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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.

Edition 2.0 continues the maintenance and evolution of physical media dependent (PMD) layer specification.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
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1.1	ITU-T G.989.2 (2014) Amd. 1	2016-04-13	15	11.1002/1000/12556
1.2	ITU-T G.989.2 (2014) Amd. 2	2017-08-13	15	11.1002/1000/13292
2.0	ITU-T G.989.2	2019-02-06	15	11.1002/1000/13745

Keywords

NG-PON2, TWDM-PON, PtP WDM-PON

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

FOREWORD

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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.

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As of the date of approval of this Recommendation, ITU had not 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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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.

This edition includes updates from Amendment 1, Amendment 2 and relaxes certain parameter values related to OOB/OOC/IBXT.

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 (2016), *Characteristics of a single-mode optical fibre and cable*.

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

[ITU-T G.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 (2012), *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 (2007), *Network node interface for the synchronous digital hierarchy (SDH)*.

[ITU-T G.709] Recommendation ITU-T G.709/Y.1331 (2016), *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 (2018), *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 (2014), *Gigabit-capable passive optical networks (G-PON): Enhancement band*.

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

[ITU-T G.987.1] Recommendation ITU-T G.987.1 (2016), *10 Gigabit-capable passive optical networks (XG-PON): General requirements*.

[ITU-T G.987.2] Recommendation ITU-T G.987.2 (2016), *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 (2014), *10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification*.

[ITU-T G.988] Recommendation ITU-T G.988 (2017), *ONU management and control interface (OMCI) specification*.

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

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

[ITU-T G.989.3] Recommendation ITU-T G.989.3 (2015), *40-Gigabit-capable passive optical networks (NG-PON2): Transmission convergence layer specification*.

[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.313] Recommendation ITU-T L.313/L.66 (2007), *Optical fibre cable maintenance criteria for in-service fibre testing in access networks*.

3 Definitions

See clause 3 of [ITU-T G.989] for definitions.

4 Abbreviations and acronyms

See clause 4 of [ITU-T G.989] for abbreviations and acronyms.

5 Conventions

See clause 5 of [ITU-T G.989] for conventions.

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).

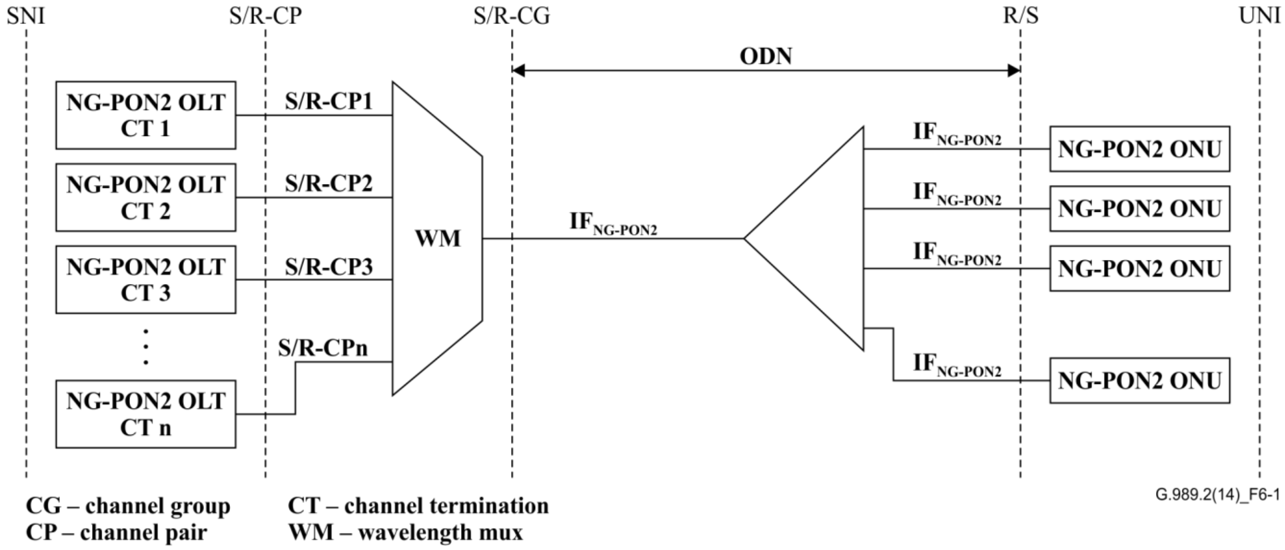


Figure 6-1 – NG-PON2 reference logical architecture

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).

The primary method of optical parameter specification is in reference to the S/R point for channel group (S/R-CG reference point of Figure 6-1 for the individual wavelength channels). This method is used in the PMD tables appearing in clause 11. An alternative informative optical parameter specification method is in reference to the S/R point for channel pair (S/R-CP reference point of Figure 6-1). The alternative method is applicable in the situations when the primary reference point, S/R-CG, is not practical or not accessible for performing measurements or it is desirable to provide a simple sensitivity specification to an OLT transceiver vendor. The informative optical parameters specification referenced to S/R-CP point (which are consistent with the primary method and are based on industry best practices with respect to the WM loss parameters) are given in Appendix XI.

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 (OPL) classes

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

The optical path loss for each class is specified between the S/R-CG and R/S reference points. It takes into account a 15 dB differential optical path loss.

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

	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 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 bit error ratio (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

The following power spectral density (PSD) values in the PMD tables in clause 11 have been optimized for TWDM 4-channel and 20 km. Investigations for TWDM 8 channel and/or DD40 (40 km) are for further study.

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].

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)

Table 9-1 – NG-PON2 wavelength bands

<table>
<tr><th rowspan="2">Wavelength compatible systems</th><th colspan="2">TWDM PON</th><th>PtP WDM PON</th></tr>
<tr><th>Downstream</th><th>Upstream</th><th>Upstream/downstream</th></tr>
<tr><td colspan="4">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.</td></tr>
</table>

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.

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 wavelength division multiplexing (WDM) technique on a single fibre.

9.3.2 Minimum extinction ratio

The minimum extinction ratio (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 at S/R-CG or R/S reference point, measured at the transmitter wavelength, 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 optical path penalties (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 maximum reflectance of equipment 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, any channel to any channel
Class 2	10 µs to 25 ms, any channel to any channel
Class 2R1	10 µs to 25 ms, any channel to a channel not more than 100 GHz away
Class 2R2	10 µs to 25 ms, any channel to a channel not more than 200 GHz away
Class 3	25 ms to 1 s, any channel to any channel

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. The details of the mask near the band edges are further discussed in App. VIII.5.

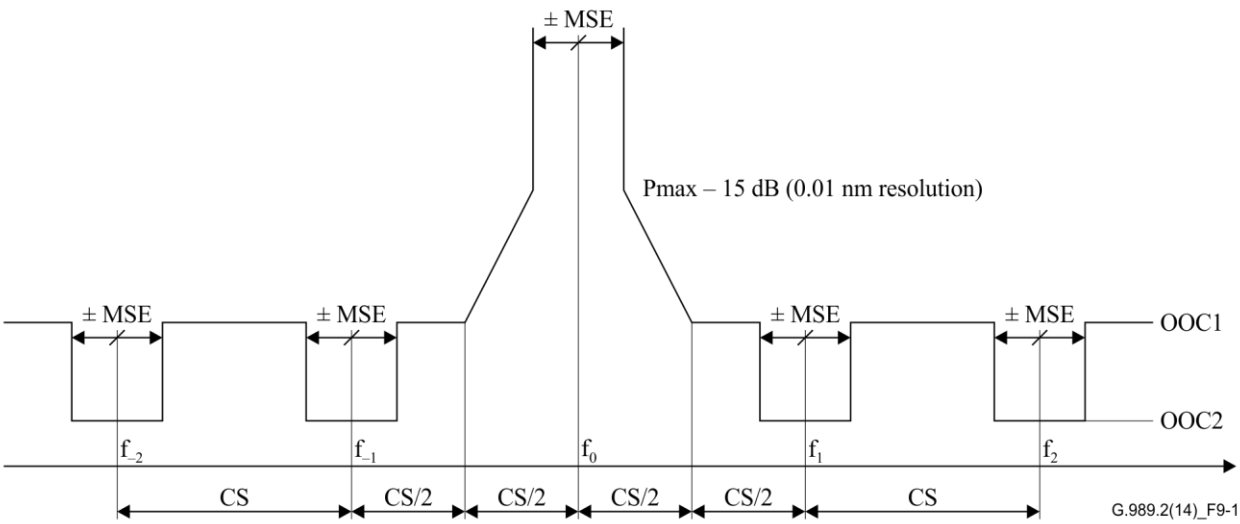


Figure 9-1 – OOC-PSD mask definition

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[1]. 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.

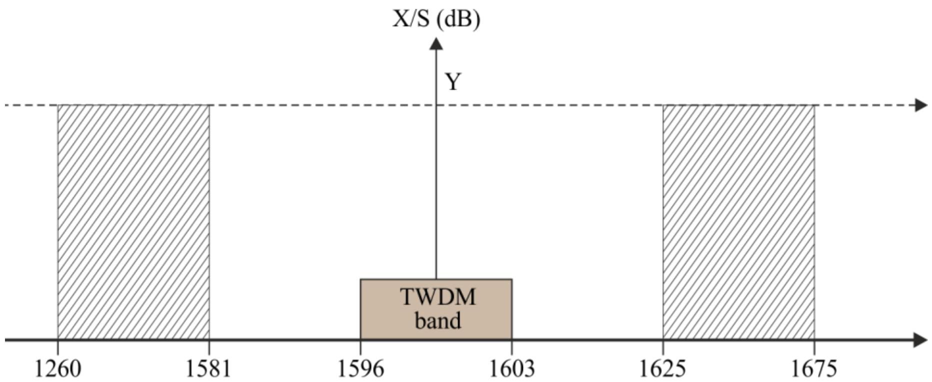
The wavelength filtering is divided into two parts: a wideband X/S, based on legacy system considerations and a narrowband X/S based on the NG-PON2 wavelength channels.

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

[1] 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.

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. 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.

