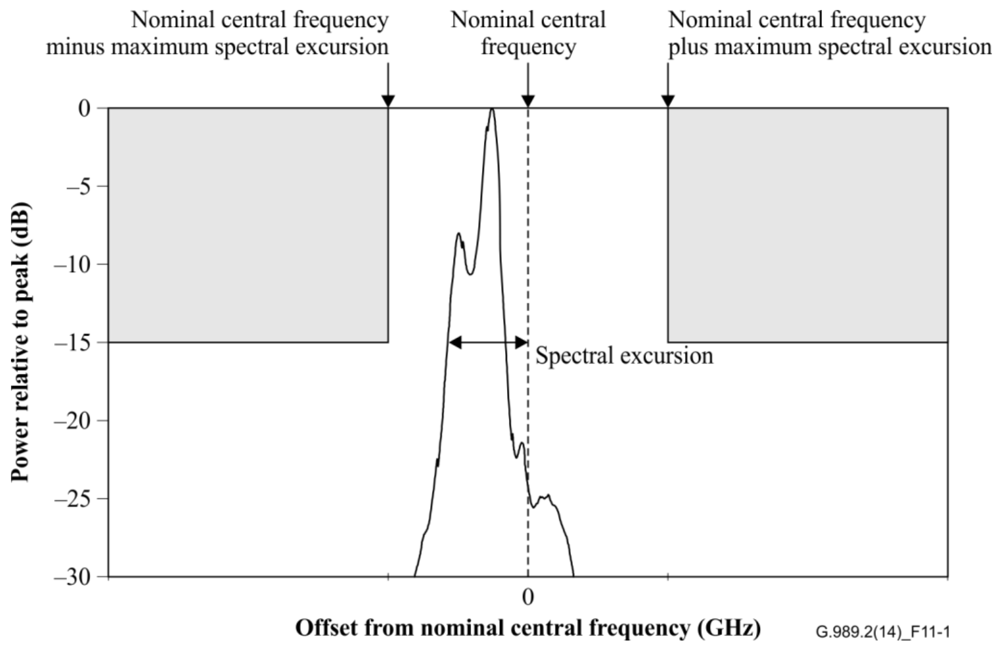


Figure 11-1 – Spectral excursion illustration

11.1.5.2.5 Minimum tuning window

The minimum tuning window is specified as a positive number in gigahertz. To satisfy the requirement, a component or device must meet or exceed the specified value.

11.1.5.2.6 Tuning granularity

The tuning granularity is specified as a positive number in gigahertz. To satisfy the requirement, a component or device must not exceed the specified value.

11.1.5.2.7 ONU transmitter power wavelength dependency

The ONU transmitter power wavelength dependency is specified as a ratio greater than one and is expressed in decibels. To satisfy the requirement a component or device must not exceed the specified value.

11.1.5.2.8 Mean launch optical power

The mean launch optical power is specified as a range to allow for some cost optimization and to cover all allowances for operation under standard operating conditions, transmitter connector degradation, measurement tolerances and ageing effects.

In the operating state, the lower figure is the minimum power to be provided and the higher one is the power never to be exceeded.

NOTE – Measurement of the launch power at the ONU reference point S optical interface must take into account the bursty nature of the upstream traffic transmitted by the ONUs.

11.1.5.2.9 Upstream optical PSD when not enabled (WNE-PSD)

In the upstream direction, the ONU transmitter ideally launches no power into the fibre in all bursts which are not assigned to that ONU. However, an optical power level less than or equal to the upstream WNE-PSD is allowed during bursts which are not assigned to that ONU. During the transmitter enable transient time immediately preceding the assigned burst, which may be used for laser pre-bias, and during the transmitter disable transient time immediately following the assigned burst, the maximum launch power level allowed is the zero level corresponding to the minimum ER and the maximum channel launch power specified in Tables 11-6 and 11-7.

The specification of the maximum transmitter enable and transmitter disable transient times is provided in Tables 11-6 and 11-7.

The relationship between ONU power levels and burst times is shown in Figure 11-2.

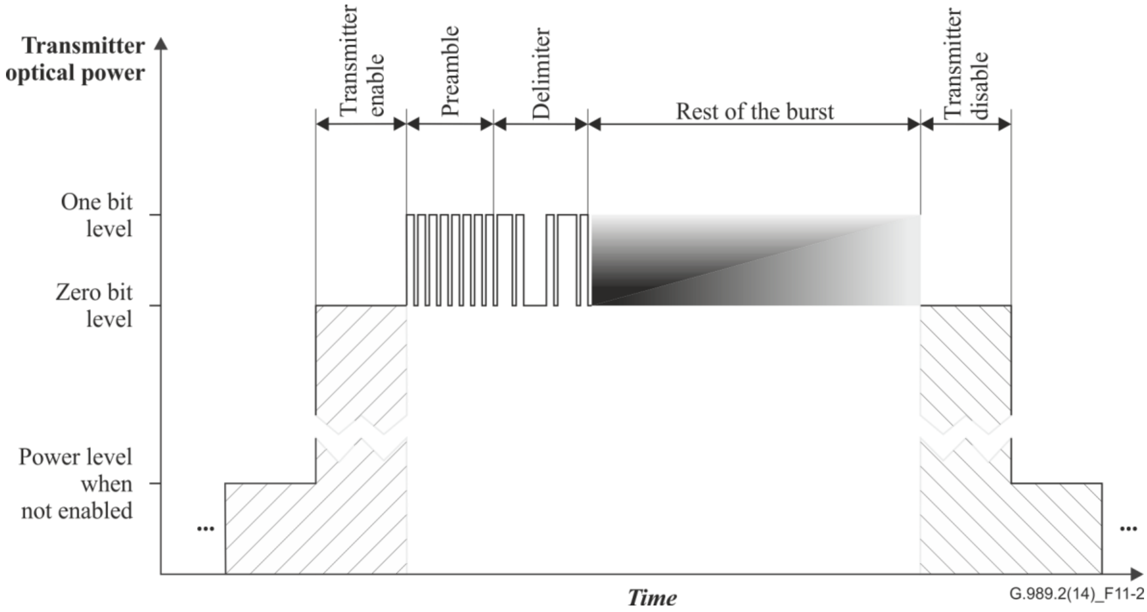


Figure 11-2 – Relationship between ONU power levels and burst times

11.1.5.3 Mask of transmitter eye diagram

This clause specifies the pulse shape characteristics for the OLT and ONU transmitters. For the purpose of assessing the transmit signal, it is important to consider not only the eye opening, but also the overshoot and undershoot limitations.

11.1.5.3.1 OLT transmitter

The parameters specifying the mask of the eye diagram (see Figure 11-3) for the OLT transmitter are shown in Table 11-8. The test set-up for the measurement of the mask of the eye diagram is shown in Figure 11-4.

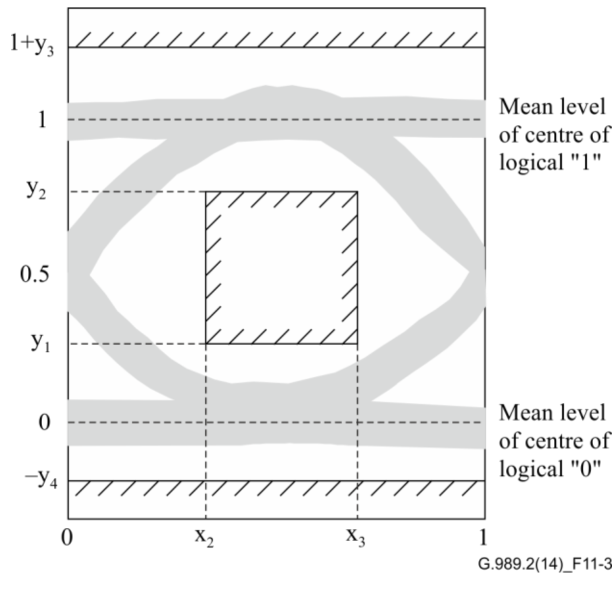
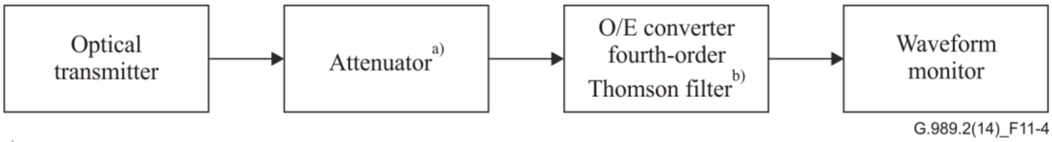


Figure 11-3 – Mask of the eye diagram for OLT transmitter

Table 11-8 – Mask of the eye diagram for OLT transmitter – numeric values

	2.48832 Gbit/s	**9.95328 Gbit/s**
x3-x2 (Note 1)	0.2	0.2
y1, y3, y4	0.25	0.25
y2	0.75	0.75
NOTE 1 – x2 and x3 of the rectangular eye mask need not be equidistant with respect to the vertical axes at 0 unit interval (UI) and 1 UI. NOTE 2 – The values are taken from [ITU-T G.959.1], clause 7.2.2.14.		



a) Attenuator is used if necessary.
b) Cut-off frequency (3 dB attenuation frequency) of the filter is 0.75 times output nominal bit rate.

Figure 11-4 – Test set-up for measuring the mask of the eye diagram for OLT transmitter

11.1.5.3.2 ONU transmitter

11.1.5.3.2.1 ONU transmitter eye diagram

The parameters specifying the mask of the eye diagram (see Figure 11-5) for the ONU transmitter are shown in Table 11-9. The test se-up for the measurement of the mask of the eye diagram is shown in Figure 11-6.

The mask of the eye diagram for the upstream direction burst mode signal is applied from the first bit of the preamble to the last bit of the burst signal, inclusive.

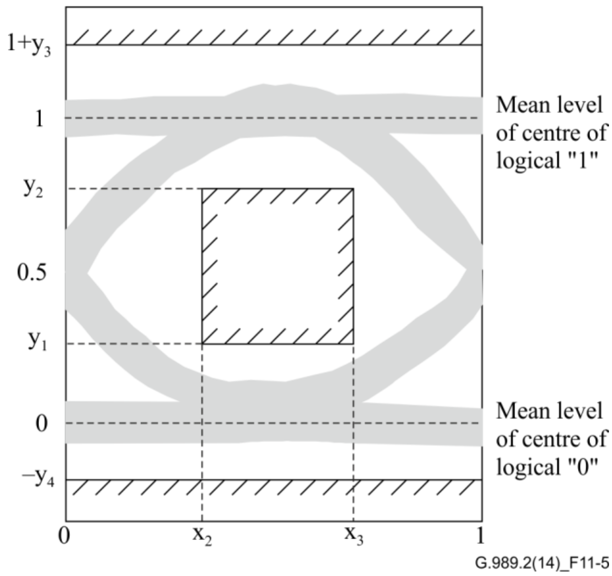
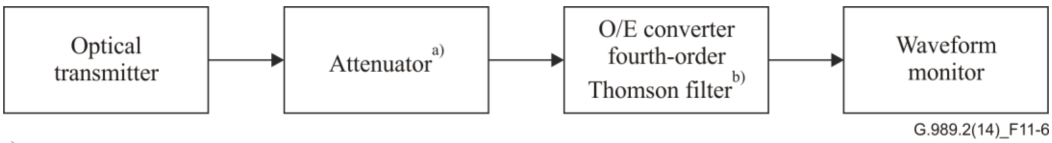


Figure 11-5 – Mask of the eye diagram for ONU transmitter

Table 11-9 – Mask of the eye diagram for ONU transmitter – numeric values

	2.48832 Gbit/s	**9.95328 Gbit/s**
x3-x2 (Note 1)	0.2	0.2
y1, y3, y4	0.25	0.25
y2	0.75	0.75
NOTE 1 – x2 and x3 of the rectangular eye mask need not be equidistant with respect to the vertical axes at 0 UI and 1 UI. NOTE 2 – The values are taken from [ITU-T G.957], clause 6.2.5.		



a) Attenuator is used if necessary.

b) Cut-off frequency (3 dB attenuation frequency) of the filter is 0.75 times output nominal bit rate.

Figure 11-6 – Test set-up for measuring the mask of the eye diagram for ONU transmitter

11.1.5.4 Jitter performance

This clause describes jitter requirements for optical interfaces of TWDM PON.

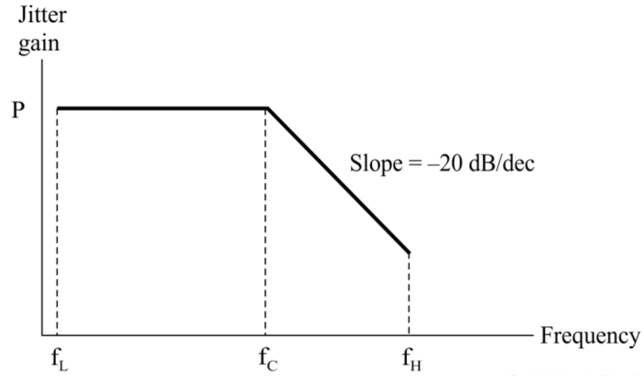
11.1.5.4.1 Jitter transfer

The jitter transfer specification applies only to the ONU.

The jitter transfer function is defined as:

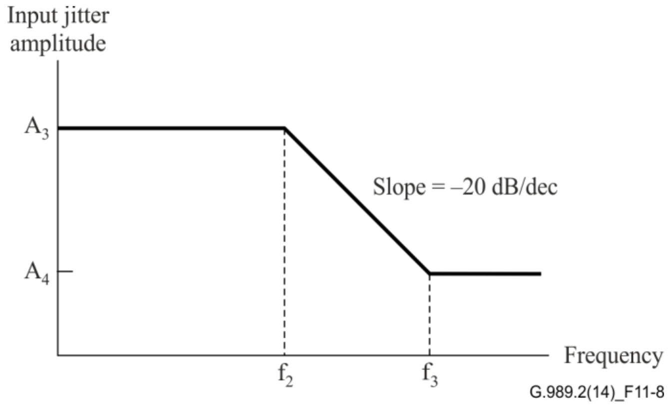
$$jitter\ transfer = 20\log_{10}\left[\frac{jitter\ on\ upstream\ signal\ UI}{jitter\ on\ downstream\ signal\ UI} \times \frac{down\ stream\ bit\ rate}{upstream\ bit\ rate}\right]$$

The jitter transfer function of an ONU shall be under the curve given in Figure 11-7, when input sinusoidal jitter up to the mask level in Figure 11-8 is applied, with the parameters specified in this figure for each line rate.



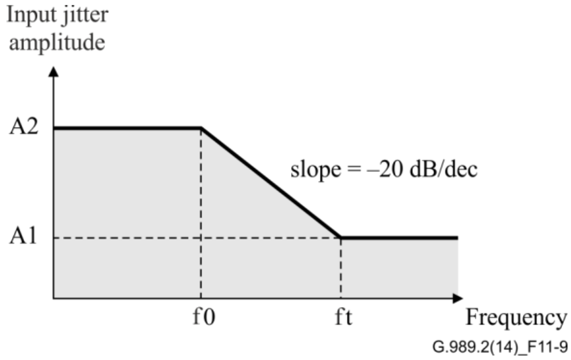
Upstream line rate (Gbit/s)	f_L (kHz)	f_C (kHz)	f_H (kHz)	P (dB)
2.48832	20	2000	20000	0.1
9.95328	10	1000	80000	0.1
NOTE – These values are taken from [ITU-T G.783].				

Figure 11-7 – Jitter transfer for ONU



Downstream line rate (Gbit/s)	A_3(UI)	A_4(UI)	f_2 (kHz)	f_3 (kHz)
2.48832	1.5	0.15	100	1000
9.95328	1.5	0.15	400	4000
NOTE – These values are taken from [ITU-T G.783].				

Figure 11-8 – High-band portion of sinusoidal jitter mask for jitter transfer



Line rate (Gbit/s)	ft (kHz)	f0 (kHz)	A1 (UIp-p)	A2 (UIp-p)
2.48832	1000	100	0.075	0.75
9.95328	4000	400	0.075	0.75
NOTE – These values are scaled to 9.95328 Gbit/s from the values in [ITU-T G.984.2].				

Figure 11-9 – Jitter tolerance mask

11.1.5.4.2 Jitter tolerance

Jitter tolerance is defined as the peak-to-peak amplitude of sinusoidal jitter applied on the input TWDM PON signal that causes a 1-dB optical power penalty at the optical receiver. Note that it is a stress test to ensure that no additional penalty is incurred under operating conditions.

The ONU must tolerate, as a minimum, the input jitter applied according to the mask in Figure 11-9, with the parameters specified in that figure for the downstream line rate. The OLT must tolerate, as a minimum, the input jitter applied according to the mask in Figure 11-9, with the parameters specified in that figure for the upstream line rate. The jitter tolerance specification for the OLT is informative as it can only be measured in a setting that permits continuous operation of the upstream.

11.1.5.4.3 Jitter generation

An ONU must not generate a peak-to-peak jitter amplitude more than shown in Table 11-10 with no jitter applied to the downstream input and with a measurement bandwidth as specified in Table 11-10. An OLT must not generate a peak-to-peak jitter amplitude more than shown in Table 11-10 with no jitter applied to its timing reference input and with a measurement band as specified in Table 11-10.

Table 11-10 – Jitter generation requirements for TWDM PON

Line rate (Gbit/s)	Measurement band (–3 dB frequencies) (Note 1)		Peak-peak amplitude (UI) (Note 2)
	high-pass (kHz)	low-pass (MHz) –60 dB/dec	
2.48832	5	20	0.30
	1000	20	0.10
9.95328	20	80	0.30
	4000	80	0.10

Table 11-10 – Jitter generation requirements for TWDM PON

Line rate (Gbit/s)	Measurement band (–3 dB frequencies) (Note 1)		Peak-peak amplitude (UI) (Note 2)
	high-pass (kHz)	low-pass (MHz) –60 dB/dec	
NOTE 1 – The high-pass and low-pass measurement filter transfer functions are defined in clause 5 of [ITU-T G.825]. NOTE 2 – The measurement time and pass/fail criteria are defined in clause 5 of [ITU-T G.825]. NOTE 3 – This table comes from [ITU-T G.783].			

11.2 Upstream physical layer overhead

Table 11-11 shows the length of the physical layer overhead bits for the upstream line rate specified in this Recommendation.

Table 11-11 – TWDM PON upstream physical layer overhead

Upstream line rate	Overhead bits
2.48832 Gbit/s	256
9.95328 Gbit/s	1024

Moreover, Appendix III provides information on the physical processes that have to be performed during the physical layer overhead time (Tplo) and some guidelines optimum use of Tplo.

Annex A

Tunable PtP WDM PON PMD layer requirements

(This annex forms an integral part of this Recommendation.)

This annex describes a PtP WDM PON system with wavelength tunability.

The characteristic of a PtP WDM PON is that each ONU is served by one pair of upstream and downstream wavelengths dedicated to this ONU. On the OLT side, downstream wavelengths are multiplexed onto a shared, bidirectional fibre connecting the wavelength WM to a branching node (BN). Figure A.1 shows a logical view of a PtP WDM PON.

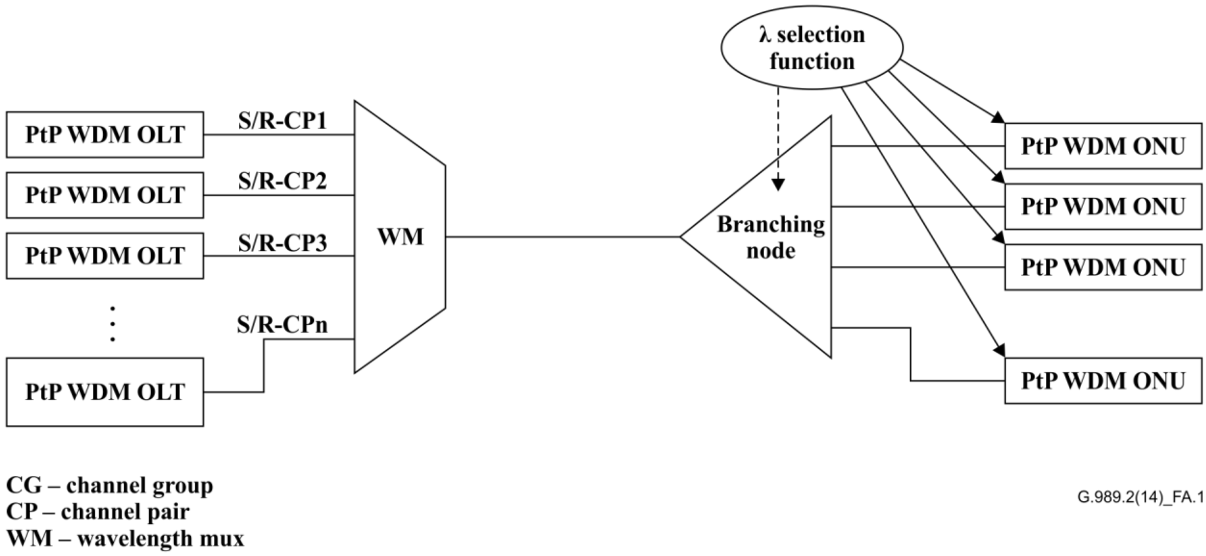


Figure A.1 – Logical architecture of a generic PtP WDM PON

Examples of PtP WDM PON clients include GbE, 10GbE and [b-CPRI]. The OLT channel pair may also exist in multiple instances, particularly to support different client types.

At a BN, the ODN branches out to drop fibres, one for each ONU. The feeder and BN may be further divided into sub-trees, and part or all of the feeder-BN tree, and even the drop fibres, may be duplicated for redundancy. The BN may include any combination of power splitters, bandpass or bandstop filters, or wavelength filters (e.g., arrayed waveguide gratings (AWGs)). Logically, a wavelength selection function is required between each port of the BN and the corresponding colourless ONU transceiver.

This wavelength selector can be located physically either within the ONU (wavelength selected case) or at a BN (wavelength routed case), giving rise to two classes of PtP WDM PON architecture:

Wavelength-selected: The λ selection function is built into the ONU. Part or all of the spectrum is available to the ONU (power split with or without bandpass filter) such that it is possible for the ONU and OLT to communicate on part or all of the spectrum. The ONU determines its wavelength in an activation process that involves the OLT. The upstream wavelength is typically established as a fixed function of the assigned downstream wavelength. This class of PtP WDM PON supports power splitter ODN.

This annex focuses on the wavelength-selected class of PtP WDM PON as an overlay to TWDM PON.

Wavelength-routed: The λ selection function is part of the BN. The ONU's wavelength is determined by its physical connectivity to the ODN, for example by a port on an AWG. Upstream and downstream wavelengths may be the same, or may differ by a multiple of the free spectral range (FSR) of the AWG. This class of PtP WDM PON supports filtered ODN.

ONUs that have no wavelength selective capability, i.e., that can only support a fully wavelength routed architecture, are out of scope of this annex.

A.1 PMD layer requirements

The PtP WDM PON system must support minimum four PtP WDM channels.

All parameters are specified as follows, and are in accordance with Table A.2 to Table A.7.

All parameter values specified are worst-case values, to be met over the range of operating conditions such as temperature and humidity, and include ageing effects, as specified in [ITU-T G.989.1]. The parameters are specified relative to a BER not worse than the values specified in Table A.2 to Table A.7, for the worst-case optical path loss (see Table 6-1) and fibre chromatic dispersion.

A.1.1 Line rate

This clause specifies the line rates required to support various PtP WDM PON clients.

Parameters to be specified are categorized by downstream and upstream, and the nominal line rates as shown in Table A.1.

The PtP WDM PON supports three classes of line rates. Each line rate applies for a symmetric service protocol, i.e., the downstream and the upstream line rates are identical for the respective service protocol. The downstream and upstream PMD parameters are specified in Table A.2 to Table A.7.

Table A.1 – Relation between PtP WDM PON line rate classes and optical parameter tables

Line rate class	Nominal line rate (Gbit/s) – Symmetric downstream and upstream	Supported UNI	Reference table downstream/upstream
1	1.24416, 1.25, 1.2288	STM-8 1G Ethernet Common public radio interface (CPRI) option 2	Table A.2/Table A.3
2	2.48832, 2.4576, 2.666	OC-48, STM-16 CPRI option 3 OTU1	Table A.4/Table A.5
3	9.95328, 9.8304, 10.709, 11.09 10.3125	OC-192, STM-64 CPRI option 7 OTU2, OTU2e 10G Ethernet	Table A.6/Table A.7
4	6.144	CPRI option 6, OBSAI	FFS

A.1.2 FEC code selection

The choice of FEC depends on the service protocol.

For CPRI, no FEC is used.

For 1 Gbit/s Ethernet services with 8b/10b coding, no FEC is used.

For 10GBASE-ER Ethernet with 64b/66b coding, no FEC is used.

For OC-48, OC-192, STM-8, STM-16 and STM-64, the inbuilt FEC according to [ITU-T G.707] and [ITU-T G.709] may be used. No extra FEC overhead is applied.

For OTU1, OTU2, and OTU2e the inbuilt FEC as of [ITU-T G.709] may be applied. No extra FEC overhead is applied.

A.1.3 Line code

Line coding for PtP WDM PON is determined by the specific application.

A.1.4 Operating wavelength

PtP WDM PON spectrum is specified according to Table 9-1, subject to spectrum otherwise assigned or in use.

Two wavelength bands for PtP WDM PON are specified:

1) Shared spectrum band: 1603-1625 nm

   Details of the sharing between TWDM PON and PtP WDM PON bands are specified in clause 9.2

2) Expanded spectrum band: 1524-1625 nm

Spectral flexibility is required to allow reuse of unoccupied bands in other coexistence scenarios where legacy bands and TWDM PON bands are available.

For the purpose of coexistence with G-PON, XG-PON1, RF video and four TWDM channels, a minimum of four PtP WDM channels is supported.

Upstream and downstream can be in separate spectral regions or share the same spectral band.

A.1.5 PMD parameters

A.1.5.1 Compatible ODN

PtP WDM PON operates over the same ODN as TWDM PON, see clause 11.1.4.1.

A.1.5.2 Optical interface parameters for line rate class 1

The following optical interface parameter tables are applicable for up to 40 km fibre length and a minimum of four PtP WDM channels.

Table A.2 – Optical interface parameters for line rate class 1 (from 1.2288 Gbit/s to 1.25 Gbit/s) downstream direction

Item	Unit	Value
OLT transmitter (optical interface S)		
Nominal line rate	Gbit/s	1.2288 to 1.25
Operating wavelength band	nm	1603-1625 (shared spectrum) 1524-1625 (expanded spectrum)
Minimum operating CS	GHz	50
Maximum operating CS	GHz	200
Maximum spectral excursion	GHz	±12.5 for 50 GHz CS ±20 for 100 GHz CS ±25 for 200 GHz CS
Line code	–	Determined by application (scrambled NRZ assumed for parameter values)

Table A.2 – Optical interface parameters for line rate class 1 (from 1.2288 Gbit/s to 1.25 Gbit/s) downstream direction

Item	Unit	Value			
Mask of the transmitter eye diagram	–	See clause A.1.6.2			
Maximum reflectance at S/R-CG, measured at transmitter wavelength	dB	NA			
Minimum ORL of ODN at S/R-CG)	dB	32			
ODN class		N1	N2	E1	E2
Mean channel launch power minimum (at S/R-CG)	dBm	–1	+1	+3	+5
Mean channel launch power maximum (at S/R-CG)	dBm	+3	+5	+7	+9
Maximum downstream WNE-PSD	dBm (15 GHz)	FFS			
Minimum ER (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^4\right]\times 20$ (DD20), 0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^4\right]\times 40$ (DD40)			
Minimum SMSR (at S/R-CP)	dB	30			
Maximum downstream per channel OOB-PSD (Note 3)	dBm (15 GHz)	–46.5			
Maximum downstream per channel OOC-PSD (Note 4)	dBm (15 GHz)	–52.1			
Jitter generation	–	see clause A.1.6.3			
ONU receiver (optical interface R)					
Maximum OPP (Note 5) – with Raman effects	dB	1.5			
Maximum reflectance at R/S, measured at receiver wavelength	dB	–20			
Bit error ratio reference level	–	10^{-12} (Note 6)			
Receiver wavelength channel tuning time		See Table 9-2			
Maximum tuning granularity	GHz	CS/20			
ODN class		N1	N2	E1	E2
Sensitivity (at R/S)	dBm	–31.5	–31.5	–31.5	–31.5
Overload (at R/S)	dBm	–10.5	–10.5	–10.5	–10.5
In-band crosstalk tolerance	dB (15 GHz)	39.3			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	see clause A.1.6.3			
NOTE 1 – A lower ER must be compensated by a larger transmitter launch power within the limits of the mean launch power maximum value.					

Table A.2 – Optical interface parameters for line rate class 1 (from 1.2288 Gbit/s to 1.25 Gbit/s) downstream direction

Item	Unit	Value
NOTE 2 – This formula [see ITU-T G.652] is used instead of the worst-case value due to the large variation of dispersion within the PtP WDM PON wavelength band. This allows implementers to build devices only to the desired dispersion specification. λ is the longest possible wavelength in each channel, in nanometer units, considering the spectral excursion. NOTE 3 – This value is based the following assumptions: OOB impact from PtP WDM PON on TWDM PON can be controlled through appropriate filtering, 0.1 dB penalty, TWDM PON operates with FEC, and eight PtP WDM channels (seven interferers). NOTE 4 – This value is based the following assumptions: OOC in downstream can be controlled through filtering from WM, 0.1 dB penalty, PtP WDM PON operates without FEC, eight PtP WDM channels (seven interferers). NOTE 5 – The specified penalty is valid up to a 40 km optical link distance. If the actual OPP is worse than the specified value, it must be compensated by the transmitter launch power increase up to the limits of the mean launch power maximum. NOTE 6 – See [b-ITU-T G.Sup39], clause 9.4.1 for additional details.		

Table A.3 – Optical interface parameters of line rate class 1 (from 1.2288 Gbit/s to 1.25 Gbit/s) upstream direction

Item	Unit	Value			
ONU transmitter (optical interface S)					
Nominal line rate	Gbit/s	1.2288 to 1.25			
Operating wavelength band	nm	1603-1625 (shared spectrum) 1524-1625 (expanded spectrum)			
Minimum tuning window	nm	Based on operating wavelength band			
Minimum operating CS	GHz	50			
Maximum operating CS	GHz	200			
Maximum spectral excursion	GHz	±12.5 for 50 GHz CS ±20 for 100 GHz CS ±25 for 200 GHz CS			
Maximum tuning granularity	GHz	CS/20			
transmitter wavelength channel tuning time	ms	see Table 9-2			
Line code	–	Determined by application (scrambled NRZ assumed for parameter values)			
Mask of the transmitter eye diagram	–	See clause A.1.6.2			
Maximum reflectance at R/S, measured at transmitter wavelength	dB	–6			
Minimum ORL of ODN at R/S	dB	32			
ODN class		N1	N2	E1	E2
Mean channel launch power minimum (at R/S)	dBm	+3	+3	+3	+3

Table A.3 – Optical interface parameters of line rate class 1 (from 1.2288 Gbit/s to 1.25 Gbit/s) upstream direction

Item	Unit	Value			
Mean channel launch power maximum (at R/S)	dBm	+8	+8	+8	+8
Minimum ER (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092 \times \lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^{4}\right] \times 20$ (DD20), 0 to $\frac{0.092 \times \lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^{4}\right] \times 40$ (DD40)			
Minimum SMSR (Note 3)	dB	30			
Maximum upstream OOB-PSD (Note 4)	dBm (15 GHz)	–59.5			
Maximum upstream OOC-PSD – OOC1 (Note 5)	dBm (15 GHz)	–33.7 for 50 GHz CS –37.5 for 100 GHz CS –41.4 for 200 GHz CS			
Maximum upstream OOC-PSD – OOC2 (Note 5)	dBm (15 GHz)	–54.5			
Jitter transfer	–	see clause A.1.6.3			
Jitter generation	–	see clause A.1.6.3			
OLT receiver (optical interface R)					
Maximum OPP (Note 6) – with Raman effects	dB	1.5			
Maximum reflectance at S/R-CG, measured at receiver wavelength	dB	–20			
Bit error ratio reference level	–	10^{-12} (Note 7)			
ODN class		N1	N2	E1	E2
Sensitivity (at S/R-CG)	dBm	–27.5	–29.5	–31.5	–33.5
Overload (at S/R-CG)	dBm	–8	–8	–8	–8
In-band crosstalk tolerance	dB (15 GHz)	34.6			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	see clause A.1.6.3			

NOTE 1 – A lower ER must be compensated by a larger transmitter launch power within the limits of the "Mean launch power maximum" value.

NOTE 2 – This formula [see ITU-T G.652] is used instead of the worst-case value due to the large variation of dispersion within the PtP WDM PON wavelength band. This allows implementers to build devices only to the desired dispersion specification. λ is the longest possible wavelength in each channel, in nanometer units, considering the spectral excursion.

NOTE 3 – For upstream, SMSR is measured on the laser output, before any filtering. This prevents a significant mode partition noise penalty. Other limitations on OOB and OOC PSD still apply to the R/S reference point.

Table A.3 – Optical interface parameters of line rate class 1 (from 1.2288 Gbit/s to 1.25 Gbit/s) upstream direction

Item	Unit	Value
NOTE 4 – This value is based the following assumptions: OOB impact from PtP WDM PON on TWDM PON can be controlled through appropriate filtering, 0.1 dB penalty, TWDM PON operates with FEC, and eight PtP WDM channels (seven interferers). NOTE 5 – This value is based the following assumptions: 1.0 dB penalty, PtP WDM PON operates without FEC, and eight PtP WDM channels (seven interferers). In some implementations, this requirement may be achieved by more tightly regulating the transmitter output power (lowering the maximum level while maintaining the minimum level). NOTE 6 – The specified penalty is valid up to a 40 km optical link distance. If the actual OPP is worse than the specified value, it must be compensated by the transmitter launch power increase up to the limits of the mean launch power maximum. NOTE 7 – See [b-ITU-T G.Sup39], clause 9.4.1 for additional details.		

A.1.5.3 Optical interface parameters for line rate class 2

The following optical interface parameter tables are applicable for up to 40 km fibre length and a minimum of four PtP WDM channels.

Table A.4 – Optical interface parameters for line rate class 2 (from 2.4576 Gbit/s to 2.666 Gbit/s) Downstream Direction

Item	Unit	Value			
OLT transmitter (optical interface S)					
Nominal line rate	Gbit/s	2.4576 to 2.666			
Operating wavelength band	nm	1603-1625 (shared spectrum) 1524-1625 (expanded spectrum)			
Minimum operating CS	GHz	50			
Maximum operating CS	GHz	200			
Maximum spectral excursion	GHz	±12.5 for 50 GHz CS ±20 for 100 GHz CS ±25 for 200 GHz CS			
Line code	–	Determined by application (scrambled NRZ assumed for parameter values)			
Mask of the transmitter eye diagram	–	see clause A.1.6.2			
Maximum reflectance at S/R-CG, measured at transmitter wavelength	dB	NA			
Minimum ORL of ODN at S/R-CG)	dB	32			
ODN class		N1	N2	E1	E2
Mean channel launch power minimum (at S/R-CG)	dBm	+3	+5	FFS	FFS
Mean channel launch power maximum (at S/R-CG)	dBm	+7	+9	FFS	FFS
Maximum downstream WNE-PSD	dBm (15 GHz)	FFS			

Table A.4 – Optical interface parameters for line rate class 2 (from 2.4576 Gbit/s to 2.666 Gbit/s) Downstream Direction

Item	Unit	Value			
Minimum ER (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092 \times \lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^4\right] \times 20$ (DD20), 0 to $\frac{0.092 \times \lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^4\right] \times 40$ (DD40)			
Minimum SMSR (at S/R-CP)	dB	30			
Maximum downstream per channel OOB-PSD (Note 3)	dBm (15 GHz)	–46.5			
Maximum downstream per channel OOC-PSD (Note 4)	dBm (15 GHz)	–52.1			
Jitter generation	–	see clause A.1.6.3			
ONU receiver (optical interface R)					
Maximum OPP (Note 5) – with Raman effects	dB	2.0			
Maximum reflectance at R/S, measured at receiver wavelength	dB	–20			
Bit error ratio reference level	–	10^{-12} (Note 6)			
Receiver wavelength channel tuning time		See Table 9-2			
Maximum tuning granularity	GHz	CS/20			
ODN class		N1	N2	E1	E2
Sensitivity (at R/S)	dBm	–28	–28	FFS	FFS
Overload (at R/S)	dBm	–7	–7	FFS	FFS
In-band crosstalk tolerance	dB (15 GHz)	43.3			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	see clause A.1.6.3			

NOTE 1 – A lower ER must be compensated by a larger transmitter launch power within the limits of the "Mean launch power maximum" value.

NOTE 2 – This formula [see ITU-T G.652] is used instead of the worst-case value due to the large variation of dispersion within the PtP WDM PON wavelength band. This allows implementers to build devices only to the desired dispersion specification. λ is the longest possible wavelength in each channel, in nanometer units, considering the spectral excursion.

NOTE 3 – This value is based the following assumptions: OOB impact from PtP WDM PON on TWDM PON can be controlled through appropriate filtering, 0.1 dB penalty, TWDM PON operates with FEC, and eight PtP WDM channels (seven interferers).

NOTE 4 – This value is based the following assumptions: OOC in downstream can be controlled through filtering from WM, 0.1 dB penalty, PtP WDM PON operates without FEC, eight PtP WDM channels (seven interferers).

Table A.4 – Optical interface parameters for line rate class 2 (from 2.4576 Gbit/s to 2.666 Gbit/s) Downstream Direction

Item	Unit	Value
NOTE 5 – The specified penalty is valid up to a 40 km optical link distance. If the actual OPP is worse than the specified value, it must be compensated by the transmitter launch power increase up to the limits of the mean launch power maximum. NOTE 6 – See [b-ITU-T G.Sup39], clause 9.4.1 for additional details.		

Table A.5 – Optical interface parameters for line rate class 2 (from 2.4576 Gbit/s to 2.666 Gbit/s) upstream direction

Item	Unit	Value			
ONU transmitter (optical interface S)					
Nominal line rate	Gbit/s	2.4576 to 2.666			
Operating wavelength band	nm	1603-1625 (shared spectrum) 1524-1625 (expanded spectrum)			
Minimum tuning window	nm	Based on operating wavelength band			
Minimum operating CS	GHz	50			
Maximum operating CS	GHz	200			
Maximum spectral excursion	GHz	±12.5 for 50 GHz CS ±20 for 100 GHz CS ±25 for 200 GHz CS			
Maximum tuning granularity	GHz	CS/20			
transmitter wavelength channel tuning time	ms	see Table 9-2			
Line code	–	Determined by application (scrambled NRZ assumed for parameter values)			
Mask of the transmitter eye diagram	–	see clause A.1.6.2			
Maximum reflectance at R/S, measured at transmitter wavelength	dB	–6			
Minimum ORL of ODN at R/S	dB	32			
ODN class		N1	N2	E1	E2
Mean channel launch power minimum (at R/S)	dBm	+3	+3	+3	+3
Mean channel launch power maximum (at R/S)	dBm	+8	+8	+8	+8
Minimum ER (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092 \times \lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^4\right] \times 20$ (DD20), 0 to $\frac{0.092 \times \lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^4\right] \times 40$ (DD40)			

Table A.5 – Optical interface parameters for line rate class 2 (from 2.4576 Gbit/s to 2.666 Gbit/s) upstream direction

Item	Unit	Value			
Minimum SMSR (Note 3)	dB	30			
Maximum upstream OOB-PSD (Assuming eight channel PtP WDM PON) (Note 4)	dBm (15 GHz)	–59.5			
Maximum upstream OOC-PSD – OOC1 (Note 5)	dBm (15 GHz)	–33.7 for 50 GHz CS –37.5 for 100 GHz CS –41.4 for 200 GHz CS			
Maximum upstream OOC-PSD – OOC2 (Note 5)	dBm (15 GHz)	–54.5			
Jitter transfer		see clause A.1.6.3			
Jitter generation	–	see clause A.1.6.3			
OLT receiver (optical interface R)					
Maximum OPP (Note 6) – with Raman effects	dB	2.0			
Maximum reflectance at S/R-CG, measured at receiver wavelength	dB	–20			
Bit error ratio reference level	–	10^{-12} (Note 7)			
ODN class		N1	N2	E1	E2
Sensitivity (at S/R-CG)	dBm	–28	–30	–32	–34
Overload (at S/R-CG)	dBm	–8	–8	–8	–8
In-band crosstalk tolerance	dB (15 GHz)	34.6			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	see clause A.1.6.3			

NOTE 1 – A lower ER must be compensated by a larger transmitter launch power within the limits of the "Mean launch power maximum" value.

NOTE 2 – This formula [see ITU-T G.652] is used instead of the worst-case value due to the large variation of dispersion within the PtP WDM PON wavelength band. This allows implementers to build devices only to the desired dispersion specification. λ is the longest possible wavelength in each channel, in nanometer units, considering the spectral excursion.

NOTE 3 – For upstream, SMSR is measured on the laser output, before any filtering. This prevents a significant mode partition noise penalty. Other limitations on OOB and OOC PSD still apply to the R/S reference point.

NOTE 4 – This value is based the following assumptions: OOB impact from PtP WDM PON on TWDM PON can be controlled through appropriate filtering, 0.1 dB penalty, TWDM PON operates with FEC, and eight PtP WDM channels (seven interferers).

NOTE 5 – This value is based the following assumptions: 1.0 dB penalty, PtP WDM PON operates without FEC, and eight PtP WDM channels (seven interferers). In some implementations, this requirement may be achieved by more tightly regulating the transmitter output power (lowering the maximum level while maintaining the minimum level).

NOTE 6 – The specified penalty is valid up to a 40 km optical link distance. If the actual OPP is worse than the specified value, it must be compensated by the transmitter launch power increase up to the limits of the mean launch power maximum.