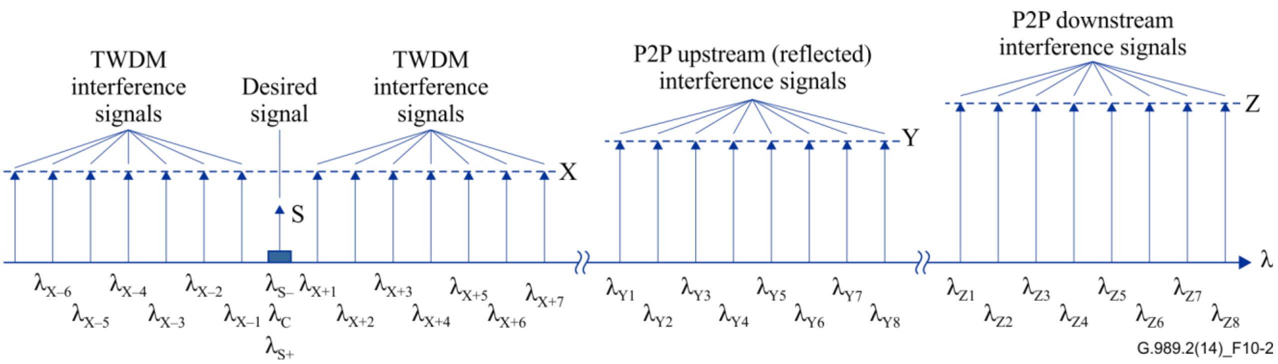


Figure 10-2 – X/S tolerance mask for TWDM PON

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
λ_{X+7}	λ_C – MSE + 7*CS
S	Receiver sensitivity + optical path penalty
X	S + 4 dB (Note 1)
λ_{Y1}	
λ_{Y2}	
λ_{Y3}	
λ_{Y4}	
λ_{Y5}	
λ_{Y6}	
λ_{Y7}	
λ_{Y8}	
Y	S + 6 dB (Note 2)
λ_{Z1}	
λ_{Z2}	
λ_{Z3}	
λ_{Z4}	
λ_{Z5}	
λ_{Z6}	
λ_{Z7}	
λ_{Z8}	

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

Parameter	Value
Z	2.48832 Gbit/s: S + 7 dB (Note 3) 9.95328 Gbit/s: S + 8 dB
NOTE 1 – 4 dB is the worst-case OLT transmitter power differential. NOTE 2 – 7 dB is the maximum PtP WDM ONU transmitter power (+9 dBm) less the ORL (32 dB) less the TWDM OLT receiver sensitivity (–30 dBm). NOTE 3 – The 2.48832 Gbit/s value (7 dB) is the maximum PtP WDM to TWDM OLT transmitter power differential for a 2.5G TWDM downstream link. The 9.95328 Gbit/s value (8 dB) is the maximum PtP WDM to TWDM OLT transmitter power differential for a 10G TWDM downstream link.	

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 + optical path penalty
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 9.95328 Gbit/s: scrambled NRZ.

Downstream line coding for 2.48832 Gbit/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.

Upstream line coding for 9.95328 Gbit/s: scrambled NRZ for 40 km reach. Other coding schemes for 40 km may be considered and could result in lower OPPs with alternative transmitter technologies. These other coding schemes are for further study.

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.313]
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 km and 40 km fibre length and 1 to 8 TWDM channels.

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 channel spacing	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 of equipment 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)	–63.5			
Minimum extinction ratio (Note 3)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range	ps/nm	0-420 (DD20) 0-840 (DD40)			

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

Item	Unit	Value			
Minimum side mode suppression ratio (at S/R-CP)	dB	30			
Maximum downstream per channel out-of-band optical PSD (Note 4)	dBm (15 GHz)	–44.9 (4 channels)			
		–52.1 (8 channels)			
Maximum downstream per channel out-of-channel optical PSD (Note 5)	dBm (15 GHz)	–34.5 (4 channels)			
		–42.4 (8 channels)			
Jitter generation	–	See clause 11.1.5.4.3			
ONU receiver (optical interface R)					
Maximum OPP (Note 6)	dB	1.0			
Maximum reflectance of equipment at R/S, measured at receiver wavelength	dB	–20			
Bit error ratio reference level	–	10^{-4} (Note 7)			
Rx wavelength channel tuning time		See Table 9-2			
Maximum tuning granularity	GHz	5			
ODN class		N1	N2	E1	E2
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.

NOTE 3 – A lower extinction ratio 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 4 or 8 interfering TWDM channels, respectively.

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 4 or 8 TWDM channels (three or seven interferers), respectively.

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 clause 9.4.1 of [b-ITU-T G.Sup39] for additional details.

NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].

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 channel spacing	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 of equipment 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
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)	–63.7			
Minimum extinction ratio (Note 3)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range	ps/nm	0-420 (DD20) 0-840 (DD40)			
Minimum side mode suppression ratio (at S/R-CP)	dB	30			
Maximum downstream per channel out-of-band optical PSD (Note 4)	dBm (15 GHz)	–44.9 (4 channels)			
		–52.1 (8 channels)			
Maximum downstream per channel out-of-channel optical PSD (Note 5)	dBm (15 GHz)	–34.5 (4 channels)			
		–42.4 (8 channels)			
Jitter generation	–	See clause 11.1.5.4.3			
ONU receiver (optical interface R)					
Maximum OPP (Note 6)	dB	2.0			
Maximum reflectance of equipment at R/S, measured at receiver wavelength	dB	–20			
Bit error ratio reference level	–	10^{-3} (Note 7)			
Rx 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	35.3			

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

Item	Unit	Value
	(15 GHz)	
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. NOTE 3 – A lower extinction ratio 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 4 or 8 interfering TWDM channels, respectively. 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 4 or 8 TWDM channels (three or seven interferers), respectively. 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 clause 9.4.1 of [b-ITU-T G.Sup39], for additional details. NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].		

11.1.4.3 Optical interface parameters of upstream direction

The following upstream optical interface parameter tables are applicable to 20 and 40 km fibre length, and 1 to 8 TWDM channels.

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 (wide band option), 1528-1540 (reduced band option) 1532-1540 (narrow band option)
Minimum operating channel spacing	GHz	50
Maximum operating channel spacing	GHz	200
Maximum spectral excursion (over 1 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 (Note 13)	dB	+/–0.05 dB/GHz
Minimum tuning window (Note 2) When using cyclic channel grid When not using cyclic channel grid	GHz	(N+1)*CS (N-1)*CS+2*MSE

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

Item	Unit	Value			
Maximum tuning granularity	GHz	CS/20			
Tx 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 of equipment at R/S, measured at transmitter wavelength (Note 19)	dB	–32			
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) (Note 14)					
– Type A link (Note 3)	dBm	+9	+9	+9	+9
– Type B link (Note 4)	dBm	+5	+5	+5	+5
Maximum Tx enable transient time	bits	320 (128.6)			
Maximum Tx disable transient time	bits	320 (128.6)			
Minimum extinction ratio (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 side mode suppression ratio (Note 6)	dB	30			
Maximum upstream out-of-band optical PSD (Note 7)	dBm (15GHz)	–57.4 (4 channels) –64.6 (8 channels)			
Maximum upstream out-of-channel optical PSD – OOC1 (Note 8)	dBm (15 GHz)	–36.7 for 50GHz CS –40.5 for 100 GHz CS –44.4 for 200 GHz CS			
Maximum upstream out-of-channel optical PSD – OOC2 (Note 8)	dBm (15 GHz)	–41.6 (4 channels) –48.8 (8 channels)			
Maximum upstream WNE-PSD (Note 9)	dBm (15 GHz)	–62.6			
Jitter transfer	–	See clause 11.1.5.4.1			
Jitter generation	–	See clause 11.1.5.4.3			

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

Item	Unit	Value			
OLT receiver (optical interface R)					
ODN class		N1	N2	E1	E2
Maximum OPP (Note 10) – with Raman effects (DD20, 4 channel) (Note 15) – with Raman effects (DD40, 4 channel) – with Raman effects (DD20, 8 channel) – with Raman effects (DD40, 8 channel)	dB	1.0 1.4 1.0 1.7	1.0 1.6 1.3 2.1	1.5 1.9 1.8 2.8	1.5 1.9 1.8 2.8
Maximum OPP excluding Raman (Note 17) – DD20 – DD40	dB	0.5 1.0			
Maximum reflectance of equipment 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, 4 channel) (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 (Type A) (Note 18) (Type B)	dB (15 GHz)	26.0 22.0	26.0 22.0	25.1 21.1	24.1 20.1
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 4 and 8 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 extinction ratio 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 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.

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

Item	Unit	Value
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 or eight interfering TWDM channels, respectively. NOTE 8 – See OOC-PSD mask in clause 9.3.9. These values are based on the following assumptions: 1 dB US OOC penalty, TWDM PON operates with FEC, and four or eight TWDM channels (three or seven interferers), respectively. In some implementations, this requirement may be achieved by more tightly regulating the Tx 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 Tx 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 clause 9.4.1 of [b-ITU-T G.Sup39] for additional details. NOTE 12 – See clause 11.1.4.3.1 for an approach to accommodate the case of 40 km and 8 wavelengths. NOTE 13 – This parameter is applicable for ONU transmitters that require OLT interaction to tune the transmitting wavelength. NOTE 14 – An optical power levelling mechanism can be applied to the ONU in order to help meet the OOB/OOC PSD and OLT Rx overload parameters. The concept of optical power levelling is described in Annex D. NOTE 15 – The 4 channel, DD20 values are rounded up from those actually calculated. NOTE 16 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989]. NOTE 17 – If the actual OPP is worse than the specified value, it must be compensated by increasing the transmitter mean launch power minimum specification by X dB for each X dB of extra OPP allowance, where X < 1.5 dB, while meeting all other Tx specifications. High penalty operation poses some risks, and PMD interoperability testing should be employed to measure the actual OPP with a receiver subject to in-band crosstalk as specified elsewhere in this table. To avoid system operation in very high penalty regimes, this note is only applicable to the DD20 fibre distance class. NOTE 18 – These values vary for each budget class based on the worst case combination of PtP WDM PON OOB, TWDM PON OOC, TWDM PON WNE-PSD and TWDM PON upstream ONU echoes (accounting for the maximum ODN split that can be obtained in each optical path loss class). NOTE 19 – This value is based on the following assumptions: consideration of multiple upstream ONU echoes and penalties of 0.4 dB (for N1) up to 0.8 dB (for E2).		