NOTE 7 – See [b-ITU-T G.Sup39], clause 9.4.1 for additional details.

A.1.5.4 Optical interface parameters for line rate class 3

The following optical interface parameter tables are applicable for up to 40 km fibre length and a minimum of four PtP WDM channels.

Table A.6 – Optical interface parameters for line rate class 3 (from 9.8304 Gbit/s to 11.09 Gbit/s) downstream direction

Item	Unit	Value			
OLT transmitter (optical interface S)					
Nominal line rate	Gbit/s	9.8304 to 11.09			
Operating wavelength band	nm	1603-1625 (shared spectrum) 1524-1625 (expanded spectrum)			
Minimum operating CS	GHz	50			
Maximum operating CS	GHz	200			
Maximum spectral excursion	GHz	±12.5 for 50 GHz CS ±20 for 100 GHz CS ±25 for 200 GHz CS			
Line code	–	Determined by application (scrambled NRZ assumed for parameter values)			
Mask of the transmitter eye diagram	–	see A.1.6.2			
Maximum reflectance at S/R-CG, measured at transmitter wavelength	dB	NA			
Minimum ORL of ODN at S/R-CG	dB	32			
ODN class		N1	N2	E1	E2
Mean channel launch power minimum (at S/R-CG)	dBm	+7.5	FFS	FFS	FFS
Mean channel launch power maximum (at S/R-CG)	dBm	+11	FFS	FFS	FFS
Maximum downstream WNE-PSD	dBm (15 GHz)	FFS			
Minimum ER (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^{4}\right]\times 20$ (DD20), 0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^{4}\right]\times 40$ (DD40)			
Minimum SMSR (at S/R-CP)	dB	30			
Maximum downstream per channel OOB-PSD (Note 3)	dBm (15 GHz)	–46.5			
Maximum downstream per channel OOC-PSD (Note 4)	dBm (15 GHz)	–52.1			
Jitter generation	–	see clause A.1.6.3			

Table A.6 – Optical interface parameters for line rate class 3 (from 9.8304 Gbit/s to 11.09 Gbit/s) downstream direction

Item	Unit	Value			
ONU receiver (optical interface R)					
Maximum OPP (Note 5) – with Raman effects	dB	2.5			
Maximum reflectance at R/S, measured at receiver wavelength	dB	–20			
Bit error ratio reference level	–	10^{-12} (Note 6)			
Receiver wavelength channel tuning time		See Table 9-2			
Maximum tuning granularity	GHz	CS/20			
ODN class		N1	N2	E1	E2
Sensitivity (at R/S)	dBm	–23.5	FFS	FFS	FFS
Overload (at R/S)	dBm	–2.5	FFS	FFS	FFS
In-band crosstalk tolerance	dB (15 GHz)	47.8			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	see clause A.1.6.3			

NOTE 1 – A lower ER must be compensated by a larger transmitter launch power within the limits of the "Mean launch power maximum" value.

NOTE 2 – This formula [see ITU-T G.652] is used instead of the worst-case value due to the large variation of dispersion within the PtP WDM PON wavelength band. This allows implementers to build devices only to the desired dispersion specification. λ is the longest possible wavelength in each channel, in nanometer units, considering the spectral excursion.

NOTE 3 – This value is based the following assumptions: OOB impact from PtP WDM PON on TWDM PON can be controlled through appropriate filtering, 0.1 dB penalty, TWDM PON operates with FEC, and eight PtP WDM channels (seven interferers).

NOTE 4 – This value is based the following assumptions: OOC in downstream can be controlled through filtering from WM, 0.1 dB penalty, PtP WDM PON operates without FEC, eight PtP WDM channels (seven interferers).

NOTE 5 – The specified penalty is valid up to a 40 km optical link distance. If the actual OPP is worse than the specified value, it must be compensated by the transmitter launch power increase up to the limits of the mean launch power maximum.

NOTE 6 – See [b-ITU-T G.Sup39], clause 9.4.1 for additional details.

Table A.7 – Optical interface parameters for line rate class 3 (from 9.8304 Gbit/s to 11.09 Gbit/s) upstream direction

Item	Unit	Value
ONU transmitter (optical interface S)		
Nominal line rate	Gbit/s	9.8304 to 11.09
Operating wavelength band	nm	1603-1625 (shared spectrum) 1524-1625 (expanded spectrum)
Minimum tuning window	nm	Based on operating wavelength band

Table A.7 – Optical interface parameters for line rate class 3 (from 9.8304 Gbit/s to 11.09 Gbit/s) upstream direction

Item	Unit	Value			
Minimum operating CS	GHz	50			
Maximum operating CS	GHz	200			
Maximum spectral excursion	GHz	±12.5 for 50 GHz CS ±20 for 100 GHz CS ±25 for 200 GHz CS			
Maximum tuning granularity	GHz	CS/20			
transmitter wavelength channel tuning time	ms	see Table 9-2			
Line code	–	Determined by application (scrambled NRZ assumed for parameter values)			
Mask of the transmitter eye diagram	–	see clause A.1.6.2			
Maximum reflectance at R/S, measured at transmitter wavelength	dB	–6			
Minimum ORL of ODN at R/S	dB	32			
ODN class		N1	N2	E1	E2
Mean channel launch power minimum (at R/S)	dBm	+3	+3	+3	FFS
Mean channel launch power maximum (at R/S)	dBm	+8	+8	+8	FFS
Minimum ER (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092 \times \lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^4\right] \times 20$ (DD20), 0 to $\frac{0.092 \times \lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^4\right] \times 40$ (DD40)			
Minimum SMSR (Note 3)	dB	30			
Maximum upstream OOB-PSD (Note 4)	dBm (15 GHz)	–59.5			
Maximum upstream OOC-PSD – OOC1 (Note 5)	dBm (15 GHz)	–33.7 for 50 GHz CS –37.5 for 100 GHz CS –41.4 for 200 GHz CS			
Maximum upstream OOC-PSD – OOC2 (Note 5)	dBm (15 GHz)	-54.5			
Jitter transfer		see clause A.1.6.3			
Jitter generation	–	see clause A.1.6.3			
Receiver (optical interface R)					
Maximum OPP (Note 6) – with Raman effects	dB	 2.5			
Maximum reflectance at S/R-CG, measured at receiver wavelength	dB	–20			

Table A.7 – Optical interface parameters for line rate class 3 (from 9.8304 Gbit/s to 11.09 Gbit/s) upstream direction

Item	Unit	Value			
Bit error ratio reference level	–	10^{-12} (Note 7)			
ODN class		N1	N2	E1	E2
Sensitivity (at S/R-CG)	dBm	–28.5	–30.5	–32.5	FFS
Overload (at S/R-CG)	dBm	–8	–8	–8	FFS
In-band crosstalk tolerance	dB (15 GHz)	34.6			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	see clause A.1.6.3			

NOTE 1 – A lower ER must be compensated by a larger transmitter launch power within the limits of the "Mean launch power maximum" value.

NOTE 2 – This formula see [ITU-T G.652] is used instead of the worst-case value due to the large variation of dispersion within the PtP WDM PON wavelength band. This allows implementers to build devices only to the desired dispersion specification. λ is the longest possible wavelength in each channel, in nanometer units, considering the spectral excursion.

NOTE 3 – For upstream at the ONU, SMSR is measured on the laser output, before any filtering. This prevents a significant mode partition noise penalty. Other limitations on OOB and OOC power still apply to the R/S reference point.

NOTE 4 – This value is based the following assumptions: OOB impact from PtP WDM PON on TWDM PON can be controlled through appropriate filtering, 0.1 dB penalty, TWDM PON operates with FEC, and eight PtP WDM channels (seven interferers).

NOTE 5 – This value is based the following assumptions: 1.0 dB penalty, PtP WDM PON operates without FEC, and eight PtP WDM channels (seven interferers). In some implementations, this requirement may be achieved by more tightly regulating the transmitter output power (lowering the maximum level while maintaining the minimum level).

NOTE 6 – The specified penalty is valid up to a 40 km optical link distance. If the actual OPP is worse than the specified value, it must be compensated by the transmitter launch power increase up to the limits of the mean launch power maximum.

NOTE 7 – See [b-ITU-T G.Sup39], clause 9.4.1 for additional details.

All parameter values in Tables A.2 to A.7 are specified without FEC. Parameter values with FEC enabled are for further study.

A.1.6 Transmitter at reference point S

This clause follows clause 11.1.5 unless otherwise specified below.

A.1.6.1 Nominal central frequency

The nominal single channel frequencies on which the digital coded information of the particular optical wavelength channels are modulated.

The central frequencies depend on the specific WM used.

A.1.6.2 Mask of transmitter eye diagram

The parameters specifying the mask of the eye diagram for both the OLT and ONU transmitters are shown in Table A.8.

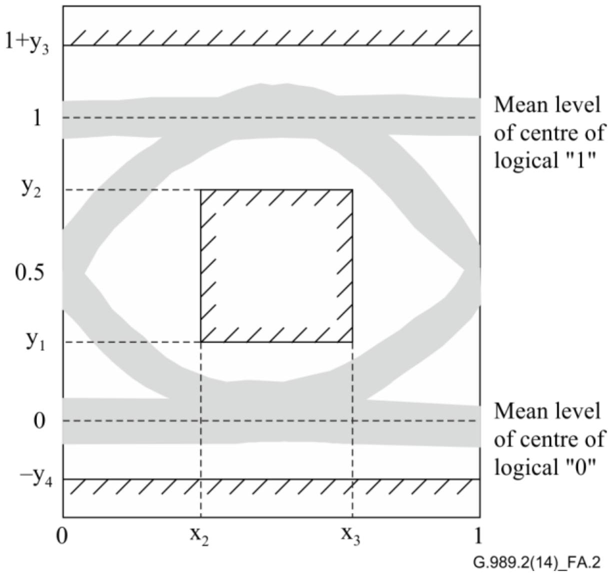


Figure A.2 – Mask of the eye diagram for OLT and ONU transmitter

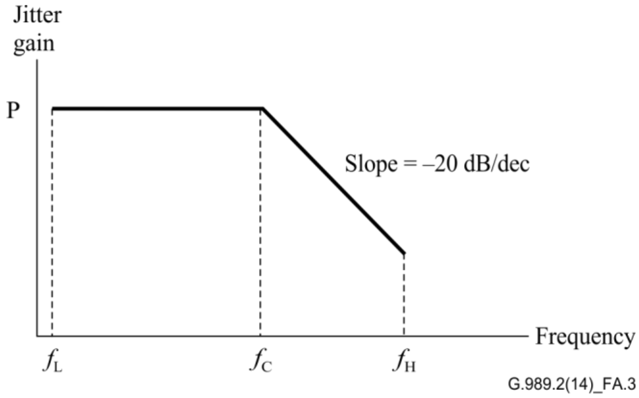
Table A.8 – Mask of the eye diagram for OLT and ONU transmitters – numeric values

Line rate class	1.25 Gbit/s	2.5 Gbit/s	10 Gbit/s
x_3-x_2 (Note 1)	0.2	0.2	0.2
y_1, y_3, y_4	0.25	0.25	0.25
y_2	0.75	0.75	0.75
NOTE 1 – x_2 and x_3 of the rectangular eye mask need not be equidistant with respect to the vertical axes at 0 UI and 1 UI. NOTE 2 – The values for the 2.5 Gbit/s and the 10 Gbit/s class are taken from [ITU-T G.959.1], clause 7.2.2.14. NOTE 3 – The values for the 1.25 Gbit/s are derived from [ITU-T G.959.1], clause 7.2.2.14.			

A.1.6.3 Jitter performance

Jitter performance of PtP WDM PON follows the definitions in clause 11.1.5.4 with the following modifications. Descriptions in clause 11.1.5.4 are repeated for completeness.

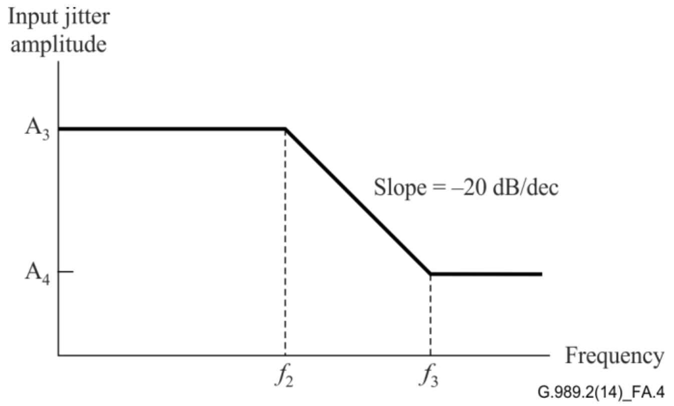
Jitter transfer for ONU is shown in Figure A.3.



Line rate class	f_L (kHz)	f_C (kHz)	f_H (kHz)	P (dB)
1	20	2000	20000	0.1
2	20	2000	20000	0.1
3	10	1000	80000	0.1
NOTE – These values are taken or derived from [ITU-T G.783].				

Figure A.3 – Jitter transfer for ONU

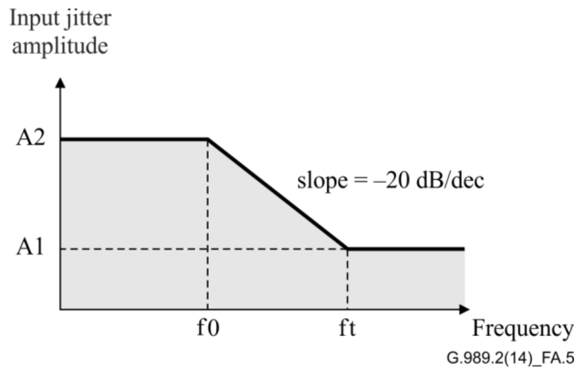
High-band portion of sinusoidal jitter mask for jitter transfer is shown in Figure A.4.



Line rate class	A_3 (UI)	A_4 (UI)	f_2 (kHz)	f_3 (kHz)
1	1.5	0.15	50	500
2	1.5	0.15	100	1000
3	1.5	0.15	400	4000
NOTE – These values are taken from [ITU-T G.783].				

Figure A.4 – High-band portion of sinusoidal jitter mask for jitter transfer

The Jitter tolerance mask is shown in Figure A.5.



Line rate class	f_t (kHz)	f_0 (kHz)	A_1 (UIp-p)	A_2 (UIp-p)
1	500	50	0.075	0.75
2	1000	100	0.075	0.75
3	4000	400	0.075	0.75
NOTE – These values are scaled to 9.95328 Gbit/s from the values in [ITU-T G.984.2].				

Figure A.5 – Jitter tolerance mask

Jitter generation requirements are shown in Table A.9.

Table A.9 – Jitter generation requirements

Line rate class	Measurement band (–3 dB frequencies) (Note 1)		Peak-peak amplitude (UI) (Note 2)
	high-pass (kHz)	**low-pass (MHz) –60 dB/dec**	
1	2.5	10	0.30
	500	10	0.10
2	5	20	0.30
	1000	20	0.10
3	20	80	0.30
	4000	80	0.10

NOTE 1 – The high-pass and low-pass measurement filter transfer functions are defined in clause 5 of [ITU-T G.825].

NOTE 2 – The measurement time and pass/fail criteria are defined in clause 5 of [ITU-T G.825].

NOTE 3 – This table comes from [ITU-T G.783]

Annex B

Auxiliary management and control channel

(This annex forms an integral part of this Recommendation.)

This annex describes the physical layer of the auxiliary management and control channel (AMCC) function for NG-PON2, which is mandatory to be implemented in the PtP WDM PON overlay channels. The AMCC must be compatible with the TWDM PON and PtP WDM PON specifications in this Recommendation's main body and Annex A.

Implementation details are for further study.

Appendix I

Wavelength considerations for NG-PON2, XG-PON1, G-PON and RF video overlay distribution services

(This appendix does not form an integral part of this Recommendation.)

When considering coexistence for NG-PON2, the following legacy PON systems were considered:

- G-PON;
- RF video overlay;
- XG-PON1;
- OTDR.

The mapping of these wavelength bands for each system is graphically shown below to provide an understanding of the considerations when coexisting with NG-PON2.

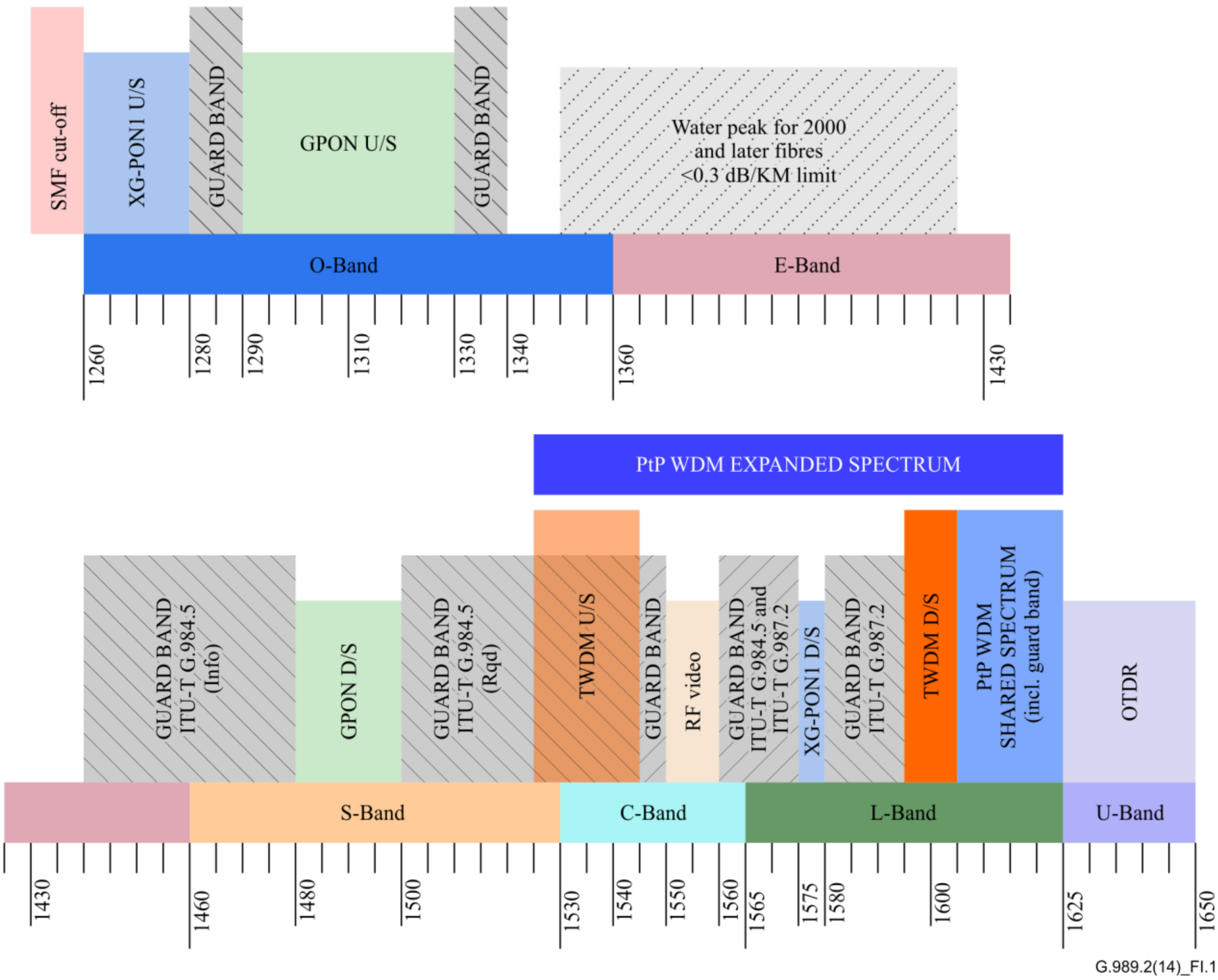


Figure I.1 – NG-PON2 wavelength plan – Coexistence representation

For legacy PONs, see Appendix I of [ITU-T G.984.5] for a generic consideration of wavelength allocation for XG-PON1, G-PON and RF video overlay distribution services.

Appendix II

Physical layer measurements required to support optical layer supervision

(This appendix does not form an integral part of this Recommendation.)

The following information was taken from Appendix IV in Amendment 2 of [ITU-T G.984.2]. Note that in addition to some changed ranges, the method of calculating the values has also changed for some parameters. These changes are indicated in this section. These functions also apply to PtP WDM PON, and further study is needed to tailor the requirements for PtP WDM PON.

Table II.1 – NG-PON2 optical digital diagnostic monitoring parameters

	Typical range (Note 1)	Resolution	Accuracy	Repeatability	Typical response time
Temperature – OLT and ONT	–45 to +90 C	0.25 C	±3 C	±1 C	1 s
Voltage – OLT and ONT (Note 4)	0 to 6.55 V	0.5% of nominal	±3% of nominal	±1% of nominal	1 s
Bias current – OLT and ONT (Note 4)	0 to 819 mA	1% of nominal	±10% of nominal	±5% of nominal	1 s
ONT transmit power	–28 to +20 dBm	0.1 dB	±3 dB	±0.5 dB (Note 2)	300 ns
ONT receive power	–53 to –4.9 dBm	0.1 dB	±3 dB (Note 5)	±0.5 dB (Note 2, 6)	300 ns
OLT transmit power	–28 to +20 dBm	0.1 dB	±2 dB	±0.5 dB (Note 2)	300 ns
OLT receive power (Note 3)	–53 to –4.9 dBm	0.1 dB	±2 dB (Note 5)	±0.5 dB (Note 2, 6)	300 ns

NOTE 1 – The typical range attempts to capture the most common range of parameters of an operational optical module. If a module has a different operational range, then the measurement range follows that range, augmented by the measurement inaccuracy on either end.

NOTE 2 – ONT and OLT optical repeatability refers to multiple measurements taken when the true values of the ONT or OLT temperature and voltage are the same at the time of measurement. However, the normal range of those parameters is exercised in between tests as a means to gauge their aging effects.

NOTE 3 – The OLT's measurement reflects the average power received during a burst. This requires the OLT to perform the measurement at the proper time with respect to the incoming burst, and that the burst is long enough to support the response time of the detector. The deviation due to non-50% duty cycle in the upstream data pattern is not to be charged against the measurement accuracy or repeatability specifications.

NOTE 4 – Nominal refers to the design value of the quantity being measured (i.e., voltage or bias current) for the particular device implementation.

NOTE 5 – Absolute accuracy is ±3 dB down to –35 dBm received optical power, and ±5 dB beyond –35 dBm.

NOTE 6 – Repeatability < 0.5 dB down to –35 dBm optical power over 1-10 second measurement time.

Transmitter bias current modifications

Originally, this parameter only covered laser "health" by monitoring the bias current to the laser. However, for NG-PON2 the parameters by which transmitter "health" is monitored has to be expanded. Currently the expectation is that some NG-PON2 solutions will encompass both EMLs and SOAs, which need to be monitored as well. Rather than adding more registers, this standard changes the single existing register into a multi-parameter register, by using the two most significant bits to code 3 types of information, as shown in Table II.2.

Table II.2 – Transmitter current monitor coding

Bit 16	Bit 15	Description
0	0	Undefined
0	1	Laser bias
1	0	SOA current
1	1	Undefined

The remaining 14 bits allow for 16384 values to be defined, using 50 µA (0.050 mA) steps.

Transmitter power modifications

The modifications to this parameter are to extend the upper and lower measurement range by adjusting the step size. By changing the step size to 1.5 µW, the ranges indicated in Table II.3 are supported.

Table II-3 – NG-PON2 optical digital diagnostic monitoring parameters

dBm		µW		Value
–28.24	=	1.5		0x00 0x01
–25.23	=	3.0		0x00 0x02
\/				\/
0	=	1e3		0x02 0x9A
0.0065	=	1.0015e3		0x02 0x9B
\/				\/
+20	=	100e3		0xFF 0xFF

Receiver power modifications

The modifications to this parameter are also to extend the upper and lower measurement range by adjusting step size. Much lower values are indicated on the lower end of the range to facilitate tuning of the ONU tunable transmitter. The parameters are specified in two ranges to allow for reasonable implementations, as indicated in Table II.1. By selecting a 0.005 µW resolution, the ranges indicated in Table II.4 are supported.

Table II.4 – NG-PON2 optical digital diagnostic monitoring parameters with 0.005 µW resolution

dBm		µW		Value
–53	=	0.005	=	0x00 0x01
–50	=	0.010	=	0x00 0x02
–48.2	=	0.015	=	0x00 0x03
\/				\/
–27.972	=	1.595	=	0x01 0x3F
–27.959	=	1.600	=	0x01 0x40
–27.945	=	1.605	=	0x01 0x41
\/				\/
–4.84	=	327.7	=	0xFF 0xFF

Appendix III

Allocation of the physical layer overhead time

(This appendix does not form an integral part of this Recommendation.)

(This appendix reference is only applicable for TWDM PON.)

The Tplo is used to accommodate five physical processes in the PON. These are: laser on/off time, timing drift tolerance, level recovery, clock recovery, and start of burst delimitation. The exact division of the physical layer time to all these functions is determined partly by constraint equations, and partly by implementation choices. This appendix reviews the constraints that the OLT must comply with, and suggests values for the discretionary values.

The Tplo can be divided into three sections with respect to what ONU data pattern is desired. For simplicity, these times can be referred to as the guard time (Tg), the preamble time (Tp) and the delimiter time (Td). During Tg, the ONU will transmit no more power than the nominal zero level. During Tp, the ONU will transmit a preamble pattern that provides the desired transition density and signal pattern for fast level and clock recovery functions. Lastly, during Td, the ONU will transmit a special data pattern with optimal autocorrelation properties that enable the OLT to find the beginning of the burst. An additional parameter of the control logic on the PON is the total peak-to-peak timing uncertainty (Tu). This uncertainty arises from variations of the time of flight caused by the fibre and component variations with temperature and other environmental factors. Figure III.1 shows the timing relationship between the various physical layer overhead times. Table III.2 gives recommended values for Tg, Tp, Td and Tplo.

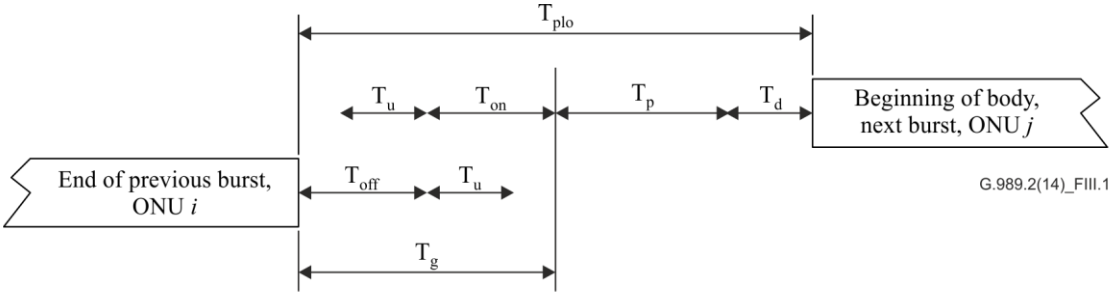


Figure III.1 – Timing relationship between the various physical layer overhead times

The constraint equations with which the OLT must comply are then:

$$Tg > Ton + Tu, \text{and}$$

$$Tg > Toff + Tu$$

These equations can be explained as follows. The first equation makes sure that the following burst's laser on ramp-up does not fall on top of the last burst's data. The second equation makes sure that the last burst's laser off tail-off does not fall on top of the following burst's preamble.

Tp must be sufficient for the physical layer to recover the signal level (essentially, setting the decision threshold) and the signal clock phase. There are many diverse design approaches to these two problems, each with its own benefits and costs. Some designs are very fast, but require an external trigger signal and produce sub-optimal error performance. Other designs are slower, but do not require a reset signal and produce bit errors that are normally distributed. In addition, each of these designs may have special requirements on the data pattern used for the preamble. Some designs prefer a maximum transition density pattern, while others prefer a pattern with a balance of transitions and controlled runs of identical digits.

Since the design is up to the OLT implementer, the OLT configures the details of the preamble that is transmitted by the ONU. This is part of the burst profile discussion below.

Td must be long enough to provide a robust delimiter function in the face of bit errors. The error resistance of the delimiter depends on the exact implementation of the pattern correlator, but a simple approximate relationship between the number of bits in the delimiter (N) and the number of bit errors tolerated (E) is:

$$E = \text{int}(N/4) - 1 \qquad \text{(III-1)}$$

Equation III-1 has been empirically verified by a numerical search of all delimiters of sizes ranging from 8 to 32 bits. This search was performed under the assumption that the preamble pattern was a "1010" repeating pattern, and that the delimiter had an equal number of zeroes and ones. The Hamming distance, D, of the best delimiter from all shifted patterns of itself and the preamble was found to be D = int(N/2) – 1; yielding the error tolerance shown.

Given a certain BER, the probability of a severely errored burst (Pseb) is given by:

$$Pseb = \binom{N}{E+1} BER^{E+1} \qquad \text{(III-2)}$$

Substituting equation III-1 into equation III-2, the resultant Pseb is given by:

$$Pseb = \binom{N}{\text{int}(N/4)} BER^{\text{int}(N/4)} \qquad \text{(III-3)}$$

If the BER equals 10^{-4}, the resultant Pseb for various delimiter lengths, N, is given in Table III.1. Inspection of this table shows that, in order to effectively suppress this kind of error, the delimiter length must be at least 16 bits long. The choice of delimiter length and pattern is made by the OLT as part of the burst profile.

Table III.1 – Probability of a severely errored burst as a function of delimiter length

N	Pseb
8	2.8×10^{-7}
12	2.2×10^{-10}
16	1.8×10^{-13}
20	1.5×10^{-16}
24	1.3×10^{-19}
32	1.1×10^{-25}
64	4.9×10^{-50}

With these considerations taken into account, the worst case and objective allocations of the physical layer overhead are given in Table III.2. This table also lists the values for the ONU transmitter enable time and transmitter disable time, and the total physical layer overhead time for reference. The worst-case values are intended to provide a reasonable bound for easy implementation, and the objective values are intended to be the design target for more efficient implementation with optimized components. These values are for a simple ODN without reach extenders. Reach extenders may require their own guard and preamble time allowances, making the total overhead larger.

Table III.2 – Recommended allocation of burst mode overhead time for TWDM PON OLT functions

	Transmitter enable (time quantum)	Transmitter disable (time quantum)	Total time, Tplo (time quantum)	Guard time, Tg (time quantum)	Preamble time, Tp (time quantum)	Delimiter time, Td (bit)
Worst case	1	1	64	4	58	64
Objective	1	1	8	2	5	32

In addition to the design dependent aspects of the burst overhead, there can be operationally dependent factors. For example, detecting an ONU's ranging burst is a more difficult problem than receiving an ONU's regular transmission. For another example, some ONUs may have higher power and are easier to detect, and therefore do not need FEC. For these reasons, the OLT may request different burst parameters depending on the context.

The concept of a burst profile captures all the aspects of burst overhead control. A burst profile specifies the preamble pattern and length, the delimiter pattern and length, and whether FEC parity is sent. The OLT establishes one or more burst profiles, and then requests a particular burst profile for each burst transmission.

The OLT has considerable latitude in setting up the profiles, because the OLT's burst receiver is sensitive to the profile parameters. Therefore, the OLT uses profiles that ensure adequate response in its burst mode receiver. However, some basic requirements from the ONU side must be met. Namely, the preamble and delimiter patterns are balanced and they have a reasonable transition density. If not, the ONU transmitter driver circuitry may be adversely affected. Also note that the preamble and delimiter patterns could differ in each profile, and this difference could be used by the OLT receiver as an in-band indication of the format of each burst (e.g., FEC active or not).

The details of distributing the burst profiles and signalling their use will be described in the transmission convergence layer specification of the ITU-T G.989 series of Recommendations.

Appendix IV

Jitter budget specifications for TWDM PON

(This appendix does not form an integral part of this Recommendation.)

See Appendix IV in [ITU-T G.987.2].

Appendix V

Measurement of TWDM PON burst mode acquisition time and burst node eye opening at OLT

(This appendix does not form an integral part of this Recommendation.)

See Appendix V in [ITU-T G.987.2] for an example using 2.48832 Gbit/s in the upstream and 9.95328 Gbit/s in the downstream. The jitter budgets for 9.95328 Gbit/s in the upstream and 2.48832 Gbit/s in the downstream are FFS. This appendix reference is only applicable for TWDM PON.

Appendix VI

Nonlinear Raman interactions in optical fibres and mitigation technologies for coexistence of multiple PONs

(This appendix does not form an integral part of this Recommendation.)

This appendix provides background information on the issues related to operating multiple PON systems on the same fibre, specifically analysis of non-linearities and optical safety. Consideration is given to G-PON (as defined in [ITU-T G.984.2]), XG-PON1 (as defined in [ITU-T G.987.2]) and the NG-PON2 systems defined in this Recommendation. Additionally consideration is also given to RF video overlay.

Nonlinear Raman interaction, i.e., stimulated Raman scattering (SRS), between optical waves propagating in a fibre is a well-known physical phenomenon that can give rise to two major undesirable effects: modulation crosstalk between the signals and power depletion of the signals at shorter wavelengths. The Raman gain spectrum in silica fibre extends to about 50 THz and the effects may be detectable between signals separated by as little as 1 THz or as much as 40 THz, as indicated in the Raman gain curve of Figure VI.1 for [ITU-T G.652] type of fibre.

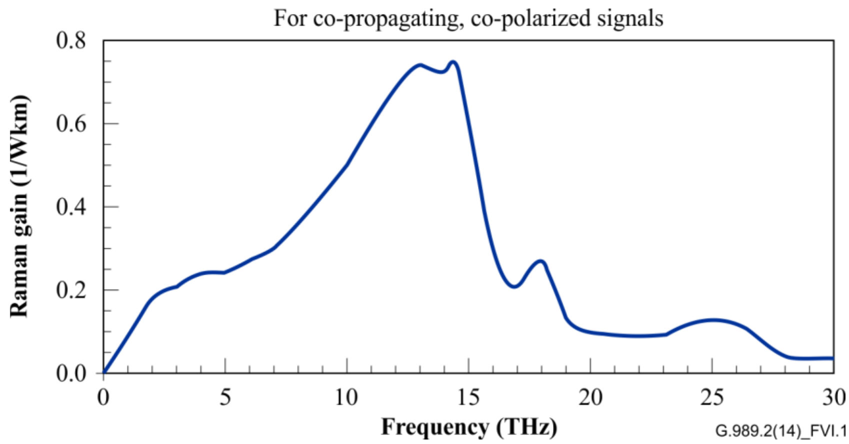


Figure VI.1 – Raman gain curve example for ITU-T G.652 type of fibre

When modulation crosstalk occurs, modulation components of one optical signal are superimposed on another optical signal at a different wavelength, which can substantially impact the information being transmitted. Modulation crosstalk due to Raman interactions only occur between co-propagating optical signals.

When optical power depletion occurs, signals at shorter wavelengths act as pump sources, i.e., experience power depletion, that amplify signals at longer wavelengths. If the optical power depletion is substantial, the quality of the transmitted information may suffer or the optical link reach may be impacted. Optical power depletion can occur in either co-propagating or counter-propagating waves in the fibre.

Mitigation techniques for nonlinear Raman interactions in optical fibres

Although SRS is an unavoidable natural phenomenon, steps can be taken to minimize its negative impacts on a multi-wavelength optical communication system. Most obvious amongst these is the prudent selection of system wavelengths, optical launch powers, and modulation formats. However, the choice of these parameters must be balanced so that other system performance requirements can be achieved as well. A number of SRS mitigation schemes have been proposed to alleviate performance impairments due to design constraints that would result in significant SRS impacts. The suggested SRS mitigation schemes include: high pass RF filtering, zero composite degree of polarization (DoP) interferer launch, dedicated transmitter, and PSD shaping.

High pass RF filtering of data signals prior to transmission (HighPassRF). The Raman crosstalk on a video RF optical carrier is primarily concerned with the lower frequency band of the RF spectrum of the TV channels. It has been proposed that the high pass filtering of the data modulation will greatly reduce the impairment caused by the SRS crosstalk while maintaining the data integrity (e.g., for a 9.95328 Gbit/s signal, attenuating the modulation spectrum below 200 MHz) With this technique, the significant attenuation of the low frequency components from the offending interferers' modulation spectra, prior to optical transmission, will reduce the RF modulation crosstalk problem and up to a 12 dB reduction in Raman crosstalk might be achievable. Figure VI.2 illustrates the HighPassRF scheme.

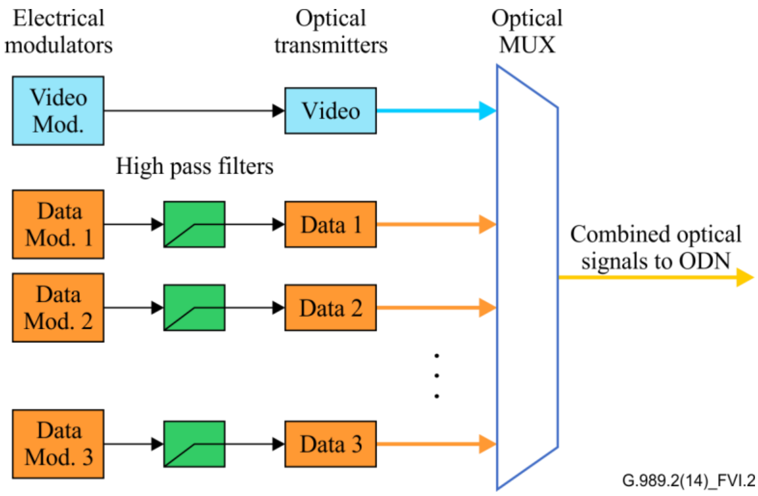


Figure VI.2 – HighPassRF – Raman crosstalk suppression scheme utilizing RF high-pass filtering of the data modulation

Zero composite DoP interferer launch (DoP0): By arranging the polarization states of the SRS interferer signals so that their weighted Stokes vectors add to zero, one creates a statistical mixture of states (signals) whose composite DoP is also zero. This statistical mixture as a whole appears to any other signal that interacts with it to be un-polarized. The zero composite DoP state also happens to be the state of maximum entropy insofar as polarization is concerned. Therefore, except for some incidental variations due to the optical fibre's polarization mode dispersion, the composite DoP of the mixture will remain very close to zero as the mixture of interferer signals propagates through any span of optical fibre. Hence, the length averaged polarization overlap probability between the mixture of interferers with any other signal, such as the RF video overlay carrier, will remain very close to 0.5 for any fibre span. This implies that, as compared to the highly unlikely case of all the interferer signals being launched in parallel to one another (DoP =1) and also to the RF video overlay signal (so that the polarization overlap probability is 1.0), the level of SRS crosstalk is 6 dB lower. Then, because of the 2:1 electrical to optical dB relationship, 3 dB more optical power could potentially be launched into the fibre for the zero composite DoP case as compared to the parallel launch 1.0 DoP case. Alternating the polarization states between two orthogonal states is one way of achieving a net weighted Stokes vector of zero. Another way is to arrange the polarization states so that the angle between consecutive Stokes vectors is 360/n, where n is the number of interferers in the mixture (this assumes equal weights for the interferers). Figure VI.3 shows the DoP0 scheme.

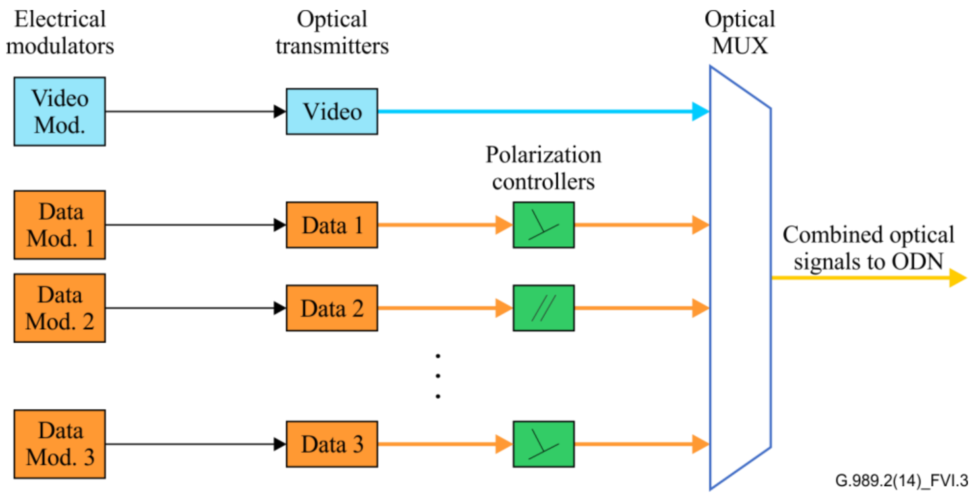


Figure VI.3 – DoP0 – Raman crosstalk suppression scheme utilizing alternating orthogonal polarization states to create a mixed state with a composite degree of polarization equal to zero

The DoP0 scheme is useful for mitigating downstream coexisting system impacts (GPON, XG-PON1, RF video overlay, etc.). When utilized, the OLT laser and WM devices are polarization controlled. In the non-integrated case, the laser is 0 degree aligned to the connector alignment pin, and the WM inputs are orthogonally aligned such that channel one is 0 degrees, channel two and channel three are 90 degrees, and then alternating thereafter every two channels. Additionally, polarization maintaining fibres must be used between the OLT transmitter and WM.