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 (wide band option), 1528-1540 (reduced band option) 1532-1540 (narrow band option)
Minimum operating channel spacing	GHz	50
Maximum operating channel spacing	GHz	200

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

Item	Unit	Value			
Maximum spectral excursion (Note 1) (over 1 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 (Note 13)	dB	+/–0.02 dB/GHz			
Minimum tuning window (Note 2) When using cyclic channel grid When not using cyclic channel grid	GHz	 (N+1)*CS (N-1)*CS+2*MSE			
Maximum tuning granularity	GHz	CS/20			
Tx wavelength channel tuning time		See Table 9-2			
Line code	–	Scrambled NRZ (20 km) Scrambled NRZ (40 km) (Note 15)			
Mask of the transmitter eye diagram	–	See clause 11.1.5.3.2			
Maximum reflectance of equipment at R/S, measured at transmitter wavelength (Note 20)	dB	–32			
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) (Note 14)					
– 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 Tx enable transient time	Bits (ns)	1280 (128.6)			
Maximum Tx disable transient time	Bits (ns)	1280 (128.6)			
Minimum extinction ratio (Note 5)	dB	6.0			
Tolerance to reflected optical power	dB	–15			
Dispersion range	ps/nm	0 to 355 (DD20)			
Minimum side mode suppression ratio (Note 6)	dB	30			
Maximum upstream out-of-band optical PSD (Note 7)	dBm (15 GHz)	–57.4 (4 channels)			
		–64.6 (8 channels)			
Maximum upstream out-of-channel optical PSD – OOC1 (Note 8)	dBm (15 GHz)	–36.7 for 50GHz CS –40.5 for 100 GHz CS –44.4 for 200 GHz CS			
Maximum upstream out-of-channel optical PSD – OOC2 (Note 8)	dBm (15 GHz)	–41.6 (4 channels)			
		–48.5 (8 channels)			

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

Item	Unit	Value			
Maximum upstream WNE-PSD (Note 9)	dBm (15 GHz)	–62.6			
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, 15)	dB				
– with Raman effects (DD20, 4 channel) (Note 16)		1.0	1.0	1.5	1.5
– with Raman effects (DD40, 4 channel)		1.9	2.1	2.4	2.4
– with Raman effects (DD20, 8 channel)		1.0	1.3	1.8	1.8
– with Raman effects (DD40, 8 channel)		2.2	2.6	3.3	3.3
Maximum OPP excluding Raman (Note 18)	dB				
– DD20		0.5			
– DD40		1.5			
Maximum reflectance of equipment 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, 4 channel) (Note 5 and Note 12)					
– Type A link (Note 3)	dBm	–26.0	–28.0	–30.5	NA
– Type B link (Note 4)	dBm	–28.0	–30.0	–32.5	–32.5
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 (Type A) (Note 19) (Type B)	dB (15 GHz)	26.0 24.0	26.0 24.0	25.1 23.1	24.1 22.1
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 4 and 8 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 4 and 8 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

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

Item	Unit	Value
precluded.		
NOTE 5 – A lower extinction ratio 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. A lower "Mean launch power minimum" is allowed but must be compensated by higher extinction ratio. For quantitative treatment of these tradeoffs, see clause 11.1.4.3.2.		
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 or eight interfering TWDM channels, respectively.		
NOTE 8 – See OOC-PSD mask in clause 9.3.9. These values are based on the following assumptions: 1 dB US OOC penalty, TWDM PON operates with FEC, and four or eight TWDM channels (three or seven interferers), respectively. In some implementations, this requirement may be achieved by more tightly regulating the Tx 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 Tx 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.		
NOTE 11 – See clause 9.4.1 [b-ITU-T G.Sup39] 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.		
NOTE 13 – This parameter is applicable for ONU transmitters that require OLT interaction to tune the transmitting wavelength.		
NOTE 14 – An optical power levelling mechanism can be applied to the ONU in order to help meet the OOB/OOC PSD and OLT Rx overload parameters. The concept of optical power levelling is described in Annex D.		
NOTE 15 – Scrambled NRZ is assumed for the OPP parameter values. Other coding schemes for 40 km may result in lower OPPs with alternative transmitter technologies. These other coding schemes are for further study.		
NOTE 16 – The 4 channel, DD20 values are rounded up from those actually calculated.		
NOTE 17 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].		
NOTE 18 – If the actual OPP is worse than the specified value, it must be compensated by increasing the transmitter mean launch power minimum specification by X dB for each X dB of extra OPP allowance, where $X < 1.5$ dB, while meeting all other Tx specifications. High penalty operation poses some risks, and PMD interoperability testing should be employed to measure the actual OPP with a receiver subject to in-band crosstalk as specified elsewhere in this table. To avoid system operation in very high penalty regimes, this note is only applicable to the DD20 fibre distance class.		
NOTE 19 – These values vary for each budget class based on the worst case combination of PtP WDM PON OOB, TWDM PON OOC, TWDM PON WNE-PSD and TWDM PON upstream ONU echoes (accounting for the maximum ODN split that can be obtained in each optical path loss class).		
NOTE 20 – This value is based on the following assumptions: consideration of multiple upstream ONU echoes and penalties of 0.4 dB (for N1) up to 0.8 dB (for E2).		

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.

11.1.4.3.2 Extinction ratio and minimum mean launch optical power trade off

This clause is applicable to transmitters subject to the requirement of Table 11-7.

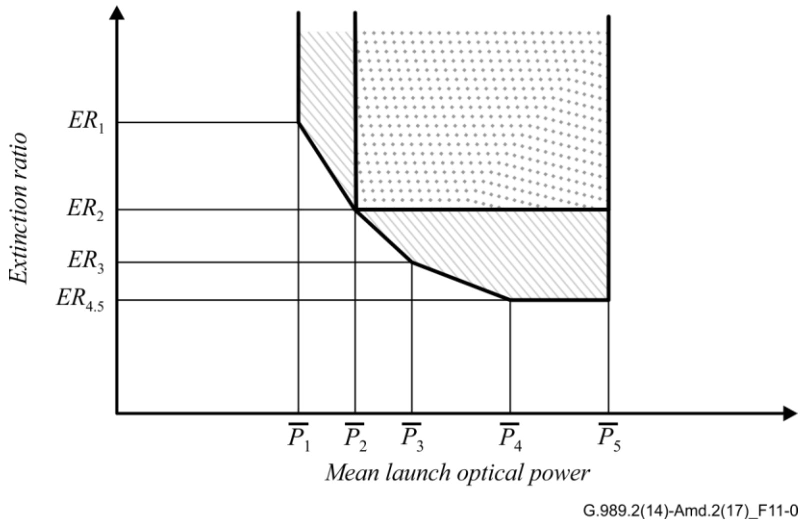


Figure 11-0 – ONU transmitter power and ER admissible region, subject to Table 11-7 requirements

The parameters of the ONU transmitter jointly specified by its mean optical launch power $\overline{P}$ and extinction ratio *ER* shall lie within an admissible region (shown as an overall shaded area in Figure 11-0) which is bounded in the mean launch power by the lines $\overline{P} \geq \overline{P}\,\mathrm{min} = \overline{P}_1$ and $\overline{P} \leq \overline{P}\,\mathrm{max} = \overline{P}_5$, and in the extinction ratio, from below, by a piece-wise linear segment specified in Table 11-7*bis* for Type A transmitters and Table 11-7*ter* for Type B transmitters.

Table 11-7*bis* – The lower boundary ER and mean launch power pairs of the Type A ONU transmitter admissible region

	$(\overline{P}_1, ER_1)$	$(\overline{P}_2, ER_2)$	$(\overline{P}_3, ER_3)$	$(\overline{P}_4, ER_4)$	$(\overline{P}_5, ER_5)$
Mean launch optical power, dBm	3.0	4.0	5.0	7.0	9.0
Extinction ratio, dB	8.0	6.0	5.0	4.0	4.0

Table 11-7*ter* – The lower boundary ER and mean launch power pairs of the Type B ONU transmitter admissible region

	$(\overline{P}_1, ER_1)$	$(\overline{P}_2, ER_2)$	$(\overline{P}_3, ER_3)$	$(\overline{P}_4, ER_4)$	$(\overline{P}_5, ER_5)$
Mean launch optical power, dBm	1.0	2.0	3.5	5.0	7.0
Extinction ratio, dB	8.0	6.0	5.0	4.0	4.0

This admissible region represents a relaxation of the transmitter parameters as compared with the requirements of Table 11-7, where the mean launch optical power and extinction ratio were specified independently from each other (thus limiting the admissible region to a densely shaded rectangular area in Figure 11-0). The boundaries shown by the square with the thin black lines represent the allowable transmit power and extinction ratio defined in Table 11-7.

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 maximum spectral excursion 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.

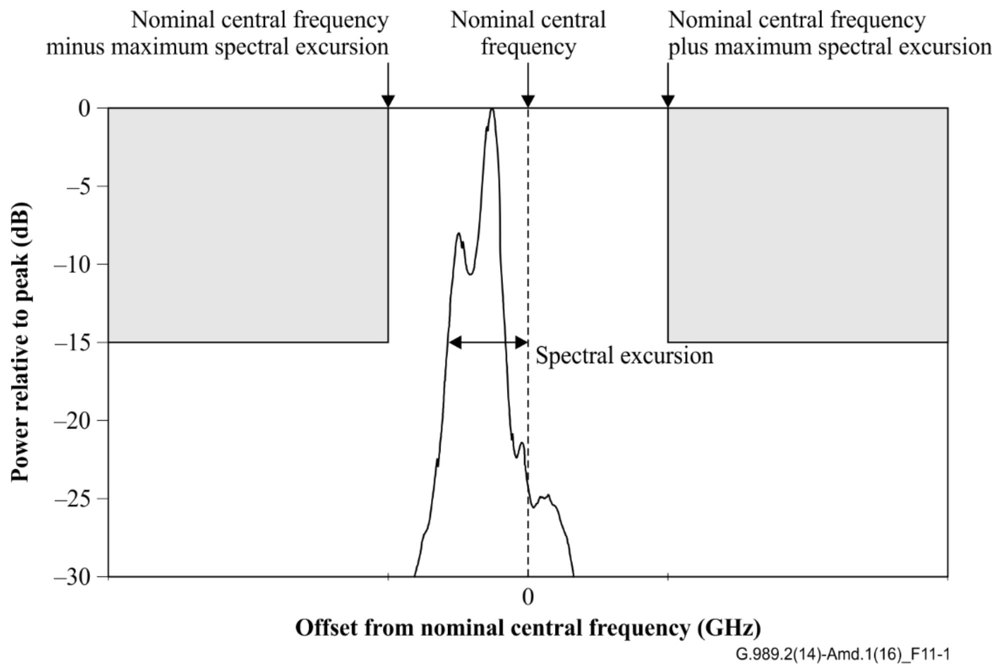


Figure 11-1 – Spectral excursion illustration

The NRZ 'zero' power is allowed outside of the MSE but impact on OOC power must be considered.

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.

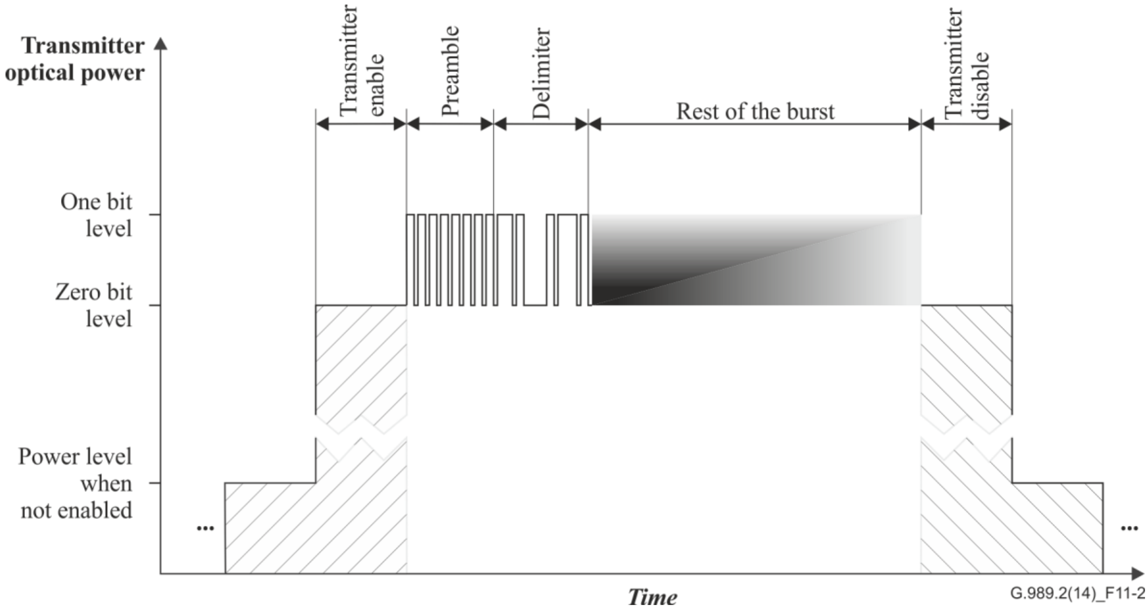


Figure 11-2 – Relationship between ONU power levels and burst times

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.

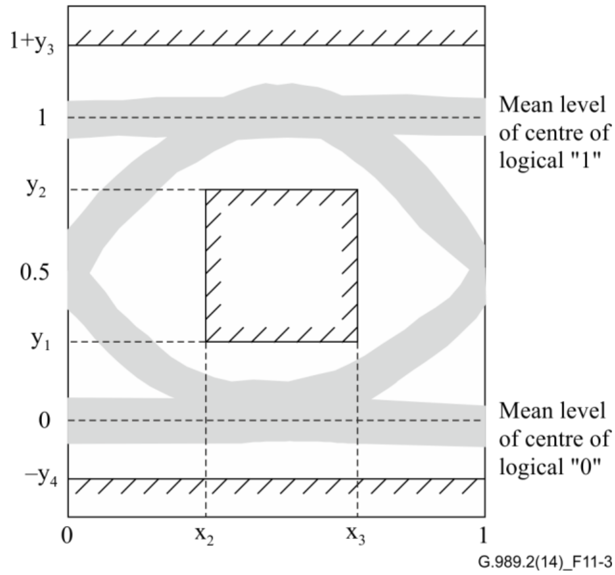
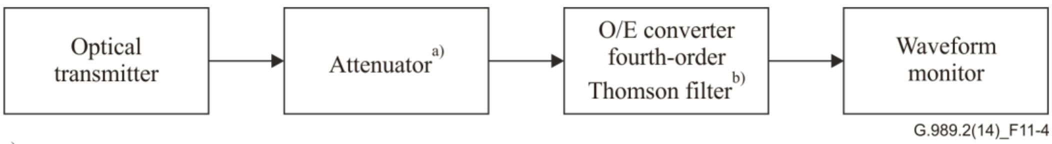


Figure 11-3 – Mask of the eye diagram for OLT transmitter

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

	2.48832 Gbit/s	**9.95328 Gbit/s**
x_3-x_2 (Note 1)	0.2	0.2
y_1, y_3, y_4	0.25	0.25
y_2	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 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.

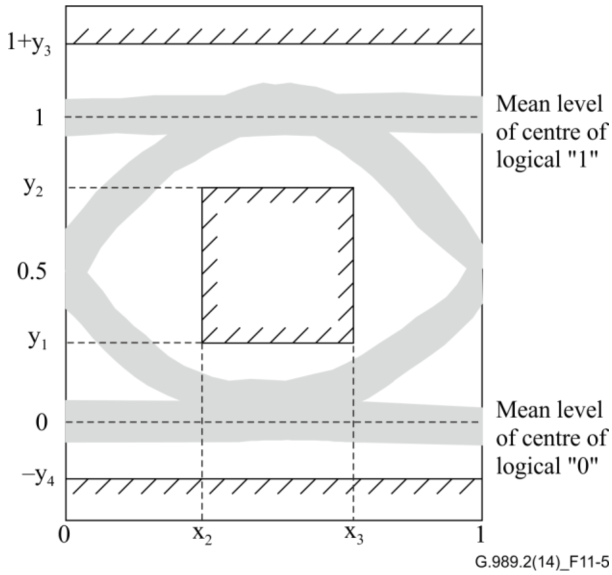
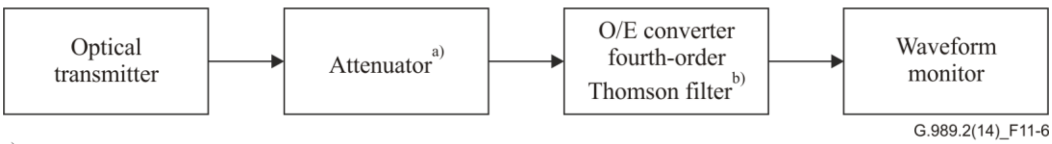


Figure 11-5 – Mask of the eye diagram for ONU transmitter

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

	2.48832 Gbit/s	**9.95328 Gbit/s**
x_3-x_2 (Note 1)	0.2	0.2
y_1, y_3, y_4	0.25	0.25
y_2	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 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.

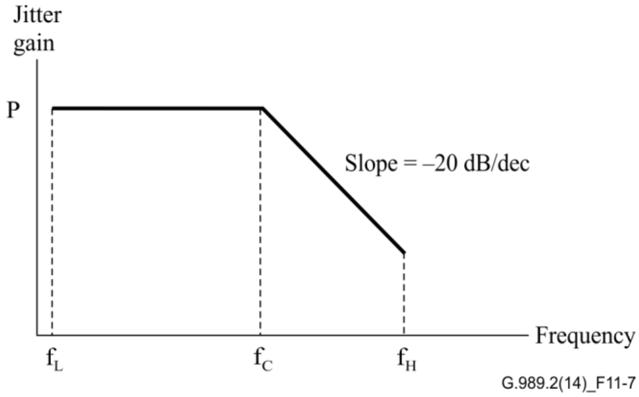
11.1.5.4.1 Jitter transfer

The jitter transfer specification applies only to the ONU.

The jitter transfer function is defined as:

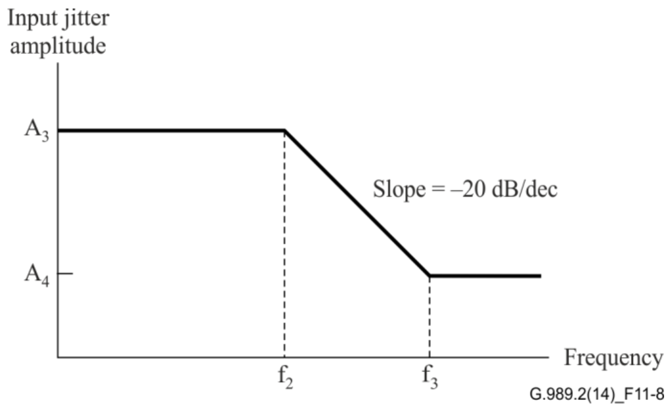
$$jitter\ transfer = 20\log_{10}\left[\frac{jitter\ on\ upstream\ signal\ UI}{jitter\ on\ downstream\ signal\ UI} \times \frac{down\ stream\ bit\ rate}{upstream\ bit\ rate}\right]$$

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.



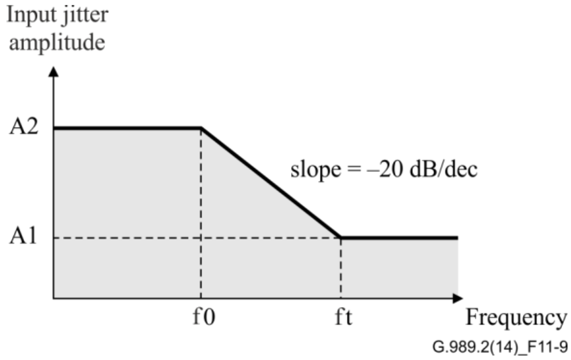
Upstream line rate (Gbit/s)	f_L (kHz)	f_C (kHz)	f_H (kHz)	P (dB)
2.48832	20	2000	20 000	0.1
9.95328	10	1000	80 000	0.1
NOTE – These values are taken from [ITU-T G.783].				

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)	f_t (kHz)	f_0 (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

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	512
9.95328 Gbit/s	2048

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 multiplexer (WM) to a branching node (BN). Figure A.1 shows a logical view of a PtP WDM PON.

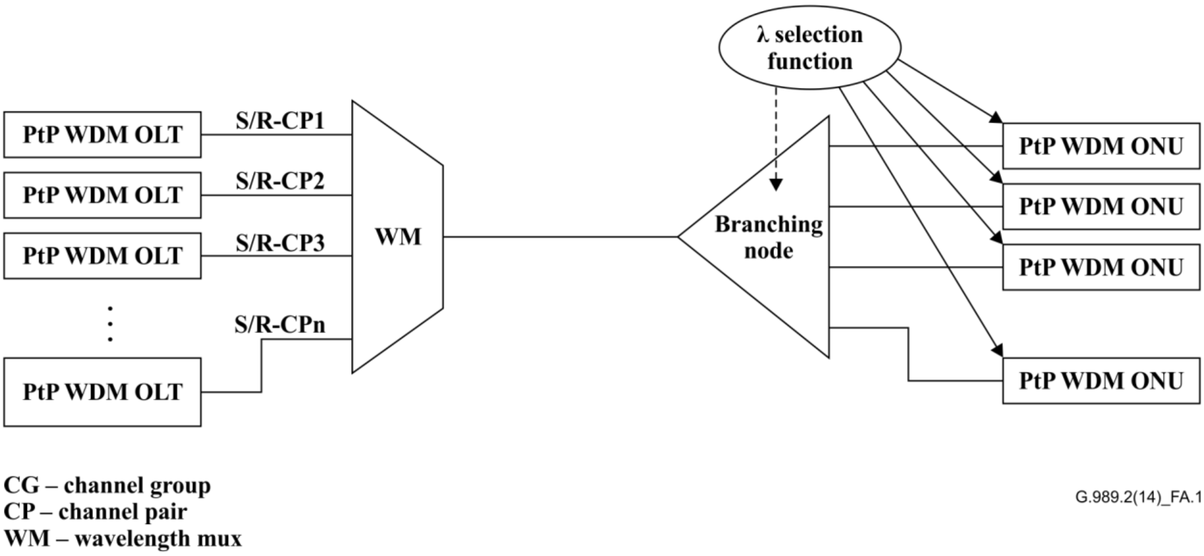


Figure A.1 – Logical architecture of a generic PtP WDM PON

Examples of PtP WDM PON clients include GbE, 10GbE and common public radio interface (CPRI) [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 DS and US	Supported UNI	Reference table downstream/upstream
1	1.24416, 1.25, 1.2288	STM-8 1G Ethernet 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	6.144 9.95328, 9.8304, 10.709, 11.09 10.3125 10.1376	CPRI option 6, OBSAI OC-192, STM-64 CPRI option 7 OTU2, OTU2e 10G Ethernet CPRI option 8	Table A.6/Table A.7