Dedicated Raman crosstalk mitigation optical transmitter (DedicatedTx): The basic scheme includes the addition to the existing system of a dedicated optical transmitter along with some passive elements at the OLT. The modulation on this dedicated Raman crosstalk suppression transmitter is appropriately prepared by the selection of its wavelength and launch power, and is also electrically modulated with properly polarized composite, yet bandwidth limited (e.g., 100 MHz for a 9.95328 Gbit/s data modulation) reproductions of the offending baseband digital modulation signals. This greatly simplifies the design of the composite modulation conditioning circuitry and also reduces the cost of the equalizer laser transmitter. The system utilizes destructive interference between the individual interferer transmitters' modulations and the terms of the composite modulation imparted upon the equalizer laser transmitter. This will effectively cancel the deleterious Raman crosstalk noise and restore the integrity of the transmitted video information. The proposed solution thereby allows for the coexistence of an optical carrier transporting television channels with co-propagating optical signals that are modulated with baseband digital traffic on the same optical distribution network. Utilizing the Raman crosstalk mitigation technology described here, the video carrier-to-Raman crosstalk ratio (CCR) can potentially be improved by 12 up to 14 dB at the low end of the RF frequency spectrum where the impact of this effect is most damaging. This system is equally effective at cancelling out the Raman crosstalk noise of incoherent or coherently related interferers. Figure VI.4 shows the DedicatedTx scheme.

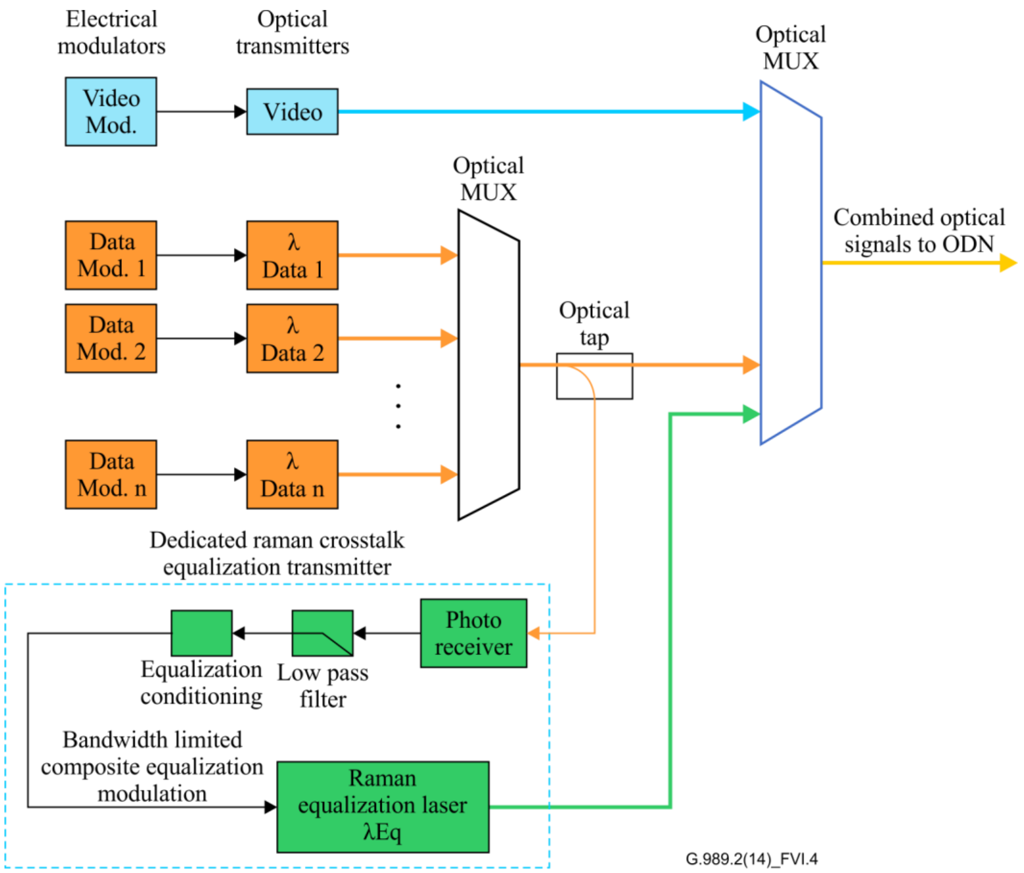


Figure VI.4 DedicatedTx – Raman crosstalk cancellation scheme utilizing a dedicated crosstalk mitigation transmitter

Power spectral density shaping (PSD-S): The principle of this technique is to mitigate or avoid PSD overlapping between legacy binary PON signal (scrambled NRZ coding) and RF video overlay signal, by means of implementing flexible digital signalling processing (DSP) functions. DSP here is understood as a general purpose mechanism for information and symbol processing designated to perform spectrum shaping by appropriate pulse shaping, data rate [b-Kim], line code [b-Al-Qazwini], or modulation schemes. Figure VI.5 shows the impact of these factors on the SRS crosstalk. Figure VI.5 assumes 0 dBm at the receiver. Frequencies up to 300 MHz are the ones more directly affecting the crosstalk in systems with 10 to 20 km reach.

The pulse repetition rate, related to the data rate, affects the PSD directly influencing the average power and introducing a set of dips in the power spectrum. The first frequency dips usually appear at frequencies related to the data rate. For NRZ, the dips appear at the baud rate frequency, for example, 2.5 Gbaud/s has the first dip at 2.5 GHz. Higher data rates for the same pulse shaping will result in lower PSDs at the lower frequencies and the appearance of the first dip at higher frequencies.

Line coding can be also used to reshape the spectrum and further change the operational margins as what relates RF video overlay crosstalk. However, this solution usually requires an overhead which will result in bandwidth efficiency loss.

When designing a system where RF video overlay coexistence is required, the potential impacts of all the above mentioned parameters need to be considered and the required margins may need to be recalculated. With tighter spectral control (done by a window function) and up-conversion (done by shifting the digital baseband signal to an upper spectrum location), the use of spectrum shaping therefore would enable a clearly separated and isolated signal spectrum that does not overlap with the spectral interference region of the RF signal, thus mitigating co-propagation Raman crosstalk effects in coexistence scenarios.

In best practice, the DSP functions used for spectrum shaping can be integrated into current TWDM PON architecture by merging DSP logic into the transmission convergence adaptation sublayer (as shown in Figure VI.6). The DSP logic can be programmable and can be enabled or disabled for backward compatibility with NRZ coding. Moreover, the optics for TWDM PON can also be reused with proper optimization to accommodate such spectrum shaping. Since DSP functions can be flexibly selected and software-defined, many other non-NRZ coding schemes and digital filtering functions can also be supported in this architecture, leading to different levels of performance for particular applications.

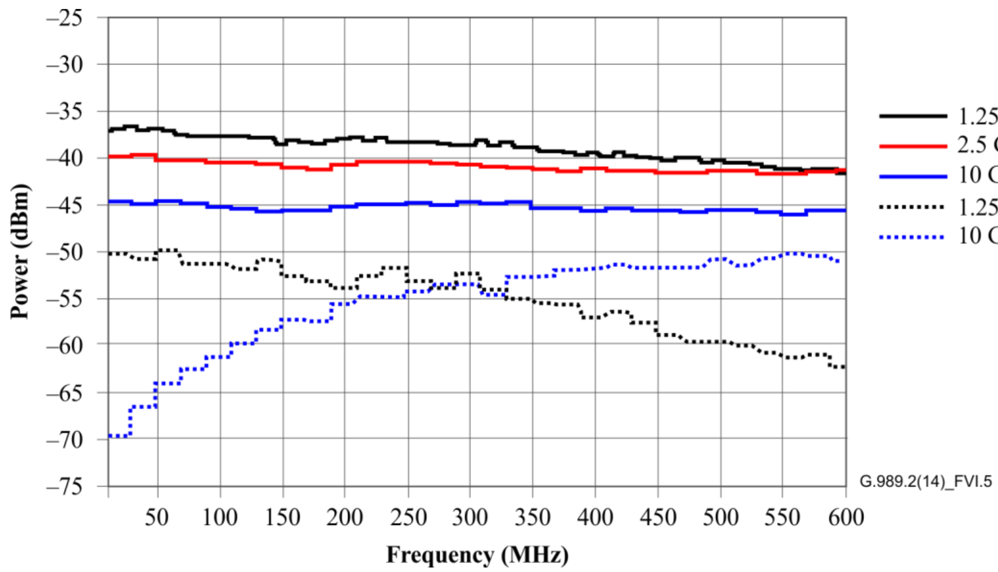


Figure VI.5 – Measured RF spectrum of several data rates, modulation formats and codings

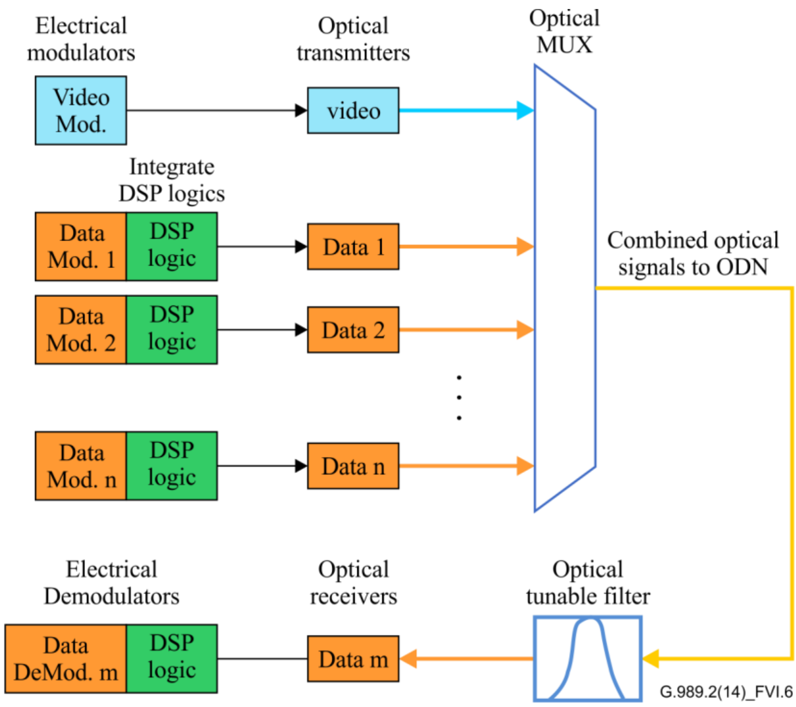


Figure VI.6 – PDS shaping scheme utilizing integrated DSP logic architecture

Appendix VII

Cyclic AWG channel grid design examples

(This appendix does not form an integral part of this Recommendation.)

This appendix provides examples of the NG-PON2 cyclic AWG channel grid design. It lists the channel grids of the TWDM PON downstream (1596 nm to 1603 nm), TWDM PON upstream (1524 nm to 1544 nm), and PtP WDM PON (1603 nm to 1625 nm). Values in this appendix are derived assuming certain device fabrication process parameters. Other values can be derived for different fabrication process parameters.

VII.1 Example AWG channel grid for 8-skip-0 at 100 GHz channel spacing

The channel grid is defined with consideration to the following aspects:

- channel spacing at 100 GHz for TWDM PON upstream/downstream with channel 196.3 THz as the reference channel;
- a port count of eight to work with tunable lasers with tuning window of 800 GHz or wider in ONUs;
- a guardband of about 800 GHz, i.e., from about 1603 nm to about 1609 nm, is reserved between the TWDM downstream and PtP WDM channels.

The main reference channel is defined in the centre of M = 0 order at $f_{0,0}$ = 196.3 THz. M is the refractive order. It is a positive or negative integer including 0. The reference channel in order M is defined at $f_{0,M} = f_{0,0} + M \cdot \text{FSR}$, with FSR = 0.800989 THz. The CS Δf_M within an order M is constant and defined to be as below:

$\Delta f_{M,100} = 100\text{ GHz} + M \cdot \Delta f_{step,100}$ for a nominal spacing of 100 GHz in the 0th order.

The difference between the frequency spacing of two adjacent refractive orders is:

$\Delta f_{step,100} = 0.416$ GHz for a nominal spacing of 100 GHz in the 0th order

The central frequency of channel n in the refractive order M for a nominal CS is defined to be:

$$f_{n,M,CS} = f_{0,0} + M \cdot \text{FSR} + n \cdot \Delta f_{M,CS}$$

where *n* is a positive or negative integer including 0. Due to the limited spectral range of each refractive order, *n* is limited as follows:

$-4 \le n \le 3$ for a nominal spacing of 100 GHz in the 0th order.

In applications using cyclic AWGs, the channels #n of all orders are assigned to the same demultiplex port of the AWG. These specifications result in the reference frequencies and wavelengths for TWDM PON and PtP WDM PON as shown in Tables VII.1 to VII.3.

Table VII.1 – Reference frequencies and wavelengths of TWDM PON upstream channels in the 8-skip-0 AWG at nominal spacing of 100 GHz

M0			M-1			M-2		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
195.900	1530.334	100.000	195.101	1536.604	99.584	194.301	1542.925	99.168
196.000	1529.553	100.000	195.200	1535.820	99.584	194.401	1542.138	99.168
196.100	1528.773	100.000	195.300	1535.037	99.584	194.500	1541.352	99.168
196.200	1527.994	100.000	195.399	1534.255	99.584	194.599	1540.566	99.168
196.300	1527.216	100.000	195.499	1533.473	99.584	194.698	1539.782	99.168
196.400	1526.438	100.000	195.599	1532.692	99.584	194.797	1538.998	99.168
196.500	1525.661	100.000	195.698	1531.912	99.584	194.896	1538.215	99.168
196.600	1524.885		195.798	1531.133		194.996	1537.433	

Table VII.2 – Reference frequencies and wavelengths of TWDM PON downstream channels in the 8-skip-0 AWG at nominal spacing of 100 GHz

M-11		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)
187.107	1602.248	95.422
187.203	1601.431	95.422
187.298	1600.615	95.422
187.394	1599.800	95.422
187.489	1598.986	95.422
187.585	1598.172	95.422
187.680	1597.360	95.422
187.775	1596.548	

Table VII.3 – Reference frequencies and wavelengths of PtP WDM channels in the 8-skip-0 AWG at nominal spacing of 100 GHz

M-13			M-14		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
185.509	1616.055	94.589	184.709	1623.049	94.173
185.603	1615.232	94.589	184.804	1622.222	94.173
185.698	1614.409	94.589	184.898	1621.395	94.173
185.793	1613.587	94.589	184.992	1620.570	94.173
185.887	1612.766	94.590	185.086	1619.745	94.173
185.982	1611.946	94.590	185.180	1618.922	94.173
186.076	1611.126	94.590	185.275	1618.099	94.174
186.171	1610.308		185.369	1617.277	

NOTE – M-13 is recommended for upstream, M-14 is recommended for downstream.

VII.2 Example AWG channel grid for 4-skip-0 at 100 GHz channel spacing

The channel grid is defined with consideration to the following aspects:

- channel spacing at 100 GHz for TWDM PON upstream/downstream with reference channel at 196.5 THz;
- a port count of four to support tunable lasers with tuning window of up to 500 GHz;
- a guardband of about 800 GHz is reserved between the TWDM PON downstream and PtP WDM channels.

The main reference channel is $f_{0,0} = 196.5$ THz. The reference channel in order M is defined at $f_{0,M} = f_{0,0} + M \cdot \mathrm{FSR}$. FSR is 0.40007 THz. The CS Δf_M within an order M is constant and defined to be as below:

$$\Delta f_{M,100} = 100\text{ GHz} + M \cdot \Delta f_{step,100}$$ for a nominal spacing of 100 GHz in the 0th order.

The difference between the frequency spacing of two adjacent refractive orders is:

$$\Delta f_{step,100} = 0.208\text{ GHz}$$ for a nominal spacing of 100 GHz in the 0th order.

The central frequency of channel n in the refractive order M for a nominal CS is defined to be:

$$f_{n,M,CS} = f_{0,0} + M \cdot \mathrm{FSR} + n \cdot \Delta f_{M,CS}$$

where n is a positive or negative integer including 0. Due to the limited spectral range of each refractive order, n is limited as follows:

$-2 \le n \le 1$ for a nominal spacing of 100 GHz in the 0th order.

In applications using cyclic AWGs, the channels #n of all orders are assigned to the same demultiplex port of the AWG. These specifications result in the reference frequencies and wavelengths for TWDM PON and PtP WDM PON as shown in Tables VII.4 to VII.6.

Table VII.4 – Reference frequencies and wavelengths of TWDM PON upstream channels in the 4-skip-0 AWG at nominal spacing of 100 GHz

M0			M-1			M-2		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
196.300	1527.216	100.000	195.900	1530.331	99.792	195.501	1533.460	99.584
196.400	1526.438	100.000	196.000	1529.552	99.792	195.600	1532.679	99.584
196.500	1525.661	100.000	196.100	1528.774	99.792	195.700	1531.899	99.584
196.600	1524.885		196.200	1527.996		195.799	1531.120	

M-3			M-4			M-5		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
195.101	1536.601	99.376	194.701	1539.755	99.168	194.302	1542.922	98.960
195.200	1535.819	99.376	194.801	1538.971	99.168	194.401	1542.137	98.960
195.300	1535.037	99.376	194.900	1538.188	99.168	194.500	1541.352	98.961
195.399	1534.257		194.999	1537.406		194.599	1540.568	

Table VII.5 – Reference frequencies and wavelengths of TWDM PON downstream channels in the 4-skip-0 AWG at nominal spacing of 100 GHz

M-22			M-23		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
187.508	1598.828	95.426	187.108	1602.243	95.218
187.603	1598.015	95.426	187.203	1601.428	95.218
187.698	1597.202	95.426	187.298	1600.614	95.218
187.794	1596.391		187.394	1599.801	

Table VII.6 – Reference frequencies and wavelengths of PtP WDM channels in the 4-skip-0 AWG at nominal spacing of 100 GHz

M-26			M-27		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
185.909	1612.576	94.594	185.509	1616.050	94.387
186.004	1611.756	94.595	185.604	1615.229	94.387
186.098	1610.937	94.595	185.698	1614.408	94.387
186.193	1610.119		185.793	1613.587	

M-28			M-29		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
185.110	1619.539	94.179	184.710	1623.044	93.971
185.204	1618.716	94.179	184.804	1622.218	93.971
185.298	1617.893	94.179	184.898	1621.394	93.971
185.392	1617.071		184.992	1620.570	

NOTE – M-26 is recommended for upstream, M-29 is recommended for downstream.

VII.3 Example AWG channel grid for 8-skip-0 at 50 GHz channel spacing

The channel grid is defined with consideration to the following aspects:

- channel spacing at 50 GHz for TWDM PON upstream/downstream, with reference channel at 196.45 THz;
- a port count of eight to support tunable lasers with tuning window of up to 500 GHz;
- a guardband of about 800 GHz is reserved between the TWDM PON downstream and PtP WDM channels.

The main reference channel is defined in the centre of M = 0 order at $f_{0,0}$ = 196.45 THz. The reference channel in the order M is defined at $f_{0,M} = f_{0,0} + M \cdot FSR$. The FSR is 0.399967 THz. The CS Δf_M within an order M is constant and defined to be as below:

$\Delta f_{M,50} = 50\ \text{GHz} + M \cdot \Delta f_{step,50}$ for a nominal spacing of 50 GHz in the 0th order.

The difference between the frequency spacing of two adjacent refractive orders is:

$\Delta f_{step,50} = 0.104$ GHz for a nominal spacing of 50 GHz in the 0th order.

The central frequency of channel n in the refractive order M for a nominal CS is defined to be

$f_{n,M,CS} = f_{0,0} + M \cdot \text{FSR} + n \cdot \Delta f_{M,CS}$

where n is a positive or negative integer including 0. Due to the limited spectral range of each refractive order, n is limited as follows:

$-4 \le n \le 3$ for a nominal spacing of 50 GHz in the 0th order.

In applications using cyclic AWGs, the channels #n of all orders are assigned to the same demultiplex port of the AWG. These specifications result in the reference frequencies and wavelengths for TWDM PON and PtP WDM PON as shown in Tables VII.7 to VII.9.