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

The 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 4 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 channel spacing	GHz	50
Maximum operating channel spacing	GHz	200
Maximum spectral excursion	GHz	+/–12.5 for 50GHz CS +/–20 for 100GHz CS +/–25 for 200GHz CS
Line code	–	Determined by application (scrambled NRZ assumed for parameter values)
Mask of the transmitter eye diagram	–	See clause A.1.6.2

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			
Maximum reflectance of equipment 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) without FEC	dBm	–1	+1	+3	+5
Mean channel launch power minimum (at S/R-CG) with FEC	dBm	0	+2	+4	+6
Mean channel launch power maximum (at S/R-CG) without FEC	dBm	+3	+5	+7	+9
Mean channel launch power maximum (at S/R-CG) with FEC	dBm	+4	+6	+8	+10
Maximum downstream WNE-PSD	dBm (15 GHz)	–63.7			
Minimum extinction ratio (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), 0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)			
Minimum side mode suppression ratio (at S/R-CP)	dB	30			
Maximum downstream per channel out-of-band optical PSD (Assuming eight Ch PtP WDM PON) (Note 3)	dBm (15 GHz)	–46.5			
Maximum downstream per channel out-of-channel optical PSD (Assuming eight Ch PtP WDM PON) (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 (without FEC)			
		1.0 (with FEC ON)			
Maximum reflectance of equipment at R/S, measured at receiver wavelength	dB	–20			
Rx wavelength channel tuning time		See Table 9-2			
Maximum tuning granularity	GHz	CS/20			
ODN Class		N1	N2	E1	E2
Sensitivity (at R/S) @ BER=10^{-12}	dBm	–31.5	–31.5	–31.5	–31.5
Sensitivity (at R/S) @ BER=10^{-4} (Note 6)	dBm	–30	–30	–30	–30
Overload (at R/S) @ BER=10^{-12}	dBm	–11	–11	–11	–11
Overload (at R/S) @ BER=10^{-4} (Note 6)	dBm	–10	–10	–10	–10

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
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 extinction ratio must be compensated by a larger transmitter launch power within the limits of the mean launch power maximum value. NOTE 2 – This formula (see clause 6.10 of [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 nanometre 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, 8 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application. NOTE 6 – See clause 9.4.1of [b-ITU-T G.Sup39] for additional details. NOTE 7 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].		

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 channel spacing	GHz	50
Maximum operating channel spacing	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
Tx wavelength channel tuning time	ms	See Table 9-2
Line code	–	Determined by application (scrambled NRZ assumed for parameter values)

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			
Mask of the transmitter eye diagram	–	See clause A.1.6.2			
Maximum reflectance of equipment 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) without FEC	dBm	+3	+3	+3	+3
Mean channel launch power minimum (at R/S) with FEC	dBm	0	0	0	0
Mean channel launch power maximum (at R/S) without FEC	dBm	+8	+8	+8	+8
Mean channel launch power minimum (at R/S) with FEC	dBm	+5	+5	+5	+5
Minimum extinction ratio (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), 0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)			
Minimum side mode suppression ratio (Note 3)	dB	30			
Maximum upstream out-of-band optical PSD (Note 4)	dBm (15 GHz)	–58.6			
Maximum upstream out-of-channel optical 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 out-of-channel optical 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 (without FEC)			
		1.0 (with FEC on)			
Maximum reflectance of equipment at S/R-CG, measured at receiver wavelength	dB	–20			
ODN Class		N1	N2	E1	E2
Sensitivity (at S/R-CG) @ BER=10^{-12}	dBm	–27.5	–29.5	–31.5	–33.5
Sensitivity (at S/R-CG) @ BER=10^{-4} (Note 7)	dBm	–30.0	–32.0	–34.0	–36.0
Overload (at S/R-CG) @ BER=10^{-12}	dBm	–6	–8	–10	–12
Overload (at S/R-CG) @ BER=10^{-4} (Note 7)	dBm	–9	–11	–13	–15

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
In-band crosstalk tolerance	dB (15GHz)	34.8
Consecutive identical digit immunity	bit	72
Jitter tolerance	–	See clause A.1.6.3

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

NOTE 2 – This formula (see clause 6.10 of [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 nanometre 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 8 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 Tx 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application.

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

NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].

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 4 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 channel spacing	GHz	50			
Maximum operating channel spacing	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 of equipment 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) without FEC	dBm	+3	+5	FFS	FFS
Mean channel launch power minimum (at S/R-CG) with FEC		0	+2	+4	+6
Mean channel launch power maximum (at S/R-CG) without FEC	dBm	+7	+9	FFS	FFS
Mean channel launch power maximum (at S/R-CG) with FEC		+4	+6	+8	+10
Maximum downstream WNE-PSD	dBm (15 GHz)	FFS			
Minimum extinction ratio (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion Range (Note 2)	ps/nm	$0 \text{ to } \frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), $0 \text{ to } \frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)			
Minimum side mode suppression ratio (at S/R-CP)	dB	30			
Maximum downstream per channel out-of-band optical PSD (Note 3)	dBm (15 GHz)	–46.5			
Maximum downstream per channel out-of-channel optical PSD (Note 4)	dBm (15 GHz)	–52.1			
Jitter generation	–	See clause A.1.6.3			

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			
ONU receiver (optical interface R)					
Maximum OPP (Note 5) – with Raman effects	dB	2.0 (without FEC)			
		1.0 (with FEC)			
Maximum reflectance of equipment at R/S, measured at receiver wavelength	dB	–20			
Rx wavelength channel tuning time		See Table 9-2			
Maximum tuning granularity	GHz	CS/20			
ODN Class		N1	N2	E1	E2
Sensitivity (at R/S) @ BER=10^{-12}	dBm	–28	–28	FFS	FFS
Sensitivity (at R/S) @ BER=10^{-4} (Note 6)	dBm	–30	–30	–30	–30
Overload (at R/S) @ BER=10^{-12}	dBm	–7	–7	FFS	FFS
Overload (at R/S) @ BER=10^{-4} (Note 6)	dBm	–10	–10	–10	–10
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 extinction ratio must be compensated by a larger transmitter launch power within the limits of the "Mean launch power maximum" value.

NOTE 2 – This formula (see clause 6.10 of [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 nanometre 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 8 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application.

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

NOTE 7 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].

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 channel spacing	GHz	50			
Maximum operating channel spacing	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			
Tx 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 of equipment 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) without FEC	dBm	+3	+3	+3	+3
Mean channel launch power minimum (at R/S) with FEC	dBm	+0	+0	+0	+0
Mean channel launch power maximum (at R/S) without FEC	dBm	+8	+8	+8	+8
Mean channel launch power maximum (at R/S) with FEC	dBm	+5	+5	+5	+5
Minimum extinction ratio (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	$0 \text{ to } \frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), $0 \text{ to } \frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)			
Minimum side mode suppression ratio (Note 3)	dB	30			
Maximum upstream out-of-band optical PSD (Assuming eight Ch PtP WDM PON) (Note 4)	dBm (15 GHz)	–58.6			
Maximum upstream out-of-channel optical 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			

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			
Maximum upstream out-of-channel optical 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)					
ODN Class		N1	N2	E1	E2
Maximum OPP – without FEC	dB	2.0	2.0	2.0	2.0
Maximum OPP – with FEC ON (Note 6)		1.0	1.0	1.5	1.5
Maximum reflectance of equipment at S/R-CG, measured at receiver wavelength	dB	–20			
ODN Class		N1	N2	E1	E2
Sensitivity (at S/R-CG) @ BER=10^{-12}	dBm	–28	–30	–32	–34
Sensitivity (at S/R-CG) @ BER=10^{-4} (Note 7)	dBm	–30	–32	–34.5	–36.5
Overload (at S/R-CG) @ BER=10^{-12}	dBm	–6	–8	–10	–12
Overload (at S/R-CG) @ BER=10^{-4} (Note 7)	dBm	–9	–11	–13	–15
In-band crosstalk tolerance	dB (15 GHz)	34.8			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	See clause A.1.6.3			

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

NOTE 2 – This formula (see clause 6.10 of [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 nanometre 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 (7 interferers). In some implementations, this requirement may be achieved by more tightly regulating the Tx 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application.

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

NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].

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 4 PtP WDM channels.

Table A.6 – Optical interface parameters for line rate class 3 (from 6.144 Gbit/s to 11.09 Gbit/s) downstream direction

Item	Unit	Value			
OLT transmitter (optical interface S)					
Nominal line rate	Gbit/s	6.144 to 11.09			
Operating wavelength band	nm	1603-1625 (shared spectrum) 1524-1625 (expanded spectrum)			
Minimum operating channel spacing	GHz	50			
Maximum operating channel spacing	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 of equipment 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) without FEC	dBm	+8	FFS	FFS	FFS
Mean channel launch power minimum (at S/R-CG) with FEC	dBm	+3.0	+5.0	+7.0	+9.0
Mean channel launch power maximum (at S/R-CG) without FEC	dBm	+11	FFS	FFS	FFS
Mean channel launch power maximum (at S/R-CG) with FEC	dBm	+7.0	+9.0	+11.0	+11.0
Maximum downstream WNE-PSD	dBm (15 GHz)	FFS			
Minimum extinction ratio (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	$0 \text{ to } \frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), $0 \text{ to } \frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)			
Minimum side mode suppression ratio (at S/R-CP)	dB	30			
Maximum downstream per channel out-of-band optical PSD (Assuming eight Ch PtP WDM PON) (Note 3)	dBm (15 GHz)	–46.5			

Table A.6 – Optical interface parameters for line rate class 3 (from 6.144 Gbit/s to 11.09 Gbit/s) downstream direction

Item	Unit	Value			
Maximum downstream per channel out-of-channel optical PSD (Assuming eight Ch PtP WDM PON) (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	2.5 (without FEC) 2.0 (with FEC)			
Maximum reflectance of equipment at R/S, measured at receiver wavelength	dB	–20			
Rx wavelength channel tuning time		See Table 9-2			
Maximum tuning granularity	GHz	CS/20			
ODN Class		N1	N2	E1	E2
Sensitivity (at R/S) @ BER=10^{-12}	dBm	–23.5	FFS	FFS	FFS
Sensitivity (at R/S) @ BER=10^{-3} (Note 6)	dBm	–28	–28	–28	–28
Overload (at R/S) @ BER=10^{-12}	dBm	–2	FFS	FFS	FFS
Overload (at R/S) @ BER=10^{-3} (Note 6)	dBm	–7.0	–7.0	–7.0	–9.0
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 extinction ratio must be compensated by a larger transmitter launch power within the limits of the "Mean launch power maximum" value.