Table VII.7 – Reference frequencies and wavelengths of TWDM PON upstream channels in the 8-skip-0 AWG at nominal spacing of 50 GHz

M0			M-1			M-2		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
196.250	1527.605	50.000	195.850	1530.721	49.896	195.451	1533.850	49.792
196.300	1527.216	50.000	195.900	1530.331	49.896	195.501	1533.460	49.792
196.350	1526.827	50.000	195.950	1529.942	49.896	195.550	1533.069	49.792
196.400	1526.438	50.000	196.000	1529.552	49.896	195.600	1532.679	49.792
196.450	1526.050	50.000	196.050	1529.163	49.896	195.650	1532.289	49.792
196.500	1525.661	50.000	196.100	1528.774	49.896	195.700	1531.899	49.792
196.550	1525.273	50.000	196.150	1528.385	49.896	195.750	1531.510	49.792
196.600	1524.885		196.200	1527.996		195.799	1531.120	

M-3			M-4			M-5		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
195.051	1536.992	49.688	194.652	1540.147	49.584	194.252	1543.315	49.480
195.101	1536.601	49.688	194.701	1539.755	49.584	194.302	1542.922	49.480
195.151	1536.210	49.688	194.751	1539.363	49.584	194.351	1542.529	49.480
195.200	1535.819	49.688	194.801	1538.971	49.584	194.401	1542.137	49.480
195.250	1535.428	49.688	194.850	1538.580	49.584	194.450	1541.744	49.480
195.300	1535.037	49.688	194.900	1538.188	49.584	194.500	1541.352	49.480
195.349	1534.647	49.688	194.949	1537.797	49.584	194.549	1540.960	49.480
195.399	1534.257		194.999	1537.406		194.599	1540.568	

Table VII.8 – Reference frequencies and wavelengths of TWDM PON downstream channels in the 8-skip-0 AWG at nominal spacing of 50 GHz

M-22			M-23		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
187.460	1599.235	47.713	187.060	1602.651	47.609
187.508	1598.828	47.713	187.108	1602.243	47.609
187.555	1598.422	47.713	187.156	1601.836	47.609
187.603	1598.015	47.713	187.203	1601.428	47.609
187.651	1597.609	47.713	187.251	1601.021	47.609
187.698	1597.203	47.713	187.298	1600.614	47.609
187.746	1596.797	47.713	187.346	1600.208	47.609
187.794	1596.391		187.394	1599.801	

Table VII.9 – Reference frequencies and wavelengths of PtP WDM channels in the 8-skip-0 AWG at nominal spacing of 50 GHz

M-26			M-27		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
185.862	1612.987	47.297	185.462	1616.462	47.193
185.909	1612.577	47.297	185.509	1616.051	47.193
185.956	1612.166	47.297	185.557	1615.640	47.193
186.004	1611.756	47.297	185.604	1615.229	47.193
186.051	1611.347	47.297	185.651	1614.818	47.193
186.098	1610.937	47.297	185.698	1614.408	47.193
186.145	1610.528	47.297	185.745	1613.998	47.193
186.193	1610.119		185.792	1613.588	

M-28			M-29		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
185.063	1619.952	47.089	184.663	1623.457	46.985
185.110	1619.540	47.089	184.710	1623.044	46.985
185.157	1619.128	47.089	184.757	1622.631	46.985
185.204	1618.716	47.089	184.804	1622.219	46.985
185.251	1618.305	47.089	184.851	1621.806	46.985
185.298	1617.893	47.089	184.898	1621.394	46.985
185.345	1617.482	47.089	184.945	1620.982	46.985
185.392	1617.072		184.992	1620.571	

NOTE – M-26 is recommended for upstream, M-29 is recommended for downstream.

VII.4 Example AWG channel grid for 4-skip-0 at 50 GHz channel spacing

The channel grid is defined with consideration to the following aspects:

- channel spacing at 50 GHz for TWDM upstream/downstream, with reference channel at 196.55 THz;
- a port count of four to support tunable lasers with tuning window of up to 500 GHz;
- a guardband of about 800 GHz is reserved between the TWDM PON downstream and PtP WDM channels.

The main reference channel is $f_{0,0}$ = 196.55 THz. The reference channel in the order M is defined at $f_{0,M} = f_{0,0} + M \cdot FSR$. The FSR is 0.200085 THz. The CS Δf_M within an order M is constant and defined to be as below:

$\Delta f_{M,50} = 50\text{ GHz} + M \cdot \Delta f_{step,50}$ for a nominal spacing of 50 GHz in the 0th order.

The difference between the frequency spacing of two adjacent refractive orders is:

$\Delta f_{step,50} = 0.052$ GHz for a nominal spacing of 50 GHz in the 0th order.

The central frequency of channel n in the refractive order M for a nominal CS is defined to be:

$$f_{n,M,CS} = f_{0,0} + M \cdot FSR + n \cdot \Delta f_{M,CS}$$

where *n* is a positive or negative integer including 0. Due to the limited spectral range of each refractive order, *n* is limited as follows:

$-2 \le n \le 1$ for a nominal spacing of 50 GHz in the 0th order.

In applications using cyclic AWGs, the channels #n of all orders are assigned to the same demultiplex port of the AWG. These specifications result in the reference frequencies and wavelengths for TWDM PON and PtP WDM PON as shown in Tables VII.10 to VII.12.

Table VII.10 – Reference frequencies and wavelengths of TWDM PON upstream channels in the 4-skip-0 AWG at nominal spacing of 50 GHz

M0			M-1			M-2		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
196.450	1526.050	50.000	196.250	1527.605	49.948	196.050	1529.163	49.896
196.500	1525.661	50.000	196.300	1527.216	49.948	196.100	1528.774	49.896
196.550	1525.273	50.000	196.350	1526.828	49.948	196.150	1528.385	49.896
196.600	1524.885		196.400	1526.439		196.200	1527.996	

M-3			M-4			M-5		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
195.850	1530.724	49.844	195.650	1532.289	49.792	195.450	1533.857	49.740
195.900	1530.335	49.844	195.700	1531.899	49.792	195.500	1533.467	49.740
195.950	1529.946	49.844	195.750	1531.509	49.792	195.550	1533.077	49.740
196.000	1529.557		195.799	1531.120		195.599	1532.687	

M-6			M-7			M-8		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
195.250	1535.428	49.688	195.050	1537.002	49.636	194.850	1538.580	49.584
195.300	1535.037	49.688	195.100	1536.611	49.636	194.900	1538.188	49.584
195.349	1534.647	49.688	195.149	1536.220	49.636	194.949	1537.797	49.584
195.399	1534.257		195.199	1535.830		194.999	1537.406	

M-9			M-10			M-11		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
194.650	1540.160	49.532	194.450	1541.744	49.480	194.250	1543.331	49.428
194.700	1539.768	49.532	194.500	1541.352	49.480	194.300	1542.939	49.428
194.749	1539.377	49.532	194.549	1540.960	49.480	194.349	1542.546	49.428
194.799	1538.985		194.599	1540.568		194.398	1542.154	

Table VII.11 – Reference frequencies and wavelengths of TWDM PON downstream channels in the 4-skip-0 AWG at nominal spacing of 50 GHz

M-44			M-45		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
187.651	1597.608	47.714	187.451	1599.312	47.662
187.699	1597.202	47.714	187.499	1598.906	47.662
187.746	1596.796	47.714	187.546	1598.500	47.662
187.794	1596.390		187.594	1598.093	

M-46			M-47		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
187.251	1601.020	47.610	187.051	1602.732	47.558
187.298	1600.613	47.610	187.098	1602.325	47.558
187.346	1600.207	47.610	187.146	1601.918	47.558
187.394	1599.800		187.194	1601.511	

Table VII.12 – Reference frequencies and wavelengths of PtP WDM channels in the 4-skip-0 AWG at nominal spacing of 50 GHz

M-52			M-53		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
186.051	1611.346	47.298	185.851	1613.080	47.246
186.098	1610.936	47.298	185.898	1612.670	47.246
186.146	1610.527	47.298	185.945	1612.260	47.246
186.193	1610.118		185.993	1611.850	

M-54			M-55		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
185.651	1614.817	47.194	185.451	1616.559	47.142
185.698	1614.407	47.194	185.498	1616.148	47.142
185.745	1613.997	47.194	185.545	1615.737	47.142
185.793	1613.587		185.592	1615.327	

M-56			M-57		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
185.251	1618.304	47.090	185.051	1620.053	47.038
185.298	1617.892	47.090	185.098	1619.641	47.038
185.345	1617.481	47.090	185.145	1619.229	47.038
185.392	1617.071		185.192	1618.818	

M-58			M-59		
Frequency (THz)	Wavelength (nm)	Spacing (GHz)	Frequency (THz)	Wavelength (nm)	Spacing (GHz)
184.851	1621.805	46.986	184.651	1623.562	46.934
184.898	1621.393	46.986	184.698	1623.149	46.934
184.945	1620.981	46.986	184.745	1622.737	46.934
184.992	1620.569		184.792	1622.325	

NOTE – M-52 is recommended for upstream, M-59 is recommended for downstream.

Appendix VIII

Wavelength multiplexer, upstream inter-channel crosstalk, ONU transmitter tuning time considerations, and upstream channel grid example

(This appendix does not form an integral part of this Recommendation.)

This appendix provides example information on the WM characteristics, upstream inter-channel crosstalk and its penalty related to the isolation specification of the WM device, along with ONU transmitter tuning time.

VIII.1 Wavelength multiplexer

Table VIII.1 provides example values for the WM device. Isolation values may vary depending on the number of wavelength channels considered, the example given in Table VIII.1 is for an eight channel case. Critical to the proper definition of WM passband, consideration must be given to the maximum tuning error (MTE) of the associated laser. MTE is the maximum spectral error allowed due to tuning. MTE is the maximum differential spectral distance of the actual wavelength to the nominal centre of the wavelength channel. Specifically the relationship between MTE and MSE is shown in Figure VIII.1 and can be represented as a formula:

MTE = MSE – (minimum single-sided spectral width at –15 dB) ≈ MSE – (data rate in Hz)

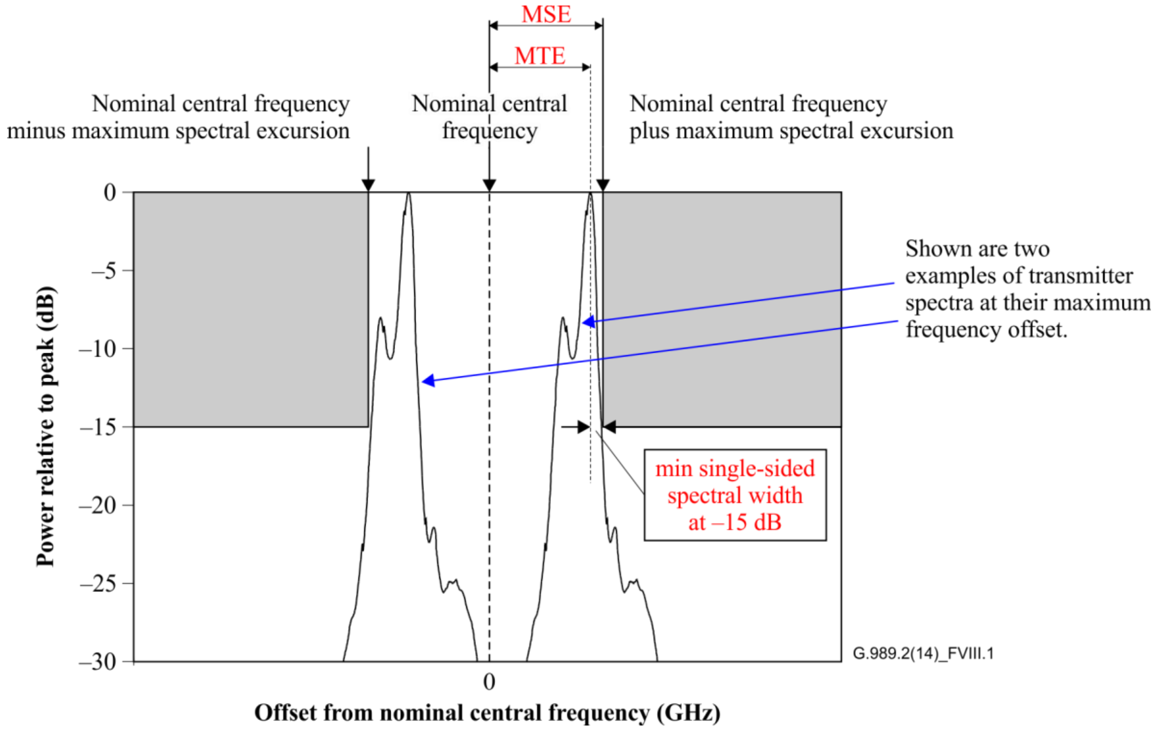


Figure VIII.1 – Relationship between MTE and MSE

Table VIII.1 – WM characteristics

Specification	Condition	Value
Loss without connectors (Note)	S/R-CPn to S/R-CG	< 2.0 dB (Low) < 4.0 dB (High)
Isolation	S/R-CG to any S/R-CPn (only applies to upstream ports)	FFS
Maximum optical power	Any individual port	+23 dBm
Return loss	Any port	> 50 dB
Directivity	Any S/R-CPn to any S/R-CPn	> 50 dB
NOTE – This is the loss without connectors when an ONU tunes to the peak wavelength ±MTE. When an ONU tunes around to maintain lock, it requires an amount of loss budget for the tuning process (which depends on the RSSI).		

NOTE – The optical parameter tables are specified at the S/R-CG & R/S points, as illustrated by Figure 6-1. In order to determine optical level at the S/R-CP point, the loss of WM must be taken into account. Table VIII.1 specifies two classes of loss for the WM, resulting in two different values. OLT transceivers indicate the compatible WM loss class (low or high). WM loss classes are likely to be technology based (e.g., AWG versus thin film filter).

The following requirements apply to each operating channel of the OLT receive filter (WM):

1) The (1+X) dB filter bandwidth[4] must be smaller than 2·MTE, where X is the transmitter power wavelength dependency.

2) The shape of the filter characteristic must be monotonically decreasing (apart from a limited ripple as specified below), on each side with respect to the filter minimum loss point, in the region delimited by the intersections with the adjacent channel filter responses extended by twice the MTE[5], as shown in Figure VIII.3.

3) The value of any residual ripple in the monotonic region specified above must be less than the OLT receive power measurement resolution.

Requirement 1 guarantees that any unacceptable (i.e., exceeding the MTE) deviation of the ONU transmitter wavelength, with respect to the filter minimum loss point (nominally the channel centre), can always be revealed at the OLT receiver.

Requirement 2 guarantees that the wavelength locking and tracking mechanism operation makes the ONU transmitter wavelength always move towards the filter minimum loss point (nominally the channel centre).

Requirement 3 guarantees that any residual ripple on the receive filter shape causes power variations which are practically unmeasurable at the OLT receiver, hence that it cannot adversely affect the operation of the wavelength locking and tracking mechanism.

Note that the maximum loss due to imperfect tuning (i.e., when the ONU locks at a distance equal to MTE away from the channel centre) coincides with the OLT receiver power measurements repeatability (total of 1dB, according to Table VIII.2). In practice, however, the tuning error and tuning loss could be reduced by averaging the OLT receive power measurements.

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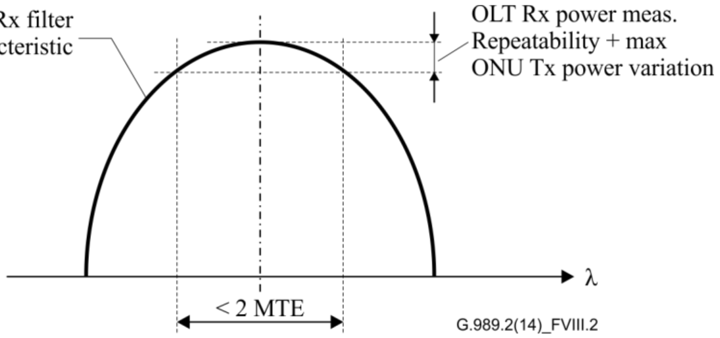
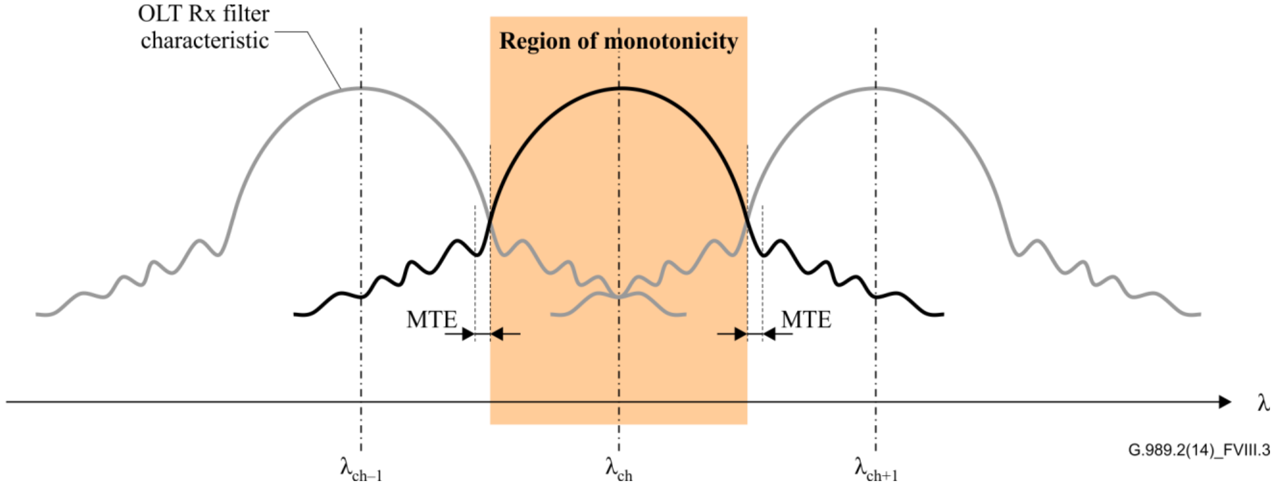
[4] Or, equivalently, the incremental loss caused by any wavelength deviation from the nominal channel wavelength greater than MTE must be greater than the OLT receive power measurement repeatability, which equals ±0.5 dB (see Table VIII.2), plus the ONU power variation, which equals the transmitter power wavelength dependency.

[5] This would require the additional specification of the ONU laser –15 dB spectral width; alternatively, MTE could be conservatively replaced here by MSE.



Tx- transmitter
Rx-receiver

Figure VIII.2 – Requirement on filter bandwidth



Rx-receiver

Figure VIII.3 – Requirement on filter monotonicity

VIII.2 Upstream inter-channel crosstalk

Figure VIII.4 shows a simplified TWDM PON reference diagram excluding coexistence (i.e., no coexistence element Type x (CEx) device) which is used as the baseline to calculate the upstream inter-channel crosstalk and its penalty.

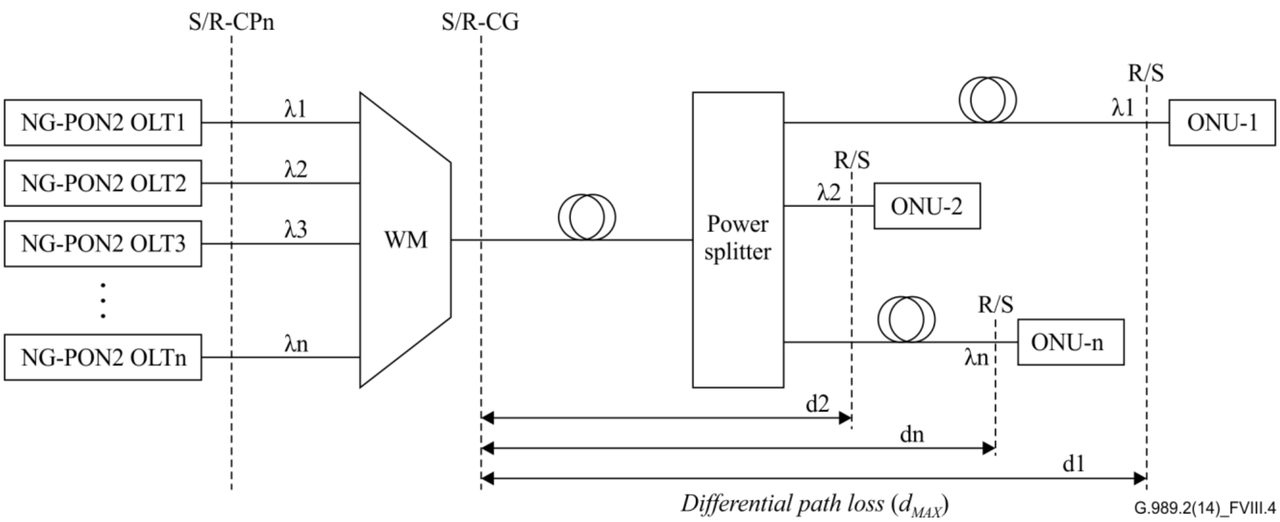


Figure VIII.4 – Reference diagram for inter-channel crosstalk calculation

Because of architectural asymmetry, ONUs can be located at different remote locations to have large differential optical path loss in the upstream direction, whereas NG-PON2 OLT ports are located near to each other to have no differential optical path loss in the downstream direction. The maximum differential optical path loss (d_{MAX}) is specified as 15 dB as in Table 11-4.

In this situation, the multichannel signal power spectrum at the S/R-CG point in front of WM device in the central office and the multichannel signal power spectrum at R/S point in front of each ONU can have quite different channel power differences as illustrated in Figure VIII.5.

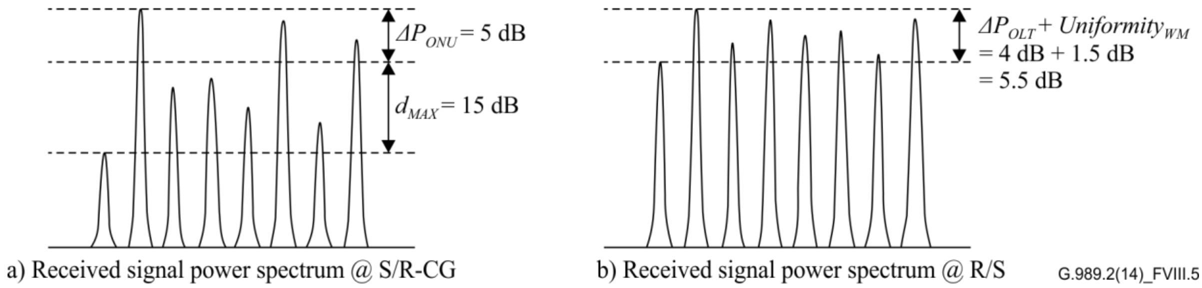


Figure VIII.5 – Signal power spectrum (a) at S/R-CG point and (b) at R/s point

According to Table 11-4, the difference between the mean launch power maximum and the mean launch power minimum of the OLT transmitter for the downstream direction (ΔP_{OLT}) is 4 dB. Considering typical 1.5 dB uniformity specification of the WM device ($Uniformity_{WM}$), the maximum power difference among the downstream signals at the R/S point in front of ONU can be as high as 5.5 dB. However, in the upstream direction, the maximum differential optical path loss (d_{MAX}) 15 dB can be added to the difference between the mean launch power maximum and the mean launch power minimum of the ONU transmitter (ΔP_{ONU}) 5 dB (per Table 11-5). And the maximum power difference among the upstream signals at the S/R-CG point in front of WM device can be as high as 20 dB.

Since the upstream signal power difference at S/R-CG point in front of WM device can be much higher (14.5 dB higher) than the downstream signal power difference at R/S point in front of ONU, care must be taken when designing the WM device regarding the isolation specification in order to reduce the inter-channel crosstalk and its penalty.

VIII.2.1 Worst-case design approach

The upstream inter-channel crosstalk (Cc) in worst-case design approach can be calculated using the following equation [b-ITU-T G.Sup39]:

$$Cc = \Delta P_{ONU} + d_{MAX} + 10\log_{10}\left(2\times 10^{-I_A/10} + (N-3)\times 10^{-I_{NA}/10}\right) \quad dB, \qquad \text{(VIII-1)}$$

where I_A and I_{NA} are the adjacent channel isolation and the non-adjacent channel isolation of the WM device, respectively, N is total number of channels. And with Gaussian approximation the inter-channel crosstalk penalty (Pc) can be calculated using the following equation [b-ITU-T G.Sup39]:

$$Pc = -5\log\left(1 - \frac{10^{2Cc/10}}{N-1}Q^2\left(\frac{ER+1}{ER-1}\right)^2\right) \qquad \text{(VIII-2)}$$

where $Q = \sqrt{2}erfc^{-1}(2\times BER)$. For a upstream BER of 10^{-4} as specified in Table 11-6, Q = 3.72. The induced optical penalty is plotted against inter-channel crosstalk for the cases of total number of channel N = 4 and N =8 in Figure VIII-6.

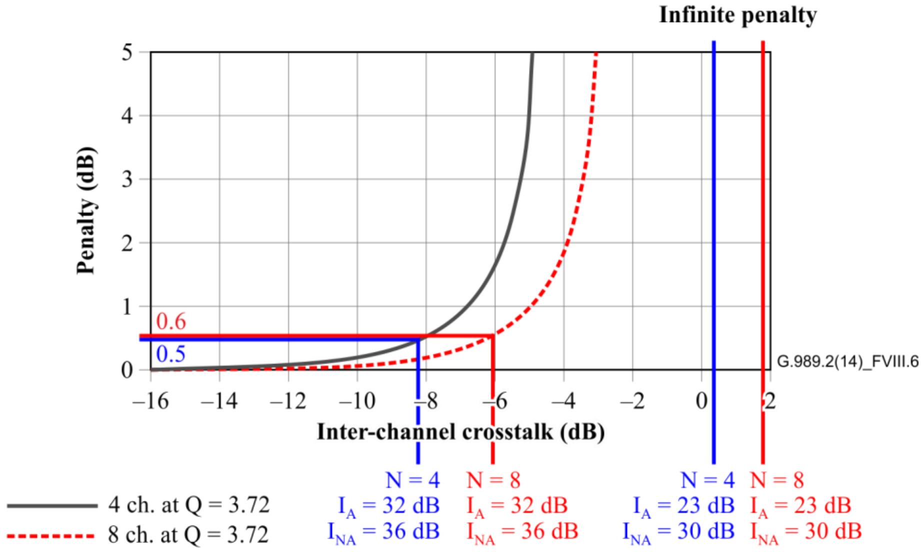


Figure VIII.6 – Optical penalty against inter-channel crosstalk for N = 4 and N = 8

The calculated inter-channel crosstalk values and its penalties are summarized in Table VIII-2 for four channel systems and eight channel systems, with WM device examples of commercially available typical AWG, filter having tight isolation specification, and cascaded filter.

Table VIII.2 – Calculated inter-channel crosstalk and its penalty in worst-case design approach

Worst-case design approach		Typical AWG	Filter with tight spec.	Cascaded filter
		I_A = 23 dB, I_{NA} = 30 dB	I_A = 26 dB, I_{NA} = 33 dB	I_A = 32 dB, I_{NA} = 36 dB
4 channel system	Cc (dB)	0.4	–2.6	–8.2
	Pc (dB)	Infinite	Infinite	0.5
8 channel system	Cc (dB)	1.8	–1.2	–6
	Pc (dB)	Infinite	Infinite	0.6

In a worst-case design approach, a WM device with very high isolation specifications (I_A = 32 dB and I_{NA} = 36 dB) is required for the TWDM PON to be reasonably bounded with optical penalty 0.6 dB added by the inter-channel crosstalk.

VIII.2.2 Statistical design approach

For the statistical design approach, the Monte Carlo simulation method is used to calculate the inter-channel crosstalk. The mean launch power of the ONU transmitter is assumed to have uniform random distribution with values varying from 4 dBm to 9 dBm (as per Table 11-6). The differential optical path loss is also assumed to have a uniform random distribution with values varying from 0 dB to 15 dB (as per Table 6-1). The inter-channel crosstalk probabilities calculated using a Monte Carlo simulation for the same WM device examples as in clause VIII.2.1 are illustrated in Figure VIII.7.

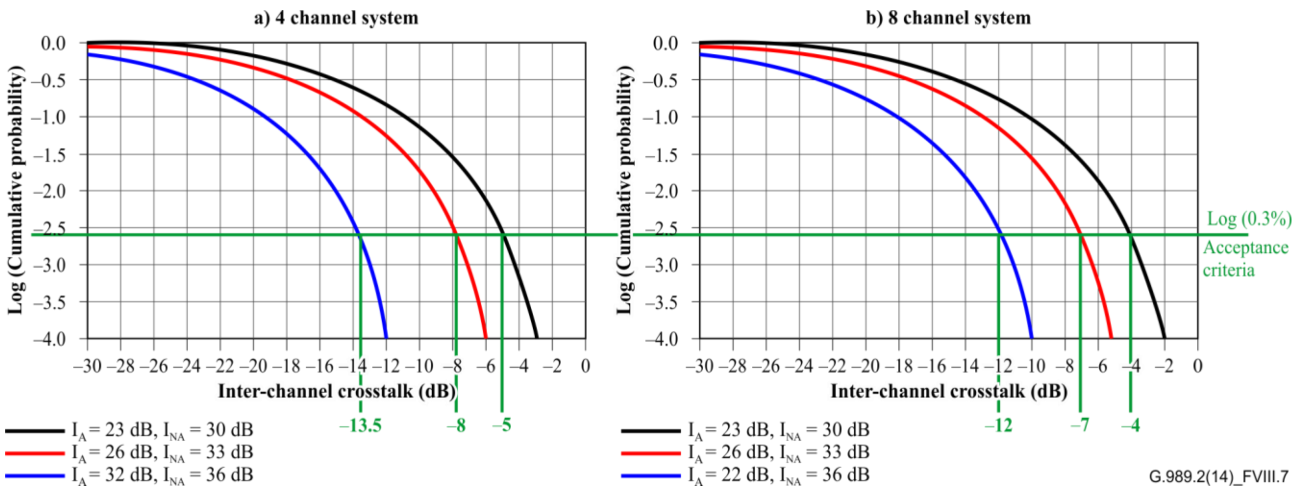


Figure VIII.7 – Monte Carlo simulation for the probability of inter-channel crosstalk for the cases (a) four channel system and (b) eight channel system

The calculated inter-channel crosstalk values and its penalties in case of statistical design approach are summarized in Table VIII.3 for four channel systems and eight channel systems, with WM device examples of commercially available typical AWG, filter having tight isolation specification, and cascaded filter. Here, probability threshold for system acceptance 0.3% is used to calculate the inter-channel crosstalk values and equation VIII-2 is used to calculate the penalties.

Table VIII.3 – Calculated inter-channel crosstalk and its penalty in statistical design approach

Statistical design approach		**Typical AWG**	**Filter with tight spec.**	**Cascaded filter**
		I_A = 23 dB, I_{NA} = 30 dB	I_A = 26 dB, I_{NA} = 33 dB	I_A = 32 dB, I_{NA} = 36 dB
4 channel system	Cc (dB)	–5	–8	–13.5
	Pc (dB)	4.1	0.5	0
8 channel system	Cc (dB)	–4	–7	–12
	Pc (dB)	1.9	0.3	0

Even in statistical design approach, a typical AWG cannot be used because of excessive inter-channel crosstalk. The WM device needs to be implemented using a filter with high isolation specifications in order for the TWDM PON to have reasonably bounded optical penalty 0.5 dB.

VIII.2.3 Method to limit the inter-channel crosstalk impairment

There could be two approaches to limit the inter-channel crosstalk impairment. One is to make the WM isolations high enough with given received signal power dynamic range in front of the WM device, either with worst-case design or with statistical design. The other is additionally to reduce the received signal power dynamic range (ΔP_{CG}) in front of the WM device by controlling ONU transmitter signal power depending on ODN insertion loss.

There are also two different specification methods to limit the inter-channel crosstalk impairment. One is to specify the adjacent channel isolation (I_A) and the non-adjacent channel isolation (I_{NA}) of the WM device between S/R-CG point and S/R-CPn point. The other is to specify the inter-channel crosstalk (Cc) at S/R-CPn point.

Based on the calculation results in the previous clause, Table VIII.4 shows example methods and specifications to limit the inter-channel crosstalk penalty as 0.5 dB or below.

Table VIII.4 – Example methods and specifications to give 0.5 dB inter-channel crosstalk penalty

Specification method	**Specifying the WM isolations only**		**Specifying the WM isolations and received signal power dynamic range**	**Specifying inter-channel crosstalk**
	Worst-case design	Statistical design	Worst-case design	
parameter				
I_A, minimum	32	26	23	NA
I_{NA}, minimum	36	33	30	NA
ΔP_{CG}, maximum	NA	NA	11	NA
Cc, maximum	NA	NA	NA	–8

VIII.3 ONU transmitter tuning time

The ONU transmitter wavelength channel tuning time may be measured using the procedure and test set-up below. The purpose of the test set-up is to measure the tuning time unambiguously. The tuning of the laser is illustrated below in Figure VIII.8.

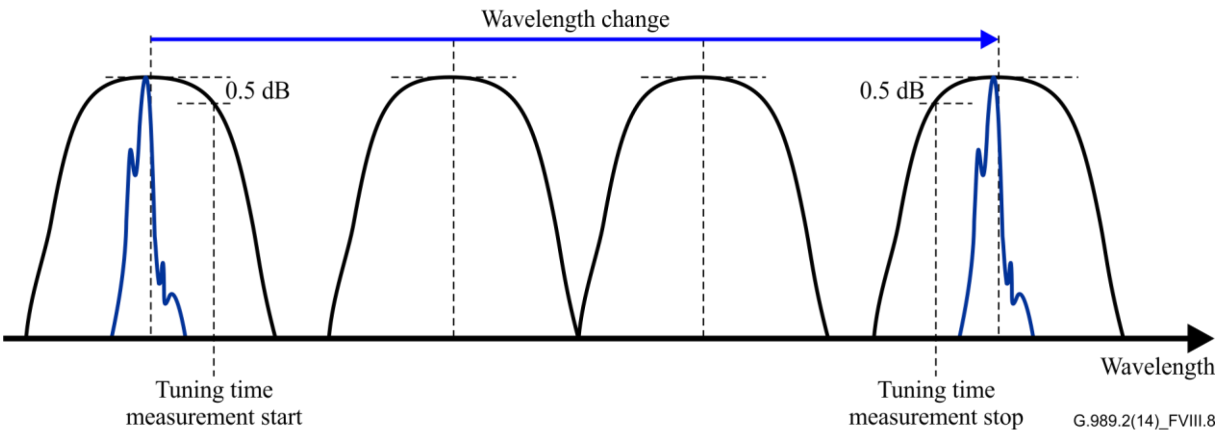


Figure VIII.8 – Illustration of laser tuning across the operating band

The tuning time as shown in the illustration does not begin when the laser begins to tune but when the laser exits the passband of the origin wavelength channel, i.e., when the optical power drops of 0.5 dB compared to the initial value, after a channel change signal in the form required by the tunable device. The tuning time ends when the laser enters the passband of the destination wavelength channel, i.e., when the optical power, in the destination wavelength channel, reaches and stays within 0.5 dB of the initial (origin channel) value. The transmitter wavelength channel tuning time is computed over all possible channel changes in the tuning range. A reference channel demultiplexer is used in the test set-up. It is required that the laser power variation during the channel change and the attenuation uniformity between channels of the reference channel demultiplexer are each below 0.25 dB.

The test set-up is shown in Figure VIII.9, while Figure VIII.10 illustrates how the tuning time parameter is measured.

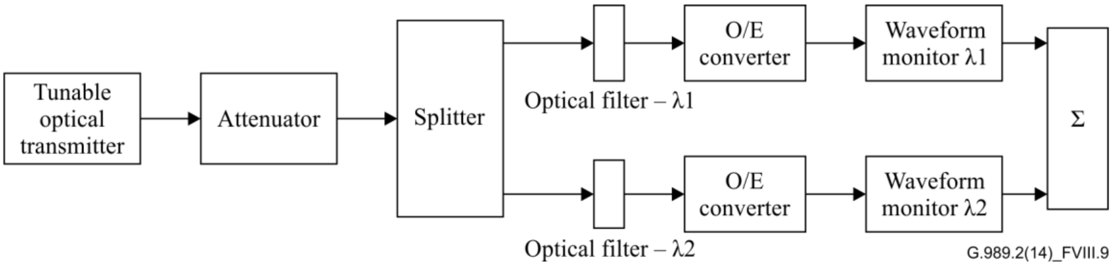


Figure VIII.9 – Test set-up for tuning time of ONU transmitter

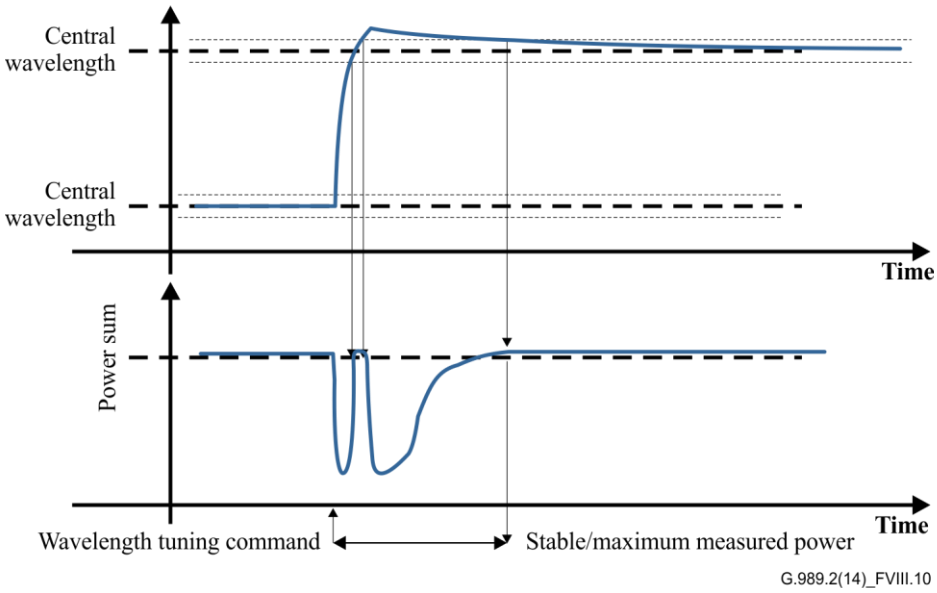


Figure VIII.10 – Optical power vs. time from summation of waveform monitors

The test set up attenuator is set such that the optical received power at the O/E converters is in range that is not close to receiver overload and the signal is high enough to be accurately measured. The laser is initially tuned to within 0.1 dB of the minimum loss point of the filter. A threshold is set at 0.5 dB below the resulting initial power measurement. The crossing of this threshold will be used to determine the points where the tuning time begins and when the tuning time ends, i.e., the signal stays above the threshold.

The optical power levels are converted and measured at the output of the summation box in the electrical domain.

Note that the same test procedure can be applied even when the transmitter module is integrated in a system and the channel change command is issued via higher layers, e.g., CLI or EMS. However it must be understood that other effects may influence the measurement in this case, for example, the transmitter may be switched off before tuning initiates and switched on again when tuning finishes. Hence the test procedure can be applied e.g., to compare the tuning time of different ONUs, excluding command transmission and processing delays, but the tuning time of the optical module itself is measured when the optical module is not part of a system and the channel change is commanded via the specific signal required by the optical module.

The reference test demultiplexer is Gaussian in shape and have a relative loss of 0.5 dB at 8 GHz from the minimum loss point.

VIII.4 TWDM PON upstream channel grid example

Table VIII.5 shows examples of TWDM PON upstream channel grid which contain eight channels with 50 GHz, 100 GHz and 200 GHz CS. The examples are sub-wavelength bands from the ITU-T grid.

Table VIII.5 – TWDM PON upstream channel grid example

	50 GHz CS		100 GHz CS		200 GHz CS	
Channel	**Frequency (THz)**	**Wavelength (nm)**	**Frequency (THz)**	**Wavelength (nm)**	**Frequency (THz)**	**Wavelength (nm)**
1	195.25	1535.43	195.6	1532.68	196.1	1528.77
2	195.20	1535.82	195.5	1533.47	195.9	1530.33
3	195.15	1536.22	195.4	1534.25	195.7	1531.90
4	195.10	1536.61	195.3	1535.04	195.5	1533.47
5	195.05	1537.00	195.2	1535.82	195.3	1535.04
6	195.00	1537.40	195.1	1536.61	195.1	1536.61
7	194.95	1537.79	195.0	1537.40	194.9	1538.19
8	194.90	1538.19	194.9	1538.19	194.7	1538.77

Appendix IX

Alternative line code for Raman mitigation

(This appendix does not form an integral part of this Recommendation.)

This appendix provides examples of NG-PON2 Raman mitigation coding schemes when using RF video overlay. Two example schemes are provided, an 8B10B scheme, and a Miller code scheme, both defined in this appendix. These codes will have to be compatible with the optical devices conforming to the NRZ based values shown in Table 11-4 and Table 11-5.

As described in their respective sections, each scheme uses a different approach to effect the mitigation. The advantage of 8B10B code is that it adds functionality into the media access control (MAC) layer, that is able to be turned on or off per the application. The advantage of Miller code is that it is contained inside the optical modules, thereby providing a standard NRZ based signal to the MAC. Each code provides different mitigation levels and potentially optical budget performance, so selection of either code can be application dependent.

IX.1 8B10B Scheme

For Raman mitigation, the 8B10B sublayer is introduced between the downstream NG-PON2 physical interface (PHY) adaption interface and the optical interfaces.

8B10B is a DC balanced encoding scheme introduced by Widmer-Franaszek in 1984. The transmission codes are further specified in [b-IEEE 802.3], clause 36.2.4 and are identical to ANSI [b-ANSI 230-1994] (FC-PH), clause 11. The NG-PON2 8B10B sublayer uses all the code-groups of Table 36-1 of [b-IEEE 802.3] and uses only the K28.5 code-group specified in Table 36-2 of [b-IEEE 802.3].

The 8B10B sublayer is independent of all other NG-PON2 MAC functions.

IX.1.1 Power spectral density of 8B10B code

Figure IX.1 presents simulated results of the PSD of traditional NRZ at 10 Gbit/s and the ANSI 8B10B code at 12.5 Gbit/s.