NOTE 2 – This formula (see clause 6.10 of [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 nanometre 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 40km 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application.

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

NOTE 7 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].

Table A.7 – Optical interface parameters for line rate class 3 (from 6.144 Gbit/s to 11.09 Gbit/s) upstream direction

Item	Unit	Value			
ONU transmitter (optical interface S)					
Nominal line rate	Gbit/s	6.144 to 11.09			
Operating wavelength band	nm	1603-1625 (shared spectrum) 1524-1625 (expanded spectrum)			
Minimum tuning window	nm	Based on operating wavelength band			
Minimum operating channel spacing	GHz	50			
Maximum operating channel spacing	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			
Tx 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 of equipment 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) without FEC	dBm	+3	+3	+3	FFS
Mean channel launch power minimum (at R/S) with FEC	dBm	+4.0	+4.0	+4.0	+4.0
Mean channel launch power maximum (at R/S) without FEC	dBm	+8	+8	+8	FFS
Mean channel launch power maximum (at R/S) with FEC	dBm	+9.0	+9.0	+9.0	+9.0
Minimum extinction ratio (Note 1)	dB	8.2			
Tolerance to reflected optical power	dB	–15			
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), 0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)			
Minimum side mode suppression ratio (Note 3)	dB	30			
Maximum upstream out-of-band optical PSD (Note 4)	dBm (15 GHz)	–58.6			
Maximum upstream out-of-channel optical PSD – OOC1 (Note 5)	dBm (15 GHz)	–33.7 for 50GHz CS –37.5 for 100 GHz CS –41.4 for 200 GHz CS			

Table A.7 – Optical interface parameters for line rate class 3 (from 6.144 Gbit/s to 11.09 Gbit/s) upstream direction

Item	Unit	Value			
Maximum upstream out-of-channel optical 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)					
ODN Class		N1	N2	E1	E2
Maximum OPP – without FEC	dB	2.5	2.5	2.5	2.5
Maximum OPP – with FEC ON (Note 6)	dB	1.5	1.5	2.0	2.0
Maximum reflectance of equipment at S/R-CG, measured at receiver wavelength	dB	–20			
ODN Class		N1	N2	E1	E2
Sensitivity (at S/R-CG) @ BER=10^{-12}	dBm	–28.5	–30.5	–32.5	FFS
Sensitivity (at S/R-CG) @ BER=10^{-3} (Note 7)	dBm	–26.5	–28.5	–31.0	NA
Overload (at S/R-CG) @ BER=10^{-12}	dBm	–6	–8	–10	FFS
Overload (at S/R-CG) @ BER=10^{-3} (Note 7)	dBm	–5.0	–7.0	–9.0	NA
In-band crosstalk tolerance	dB (15 GHz)	34.8			
Consecutive identical digit immunity	bit	72			
Jitter tolerance	–	See clause A.1.6.3			

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

NOTE 2 – This formula (see clause 6.10 of [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 nanometre 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 Tx 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application.

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

NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is

Table A.7 – Optical interface parameters for line rate class 3 (from 6.144 Gbit/s to 11.09 Gbit/s) upstream direction

Item	Unit	Value
defined in clause 3.2.2.10 of [ITU-T G.989].		

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, illustrated in Figure A.2, for both the OLT and ONU transmitters are shown in Table A.8.

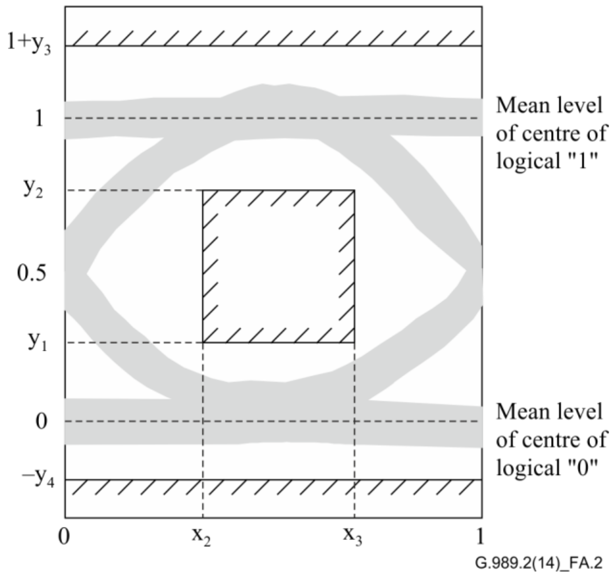


Figure A.2 – Mask of the eye diagram for OLT and ONU transmitter

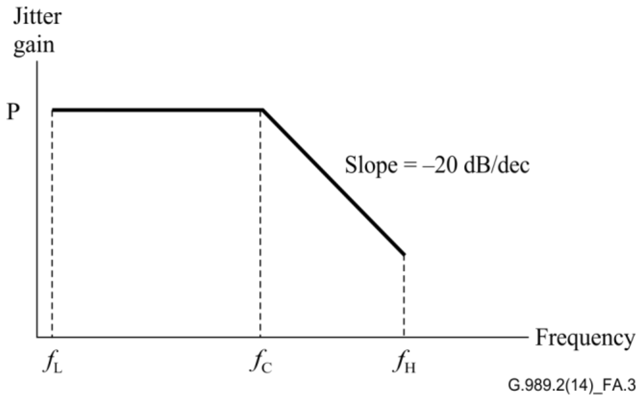
Table A.8 – Mask of the eye diagram for OLT and ONU transmitters – numeric values

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.

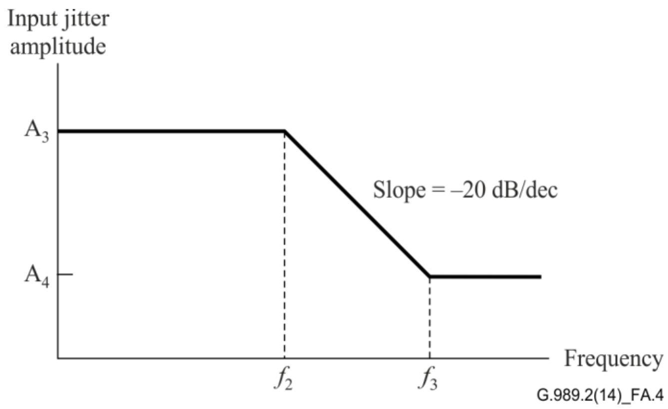
Jitter transfer for ONU is shown in Figure A.3.



Line rate class	f_L (kHz)	f_C (kHz)	f_H (kHz)	P (dB)
1	20	2000	20 000	0.1
2	20	2000	20 000	0.1
3	10	1000	80 000	0.1
NOTE – These values are taken or derived from [ITU-T G.783].				

Figure A.3 – Jitter transfer for ONU

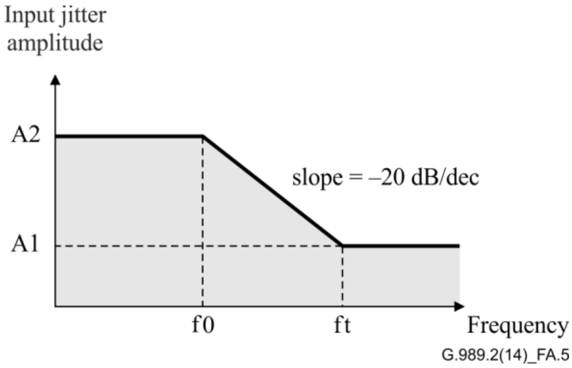
High-band portion of sinusoidal jitter mask for jitter transfer is shown in Figure A.4.



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.

B.1 Introduction

In the PtP WDM PON part of NG-PON2, a so-called auxiliary management and control channel is needed in order to convey wavelength assignment and allocation information and OAM data. The AMCC is added to each individual wavelength in both, downstream and upstream direction. Two different physical-layer implementations of the AMCC exist. These determine the way the AMCC content is transported over the physical channel. The content of the AMCC is independent of the way it is transmitted and is described in clause 6 and Annex G of [ITU-T G.989.3].

For the case that the PtP WDM PON system has to transparently transport a payload bitstream, without terminating any part of its frame structure, the AMCC has to be added to the payload at the same wavelength with only minor interference of the AMCC and the payload data. This case is called *transparent AMCC*. The framed AMCC data is added to the payload with low-modulation-index baseband over-modulation (i.e., a low-frequency amplitude modulation which is superimposed to the (amplitude) modulation of the payload bitstream). Alternatively, electrical-addition of amplitude-modulated signal with low-frequency carrier to the payload, called RF-pilot-tone-style, can be employed for accommodating the framed AMCC data. The detection of the baseband-overmodulation-based AMCC can (for example) be done by low-pass filtering of the detected payload signal and passing the amplified resulting signal into a simple threshold detector. The RF-pilot-tone-style AMCC can (for example) be detected by simple digital signal processing offering the functions of band-pass filtering, down-conversion and symbol decision.

In the case that the PtP WDN PON system converts the payload data encoding from one to another, the AMCC data can be transmitted by means of code transformation. This case is called *transcoding AMCC* and is described in Annex G of [ITU-T G.989.3].

B.2 Transparent AMCC

B.2.1 Baseband overmodulation

The physical transport layer for the overmodulation-based AMCC is realized as a low-bitrate, low-modulation-index baseband amplitude over-modulation over the optical PtP payload signal. The modulation index M is calculated (in percent) as $M = 100 * \frac{P_{\max} - P_{\min}}{P_{average}}$ with $P_{\max}$, $P_{\min}$ and $P_{average}$ referring to the maximum, minimum and average power values of the envelope of the over-modulated PtP signal. The optical interface parameters for the AMCC are given in Table B.1.

Table B.1 – Optical interface parameters of transparent AMCC

Item	Unit	Value
Nominal line rate	kb/s	115
Modulation index	%	10
Pulse shape	–	Rectangular

B.2.2 RF-pilot-tone

The physical transport layer for the RF-pilot-tone-based AMCC is realized as a low-bitrate, low-carrier-frequency, low-modulation-index amplitude modulation signal which is added to the PtP payload signal in the electrical domain. The modulation index M is defined (in percent) as $M = 100 * \frac{V_{pp,AMCC}}{V_{pp,payload}}$, with $V_{pp,AMCC}$ and $V_{pp,payload}$ referring to the peak to peak voltage values of the AMCC and the PtP signal in the electrical domain. The interface parameters for the RF-pilot-tone-style AMCC are given in Table B.2.

Table B.2 – Electrical interface parameters of transparent AMCC

Item	Unit	Value
Nominal line rate	kb/s	128
Modulation index	%	10
carrier-frequency	kHz	500

Annex C

Low loss (LL) PtP WDM PON PMD layer requirements

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

This annex describes a low loss PtP WDM PON system that caters to the wavelength routed (WR) use cases within NG-PON2.

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 multiplexer (WM) to a branching node. Figure C.1 shows a logical view of a PtP WDM PON based on wavelength routed ODN, which is one of the optional use cases of NG-PON2. The wavelength-routed PtP WDM PON (WR PtP WDM PON) has the λ selection function as part of the branching node. The ONU's wavelength is determined by its physical connectivity to the ODN, for example by a port on an AWG.

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

At a branching node (BN), the ODN branches out to drop fibres, one for each ONU. The BN may include any combination of power splitters, bandpass or bandstop filters, or wavelength filters (e.g., AWGs). In the specific case of wavelength-routed PtP WDM PON, a wavelength selection function is required in the branching node, one wavelength per direction for each drop fibre.

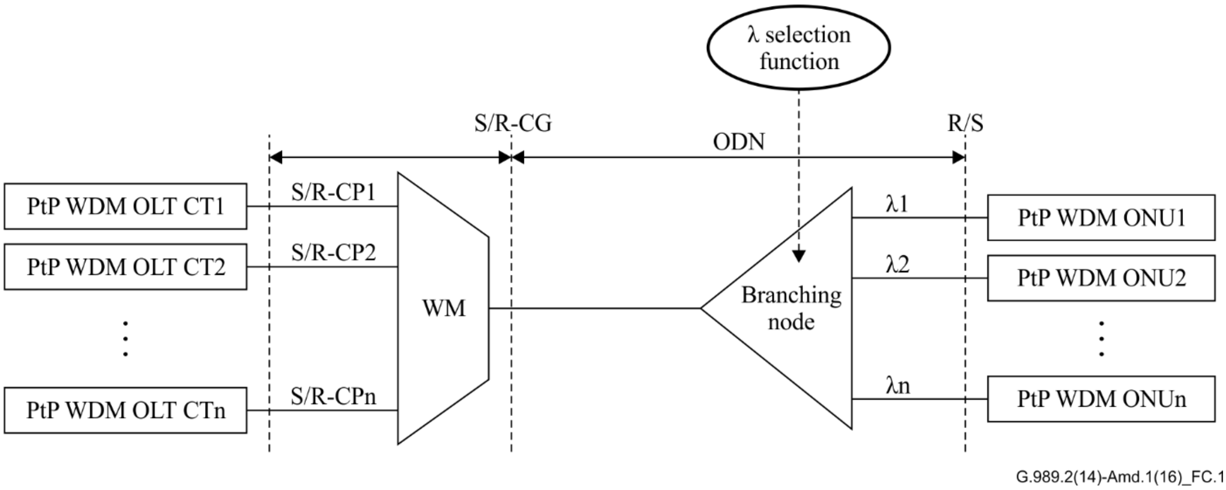


Figure C.1 – Logical architecture of wavelength routed PtP WDM PON
(one use case in the NG-PON2 system)

C.1 PMD layer requirements

All parameters are specified as follows, and are in accordance with Table C.3 to Table C.8.

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 clause 9.9 of [ITU-T G.989.1]. The parameters are specified relative to a bit error ratio (BER) not worse than the values specified in Table C.3 to Table C.8.

C.1.1 ODN optical path loss classes

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

The optical path loss for each class is specified between S/R-CG at the OLT and R/S at the ONU side in each direction. OLT side WM is not included in ODN, but it will impact OLT launch power and sensitivity.

Table C.1 – ODN optical path loss classes (ODN classes)

	Class L1	Class L2
Minimum optical path loss	8 dB	16 dB
Maximum optical path loss	17 dB	25 dB
Maximum differential optical path loss	9 dB	

C.1.2 Fibre distance classes

Fibre distance classes are specified in Table 6-2.

C.1.3 Line rate

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

Parameters to be defined are categorized by downstream and upstream, and the nominal line rates as shown in Line rate class.

The LL 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 C.3 to Table C.8.

Table C.2 – Relation between LL PtP WDM PON line rate classes and optical parameter tables

Line rate class	Nominal line rate [Gbit/s] – Symmetric DS and US	Supported UNI	Reference table downstream/upstream
1	1.24416, 1.25, 1.2288	STM-8 1G Ethernet CPRI option 2	Table C.3/Table C.4
2	2.48832, 2.4576, 2.666	OC-48, STM-16 CPRI option 3 OTU1	Table C.5/Table C.6
3	6.144 9.95328, 9.8304, 10.709, 11.09 10.3125 10.1376	CPRI option 6, OBSAI OC-192, STM-64 CPRI option 7 OTU2, OTU2e 10G Ethernet CPRI option 8	Table C.7/Table C.8

C.1.4 FEC code selection

The choice of FEC depends on the service protocol.

Both FEC ON and FEC OFF (or no FEC) can be supported.

C.1.5 Line code

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

C.1.6 Operating wavelength

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

Two wavelength bands for LL PtP WDM PON are specified:

1) Shared spectrum band: 1603-1625 nm;

2) Expanded spectrum band: 1524-1625 nm.

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

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

C.1.7 PMD parameters

The assumptions for the physical media dependent (PMD) parameters for the low loss PtP WDM PON in the following tables are different than those used for Annex A. This is due to the fact that one aspect of the low loss approach is to allow wavelength routed ODNs which facilitate a larger number of PtP channels. This affects the calculations of OOB, OOC and inter-channel cross talk, as is noted in the particular tables.

C.1.7.1 Optical interface parameters for line rate class 1

The following optical interface parameter tables are applicable for up to 40 km fibre length.

Table C.3 – 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 channel spacing	GHz	50	
Maximum operating channel spacing	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 C.1.8.2	
Maximum reflectance of equipment at S/R-CG, measured at transmitter wavelength	dB	NA	
Minimum ORL of ODN at S/R-CG	dB	32	
ODN Class		L1	L2
Mean channel launch power minimum (at S/R-CG) without FEC	dBm	–5	+3
Mean channel launch power minimum (at S/R-CG) with FEC	dBm	–8	0
Mean channel launch power maximum	dBm	–1	+7

Table C.3 – Optical interface parameters for line rate class 1 (from 1.2288 Gbit/s to 1.25 Gbit/s) downstream direction

Item	Unit	Value	
(at S/R-CG) without FEC			
Mean channel launch power maximum (at S/R-CG) with FEC	dBm	–4	+4
Maximum downstream WNE-PSD	dBm (15 GHz)	FFS	
Minimum extinction ratio (at S/R-CG) (Note 1)	dB	8.2	
Tolerance to reflected optical power	dB	–15	
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), 0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)	
Minimum side mode suppression ratio (Note 3)	dB	30	
Maximum downstream per channel out-of-band optical PSD (Note 6)	dBm (15 GHz)	–49.2	
Maximum downstream per channel out-of-channel optical PSD (Note 7)	dBm (15 GHz)	–61.2	
Jitter generation	–	See clause C.1.8.3	
ONU receiver (optical interface R)			
Maximum OPP (Note 4) – with Raman effects	dB	2.0 (without FEC)	
		1.0 (with FEC ON)	
Maximum reflectance of equipment at R/S, measured at receiver wavelength	dB	–20	
Rx wavelength channel tuning time		See Table 9-2	
Maximum tuning granularity	GHz	CS/20	
ODN Class		L1	L2
Sensitivity (at R/S) @ BER=10^{-12}	dBm	–24	–24
Sensitivity (at R/S) @ BER=10^{-4} (Note 5)	dBm	–26	–26
Overload (at R/S) @ BER=10^{-12}	dBm	–2	–2
Overload (at R/S) @ BER=10^{-4} (Note 5)	dBm	–5	–5
In-band crosstalk tolerance	dB (15 GHz)	37.2	
Consecutive identical digit immunity	bit	72	
Jitter tolerance	–	See clause C.1.8.3	

Table C.3 – Optical interface parameters for line rate class 1 (from 1.2288 Gbit/s to 1.25 Gbit/s) downstream direction

Item	Unit	Value
NOTE 1 – A lower extinction ratio must be compensated by a larger transmitter launch power within the limits of the mean launch power MAX value. NOTE 2 – This formula (see clause 6.10 of [ITU-T G.652]) is used instead of the worst case value due to the large variation of dispersion within the LL 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 nanometre units, considering the spectral excursion. NOTE 3 – For downstream, SMSR is measured on the laser output, before any filtering. This prevents a significant mode partition noise penalty. NOTE 4 – 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application. NOTE 5 – See clause 9.4.1 of [b-ITU-T G.Sup39] for additional details. NOTE 6 – 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 16 PtP WDM channels (15 interferers). NOTE 7 – 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, 16 PtP WDM channels (15 interferers). NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].		