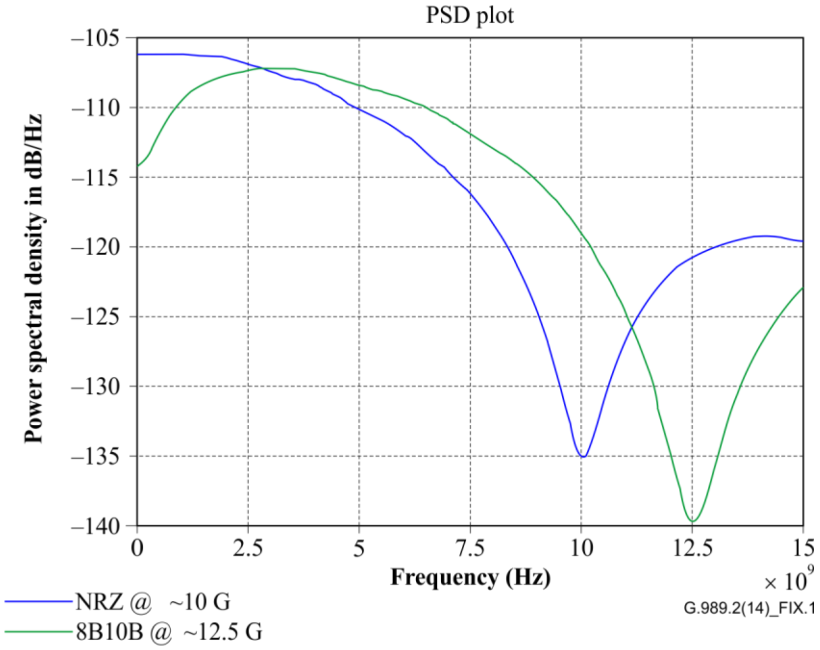


Figure IX.1 – Power spectral density of NRZ and 8B10B codes

IX.1.2 Encode and decode operations

IX.1.2.1 OLT encode

For the OLT, the 8B10B sublayer is responsible for encoding and performs the following encoding operations

For the first octet of the downstream physical synchronization block (PSBd) physical synchronization sequence (PSync) field (0xC5) the special code-group K28.5 is chosen from Table 36-2 of [b-IEEE 802.3]. Once the code-group is selected, the current value of the transmitter's running disparity is used to select the code-group from its corresponding column. For each code-group transmitted, a new value of the running disparity is calculated. This new value is used as the transmitter's current running disparity for the next octet to be encoded and transmitted.

With the exception of the first octet of the PSBd PSync field (0xC5), valid code-groups are selected using the NG-PON2 PMD octets as indexes into Table 36-1 of [b-IEEE 802.3]. Once the code-group is selected, the current value of the transmitter's running disparity is used to select the code-group from its corresponding column. For each code-group transmitted, a new value of the running disparity is calculated. This new value is used as the transmitter's current running disparity for the next octet to be encoded and transmitted.

IX.1.2.2 ONU decode

For the ONU, the 8B10B sublayer is responsible for decoding and performs the following operations

Syncs to the K28.5 character code-group: Synchronization is performed using the receiver state description of [b-ANSI 230-1994] (FC-PH), clause 12.1.

Replace the octet associated with the K28.5 croup with the original PSync PSBd value of 0xC5,

Replace the octet associated with received the data code-group with the associated octet.

IX.1.2.3 Running disparity rules

After powering on or exiting a test mode, the transmitter assumes the negative value for its initial running disparity. Upon transmission of any code-group, the transmitter calculates a new value for its running disparity based on the contents of the transmitted code-group.

After powering on or exiting a test mode, the receiver assumes either the positive or negative value for its initial running disparity. Upon the reception of any code-group, the receiver determines whether the code-group is valid or invalid and calculates a new value for its running disparity based on the contents of the received code-group.

The following rules for running disparity are used to calculate the new running disparity value for code-groups that have been transmitted (transmitter's running disparity) and that have been received (receiver's running disparity).

Running disparity for a code-group is calculated on the basis of sub-blocks, where the first six bits (abcdei) form one sub-block (six-bit sub-block) and the second four bits (fghj) form the other sub-block (four-bit sub- block). Running disparity at the beginning of the six-bit sub-block is the running disparity at the end of the last code-group. Running disparity at the beginning of the four-bit sub-block is the running disparity at the end of the six-bit sub-block. Running disparity at the end of the code-group is the running disparity at the end of the four-bit sub-block.

Running disparity for the sub-blocks is calculated as follows:

- Running disparity at the end of any sub-block is positive if the sub-block contains more ones than zeros. It is also positive at the end of the six-bit sub-block if the six-bit sub-block is 000111, and it is positive at the end of the four-bit sub-block if the four-bit sub-block is 0011.
- Running disparity at the end of any sub-block is negative if the sub-block contains more zeros than ones. It is also negative at the end of the six-bit sub-block if the six-bit sub-block

is 111000, and it is negative at the end of the four-bit sub-block if the four-bit sub-block is 1100.

Otherwise, running disparity at the end of the sub-block is the same as at the beginning of the sub-block.

NOTE – All sub-blocks with equal numbers of zeros and ones are disparity neutral. In order to limit the run length of 0's or 1's between sub-blocks, the 8B/10B transmission code rules specify that sub-blocks encoded as 000111 or 0011 are generated only when the running disparity at the beginning of the sub-block is positive; thus, running disparity at the end of these sub-blocks is also positive. Likewise, sub-blocks containing 111000 or 1100 are generated only when the running disparity at the beginning of the sub-block is negative; thus, running disparity at the end of these sub-blocks is also negative.

IX.1.2.4 Checking the validity of received code-groups

The following rules are used to determine the validity of received code-groups:

The column in Tables 36-1 and 36-2 of [b-IEEE 802.3] corresponding to the current value of the receiver's running disparity is searched for the received code-group.

If the received code-group is found in the proper column, according to the current running disparity, then the code-group is considered valid and, for data code-groups, the associated data octet determined (decoded).

If the received code-group is not found in that column, then the code-group is considered invalid.

Independent of the code-group's validity, the received code-group is used to calculate a new value of running disparity. The new value is used as the receiver's current running disparity for the next received code-group.

Detection of an invalid code-group does not necessarily indicate that the code-group in which the invalid code-group was detected is in error. Invalid code-groups may result from a prior error which altered the running disparity of the PHY bit stream but which did not result in a detectable error at the code-group in which the error occurred.

The number of invalid code-groups detected is proportional to the BER of the link. Optical link error monitoring may be performed by counting invalid code-groups.

IX.1.3 Eye mask and PMD

The eye mask of the OLT transmitter when encoded with the 8B10B code is the same as Figure 11-3. However, there are potential direct impacts to the PMD parameters of ER and receiver sensitivity when using 8B10B at 12.5 Gbit/s with 10 Gbit/s compliant transceiver components. In addition to direct impacts of the reduction in ER, there are indirect impacts on other parameters that are ER dependent e.g., in-band crosstalk penalty.

The impact on effective ONU receiver sensitivity are not specified but must be accounted for in equipment applying the 8B10B technique. As allowed by Note 3 in the downstream PMD Tables 11-4 and 11-5, this impact can be compensated for with an appropriate increase in minimum mean channel launch power of the OLT transmitter.

IX.2 Miller & Miller squared scheme

Miller code (also called delay modulation, or modified frequency modulation) is a run length limited code where at least two and at most four consecutive like symbols may occur in the transmitted sequence. More specifically, in Miller code, a bit 1 is represented by a transition at the middle of the bit period, and there is no transition for bit 0 unless it is followed by another bit 0, in which case there is a transition at the end of the first bit 0. Based on Miller code, Miller squared code (also called Miller-Miller code, or M^2 code) was developed to provide DC balance. Miller squared code adopts all the Miller code rules and adds one addition rule that when an even number of bit 0's occurs between bit 0's, the transition for the last bit 1 is suppressed. Encoding and decoding of Miller and Miller squared codes can be easily implemented with synchronous logic circuit. Figure IX.2 shows an example of coding binary data into Miller code. These codes (Miller and Miller squared) provide good timing content and reduced bandwidth compared to NRZ code. In addition, the PSD at low frequencies is relatively low with the potential for Raman crosstalk mitigation.

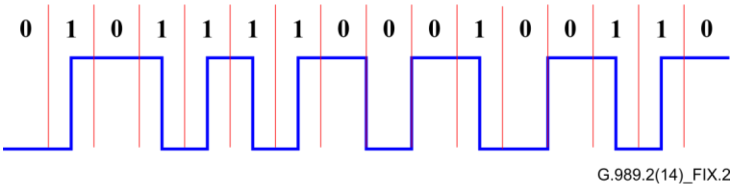


Figure IX.2 – Miller code

IX.2.1 Modified definitions for Miller code

IX.2.1.1 Minimum extinction ratio

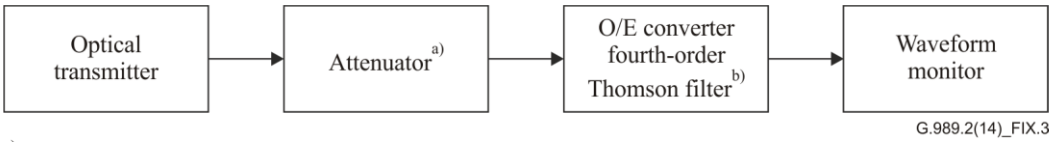
With respect to a Miller code signal generated by an optical transmitter, the ER is defined as the average optical power level at the centre of the high level (*A*) to the average optical power level at the centre of the low level (*B*):

$$ER = 10 \log_{10} (A/B)$$

Note that the high and low levels in Miller code are simply the corresponding optical signal levels, and the Miller code specifies how to map the optical signal into its data signal.

IX.2.1.2 Launch optical power without input to the transmitter

In the upstream direction, the ONU transmitter ideally launches no power into the fibre in all bursts which are not assigned to that ONU. However, an optical power level less than or equal to the WNE-PSD is allowed during bursts which are not assigned to that ONU. During the transmitter Enable bit period immediately preceding the assigned burst, which may be used for laser pre-bias, and during the bit period immediately following the disable of the TxEnable signal, the maximum launch power level allowed is the low level.



a) Attenuator is used if necessary.
b) Cut-off frequency (3 dB attenuation frequency) of the filter is 0.75 times output nominal bit rate.

Figure IX.3 – Test set-up for mask of the eye diagram for ONU transmitter

IX.2.2 Power spectral density of Miller code

Miller coding scheme can be modeled as a Markov source with four states with equal stationary state probability. Based on the state transition matrix and the autocorrelation for the Miller code, its PSD can be found as:

$$S(\omega) = \frac{2}{\omega^2 T[17 + 8\cos 4\omega T]} \cdot [23 - 2\cos \omega T/2 - 22\cos \omega T - 12\cos 3\omega T/2 + 5\cos 2\omega T + 12\cos 5\omega T/2 + 2\cos 3\omega T - 8\cos 7\omega T/2 + 2\cos 4\omega T],$$

where ω is the angular frequency and *T* is the bit period. Figure IX.4 shows the PSDs of the NRZ and Miller line codes. Compared to NRZ modulation, Miller code has a narrower bandwidth and reduced energy content at low frequencies. These are the desired properties for TWDM PONs. With reduced energy at low frequencies, Miller code can mitigate the Raman crosstalk of the TWDM PON signals onto the RF video overlay. With narrower bandwidth, Miller code can also reduce the fibre dispersion penalty. Hence, a DML, instead of an EML (electro-absorption modulated laser), can be used at 9.95328 Gbit/s for TWDM PON downstream transmission in the L-band or upstream transmission in the C band.

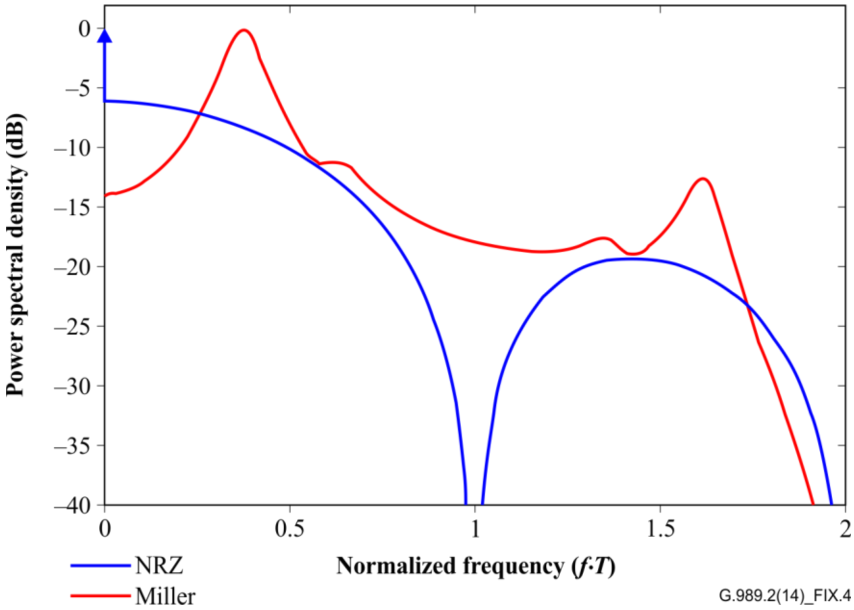


Figure IX.4 – Power spectral density of NRZ and Miller codes

IX.2.3 Encode and decode operations

Even though encoding and decoding of Miller and Miller squared codes can be easily implemented with synchronous logic circuit, there exists a potential time/phase ambiguity in the reception and decoding of Miller coded waveform. For example, as shown in Figure IX.2, with a clock phase shift of 180 degree, consecutive 1 bits will be decoded as consecutive 0 bits, or vice versa. The only unambiguous pattern is the 101 bit combination. Under the wrong phase shift of 180 degree, the waveform appears to be two consecutive 0 bits without a transition between them. This is a code violation, and it can be used to correct 180-degree phase alignment error.

Alternatively, phase alignment error can be detected by counting the number of transition edges or using parity check. According to the coding rule, there is always a transition in the middle of 1 bit, while at the bit boundaries, transition only happens between two consecutive 0 bits. Hence, for random data, the transition density in the middle of the bits is twice the transition density at the bit boundaries. In addition to looking for transition density, the parity between 0 and 1 can also be used for phase alignment. As a transition in the middle of the bit period is decoded as 1 bit, while no transition in the middle of the bit period is decoded as 0 bit. If the alignment is out of phase by 180 degree, the transition density in the middle of the bit period, for random data, is reduced to a half of that with correct phase alignment. In other words, the number of decoded 1 bits will be half of the decoded 0 bits.

In addition to look at bit pattern and transition density, fixed data pattern in the PON protocol, such as the PSync in the downstream and the preamble in upstream, can be used for phase alignment. For example, the downstream PSync pattern is 0xC5E5 1840 FD59 BB49 in XG-PON1. With 180-degree phase alignment error at the receiver, the 101 patterns in the PSync appear to be coding violations, and the decoded PSync field becomes a wrong pattern. With 180 degree phase alignment error at the receiver for upstream, code violations appear for the commonly used 1010… pattern. To maximize the number of transitions in Miller code waveform, 0000 or 1111 preamble in upstream is preferred.

In this case, the OLT receiver with 180 degree phase alignment error will decode the 0000 preamble as 1111, and the 1111 preamble as 0000.

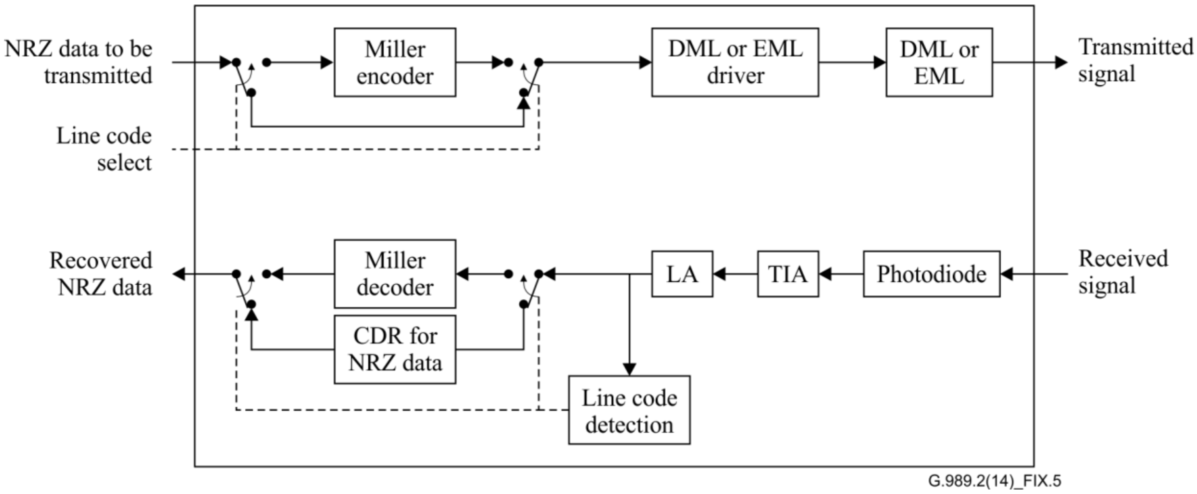


Figure IX.5 – Optical transceiver for NRZ and Miller codes

Since the Miller code is a binary code and its bandwidth is narrower than the NRZ code, conventional transmitter and receiver front end circuits commonly used in NRZ transceivers can be reused for Miller code. Therefore, it is possible to design a transceiver that can transmit and receive both NRZ and Miller coded signals, as shown in Figure IX.5. The transceiver will use the same analogue front end (i.e., laser driver at the transmitter side, transimpedance amplifier and limiting amplifier at the receiver side) for both NRZ and delay modulation signals. At the transmitter side, a line code select signal will switch the Miller encoder in and out of the signal path. The line code select signal comes from the line card to set the line code to be used in the system. At the receiver side, a line code detection signal will switch the received signal either to the clock and data recovery (CDR) circuit for NRZ code or decoder for Miller code. The line code detection circuit can be implemented in a number of approaches with the same logic function. It is up to the implementer to choose it.

The line code detection circuit could have two filters; one lowpass filter passes frequencies from DC to $0.2/T$, and the other bandpass filter passes frequencies from $0.4/T$ to $0.6/T$, where T is the bit period. A comparator will compare the power measured after these two filters. If the power after the bandpass filter is much larger than the power after the lowpass filter, Miller code is selected.

The line code detection circuit will count the maximum number of identical and consecutive symbols. If the maximum number of identical and consecutive symbols is significantly larger than four, the line code is determined to be NRZ.

The line code detection circuit will look at the duration between two transitions. If there exists a large number of occurrences that the duration between two transitions is one and a half bit period, the line code is determined to be Miller code.

The transceiver will decode the received signal as NRZ and Miller code, and then the line code detection circuit will select the correct line code based on which code leads to correct data in the protocol specific pattern (e.g., PSync in the downstream or the preamble in the upstream).

The transceiver will decode the received signal as NRZ and Miller code, and then send both decoded data to FEC (feedforward correction). The line code selection circuit will select the line code that produces the least number of error bits from FEC. This approach requires FEC block before the line code can be selection. However, implementing a FEC circuit inside optical transceiver is not a common practice, so this approach is less suitable for dual line code transceivers.

Using such a transceiver with NRZ and Miller line codes, the interface between the transceiver and TWDM PON MAC remains the conventional NRZ code. Hence, MAC layer can remain untouched regardless of the line code used in the system, but TWDM PON system becomes adaptive to the deployment scenarios. If the TWDM PON system coexists with RF video overlay service, Miller code can be used to mitigate the Raman crosstalk. If there is no RF video overlay service, either NRZ or Miller code can be used.

With Miller code, any violation in the received line code could indicate an error bit. As the locations of the error bits are known based on line code violation, this information can be used for error detection or correction. For example, it can improve the performance of FEC. In this case, the transceiver can be designed to detect code violation and report the error bits to the FEC.

IX.2.4 Eye mask

Figure IX.6 presents the eye mask of the OLT transmitter when encoded with the Miller code. The values are X = 0.15, Y = 0.25.

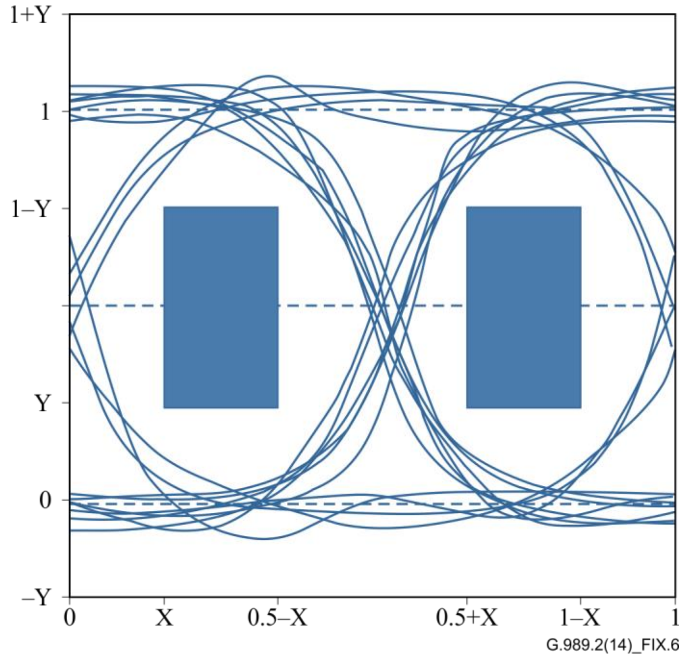


Figure IX.6 – Miller encoded eye mask

IX.3 Raman mitigation suppression levels

Table IX.1 provides an example of required Raman mitigation for class N2 and the specified number of wavelengths. The numbers are based on a typical operator RF video overlay scheme, with the following assumptions:

– a polarization overlap factor of 0.6;

– 256-quadrature amplitude modulation (QAM) RF video.

Table IX.1 – Required mitigation

		Required mitigation	
Class	Budget	4 Wavelength	8 Wavelength
N2	31 dB	6 dB	FFS
NOTE – Required mitigation is to allow 1 dB penalty in overall CNR due to Raman cross talk			

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