Table C.4 – 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 operating channel spacing	GHz	50
Maximum operating channel spacing	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
Tx 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 C.1.823
Maximum reflectance of equipment at R/S, measured at transmitter wavelength	dB	–6

Table C.4 – Optical interface parameters of line rate class 1 (from 1.2288 Gbit/s to 1.25 Gbit/s) upstream direction

Item	Unit	Value	
Minimum ORL of ODN at R/S	dB	32	
ODN Class		L1	L2
Mean channel launch power minimum (at R/S) without FEC	dBm	–1	–1
Mean channel launch power minimum (at R/S) with FEC	dBm	–4	–4
Mean channel launch power maximum (at R/S) without FEC	dBm	4	4
Mean channel launch power minimum (at R/S) with FEC	dBm	1	1
Minimum extinction ratio (Note 1)	dB	8.2	
Tolerance to reflected optical power	dB	–15	
Dispersion range (Note 2)	ps/nm	$0 \text{ to } \frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), $0 \text{ to } \frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)	
Minimum side mode suppression ratio (Note 3)	dB	30	
Maximum upstream out-of-band optical PSD (Note 6)	dBm (15 GHz)	–55.7	
Maximum upstream out-of-channel optical PSD – OOC1 (Note 7)	dBm (15 GHz)	–31.7 for 50GHz CS –35.5 for 100 GHz CS –39.4 for 200 GHz CS	
Maximum upstream out-of-channel optical PSD – OOC2 (Note 7)	dBm (15 GHz)	–58.2	
Jitter transfer	–	See clause C.1.8.3	
Jitter generation	–	See clause C.1.8.3	
OLT receiver (optical interface R)			
Maximum OPP (Note 4) – with Raman effects	dB	2.0 (without FEC)	
		1.0 (with FEC on)	
Maximum reflectance of equipment at S/R-CG, measured at receiver wavelength	dB	–20	
ODN Class		L1	L2
Sensitivity (at S/R-CG) @ BER=10^{-12}	dBm	–20	–28
Sensitivity (at S/R-CG) @ BER=10^{-4} (Note 5)	dBm	–22	–30
Overload (at S/R-CG) @ BER=10^{-12}	dBm	3	–5
Overload (at S/R-CG) @ BER=10^{-4} (Note 5)	dBm	1	–7

Table C.4 – Optical interface parameters of line rate class 1 (from 1.2288 Gbit/s to 1.25 Gbit/s) upstream direction

Item	Unit	Value
In-band crosstalk tolerance	dB (15 GHz)	–37.4
Consecutive identical digit immunity	bit	72
Jitter tolerance	–	See clause C.1.8.3

NOTE 1 – A lower extinction ratio must be compensated by a larger transmitter launch power within the limits of the mean launch power MAX value.

NOTE 2 – This formula (see clause 6.10 of [ITU-T G.652]) is used instead of the worst case value due to the large variation of dispersion within the LL 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 nanometre 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.

NOTE 4 – 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the Expanded Spectrum are determined by application.

NOTE 5 – See clause 9.4.1 of [b-ITU-T G.Sup39] for additional details.

NOTE 6 – This value is based the following assumptions: remote node is 1:16 splitter limited by the 9 dB differential loss, OOB impact from PtP WDM PON on TWDM PON can be controlled through filtering from WM, 0.1 dB penalty, TWDM PON operates with FEC and 16 PtP WDM channels (15 interferers).

NOTE 7 – This value is based the following assumptions: remote node is 1:16 splitter limited by the 9 dB differential loss, OOC in upstream can be controlled through filtering from WM, 0.1 dB penalty, PtP WDM PON operates without FEC, 16 PtP WDM channels (15 interferers).

NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].

C.1.7.2 Optical interface parameters for line rate class 2

The following optical interface parameter tables are applicable for up to 40 km fibre length.

Table C.5 – 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 channel spacing	GHz	50	
Maximum operating channel spacing	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 C.1.8.2	
Maximum reflectance of equipment at S/R-CG, measured at transmitter wavelength	dB	NA	
Minimum ORL of ODN at S/R-CG	dB	32	
ODN Class		L1	L2
Mean channel launch power minimum (at S/R-CG) without FEC	dBm	–5	+3
Mean channel launch power minimum (at S/R-CG) with FEC	dBm	–8	-0
Mean channel launch power maximum (at S/R-CG) without FEC	dBm	–1	+5
Mean channel launch power maximum (at S/R-CG) with FEC	dBm	–4	+4
Maximum downstream WNE-PSD	dBm (15 GHz)	FFS	
Minimum extinction ratio (at S/R-CG) (Note 1)	dB	8.2	
Tolerance to reflected optical power	dB	–15	
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), 0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)	
Minimum side mode suppression ratio (Note 3)	dB	30	
Maximum downstream per channel out-of-band optical PSD (Note 6)	dBm (15 GHz)	–49.2	
Maximum downstream per channel out-of-channel optical PSD (Note 7)	dBm (15 GHz)	–61.2	
Jitter generation	–	See clause C.1.8.3	
ONU receiver (optical interface R)			

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

Item	Unit	Value	
Maximum OPP (Note 4) – with Raman effects	dB	2.0 (without FEC)	
		1.0 (with FEC ON)	
Maximum reflectance of equipment at R/S, measured at receiver wavelength	dB	–20	
Rx wavelength channel tuning time		See Table 9-2	
Maximum tuning granularity	GHz	CS/20	
ODN Class		L1	L2
Sensitivity (at R/S) @ BER=10^{-12}	dBm	–24	–24
Sensitivity (at R/S) @ BER=10^{-4} (Note 5)	dBm	–26	–26
Overload (at R/S) @ BER=10^{-12}	dBm	–2	–2
Overload (at R/S) @ BER=10^{-4} (Note 5)	dBm	–5	–5
In-band crosstalk tolerance	dB (15 GHz)	–37.2	
Consecutive identical digit immunity	bit	72	
Jitter tolerance	–	See clause C.1.8.3	

NOTE 1 – A lower extinction ratio must be compensated by a larger transmitter launch power within the limits of the mean launch power MAX value.

NOTE 2 – This formula (see clause 6.10 of [ITU-T G.652]) is used instead of the worst case value due to the large variation of dispersion within the LL 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 nanometre units, considering the spectral excursion.

NOTE 3 – For downstream, SMSR is measured on the laser output, before any filtering. This prevents a significant mode partition noise penalty.

NOTE 4 – 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application.

NOTE 5 – See clause 9.4.1 of [b-ITU-T G.Sup39] for additional details.

NOTE 6 – 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 16 PtP WDM channels (15 interferers).

NOTE 7 – 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, 16 PtP WDM channels (15 interferers).

NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].

Table C.6 – 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 operating channel spacing	GHz	50	
Maximum operating channel spacing	GHz	200	
Maximum tuning granularity	GHz	CS/20	
Tx 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 C.1.8.2	
Maximum reflectance of equipment at R/S, measured at transmitter wavelength	dB	–6	
Minimum ORL of ODN at R/S	dB	32	
ODN Class		L1	L2
Mean channel launch power minimum (at R/S) without FEC	dBm	–1	–1
Mean channel launch power minimum (at R/S) with FEC	dBm	–4	–4
Mean channel launch power maximum (at R/S) without FEC	dBm	4	4
Mean channel launch power minimum (at R/S) with FEC	dBm	1	1
Minimum extinction ratio (Note 1)	dB	8.2	
Tolerance to reflected optical power	dB	–15	
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), 0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)	
Minimum side mode suppression ratio (Note 3)	dB	30	
Maximum upstream out-of-band optical PSD (Note 6)	dBm (15 GHz)	–55.7	
Maximum upstream out-of-channel optical PSD – OOC1 (Note 7)	dBm (15 GHz)	–31.7 for 50 GHz CS –35.5 for 100 GHz CS –39.4 for 200 GHz CS	
Maximum upstream out-of-channel optical PSD – OOC2 (Note 7)	dBm (15 GHz)	–58.2	
Jitter transfer	–	See clause C.1.8.3	
Jitter generation	–	See clause C.1.8.3	
OLT receiver (optical interface R)			

Table C.6 – Optical interface parameters for line rate class 2 (from 2.4576 Gbit/s to 2.666 Gbit/s) upstream direction

<table>
<tr><th>Item</th><th>Unit</th><th colspan="2">Value</th></tr>
<tr><td rowspan="2">Maximum OPP (Note 4)
– with Raman effects</td><td rowspan="2">dB</td><td colspan="2">2.0 (without FEC)</td></tr>
<tr><td colspan="2">1.0 (with FEC on)</td></tr>
<tr><td>Maximum reflectance of equipment at S/R-CG, measured at receiver wavelength</td><td>dB</td><td colspan="2">–20</td></tr>
<tr><td colspan="2">ODN Class</td><td>L1</td><td>L2</td></tr>
<tr><td>Sensitivity (at S/R-CG) @ BER=$10^{–12}$</td><td>dBm</td><td>–20</td><td>–28</td></tr>
<tr><td>Sensitivity (at S/R-CG) @ BER=$10^{–4}$ (Note 5)</td><td>dBm</td><td>–22</td><td>–30</td></tr>
<tr><td>Overload (at S/R-CG) @ BER=$10^{–12}$</td><td>dBm</td><td>3</td><td>–5</td></tr>
<tr><td>Overload (at S/R-CG) @ BER=$10^{–4}$ (Note 5)</td><td>dBm</td><td>1</td><td>–7</td></tr>
<tr><td>In-band crosstalk tolerance</td><td>dB
(15 GHz)</td><td colspan="2">–37.4</td></tr>
<tr><td>Consecutive identical digit immunity</td><td>bit</td><td colspan="2">72</td></tr>
<tr><td>Jitter tolerance</td><td>–</td><td colspan="2">See clause C.1.8.3</td></tr>
<tr><td colspan="4">NOTE 1 – A lower extinction ratio must be compensated by a larger transmitter launch power within the limits of the mean launch power MAX value.
NOTE 2 – This formula (see clause 6.10 of [ITU-T G.652]) is used instead of the worst case value due to the large variation of dispersion within the LL 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 nanometre 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.
NOTE 4 – 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application.
NOTE 5 – See clause 9.4.1 of [b-ITU-T G.Sup39] for additional details.
NOTE 6 – This value is based the following assumptions: remote node is 1:16 splitter limited by the 9 dB differential loss, OOB impact from PtP WDM PON on TWDM PON can be controlled through filtering from WM, 0.1 dB penalty, TWDM PON operates with FEC and 16 PtP WDM channels (15 interferers).
NOTE 7 – This value is based the following assumptions: remote node is 1:16 splitter limited by the 9 dB differential loss, OOC in upstream can be controlled through filtering from WM, 0.1 dB penalty, PtP WDM PON operates without FEC, 16 PtP WDM channels (15 interferers).
NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].</td></tr>
</table>

C.1.7.3 Optical interface parameters for line rate class 3

The following optical interface parameter tables are applicable for up to 40 km fibre length.

Table C.7 – Optical interface parameters for line rate class 3 (from 6.144 Gbit/s to 11.09 Gbit/s) downstream direction

Item	Unit	Value	
OLT transmitter (optical interface S)			
Nominal line rate	Gbit/s	6.144 to 11.09	
Operating wavelength band	nm	1603-1625 (shared spectrum) 1524-1625 (expanded spectrum)	
Minimum operating channel spacing	GHz	50	
Maximum operating channel spacing	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 C.1.8.2	
Maximum reflectance of equipment at S/R-CG, measured at transmitter wavelength	dB	NA	
Minimum ORL of ODN at S/R-CG	dB	32	
ODN Class		L1	L2
Mean channel launch power minimum (at S/R-CG) without FEC	dBm	–4	4
Mean channel launch power minimum (at S/R-CG) with FEC	dBm	–6	2
Mean channel launch power maximum (at S/R-CG) without FEC	dBm	0	8
Mean channel launch power maximum (at S/R-CG) with FEC	dBm	–2	6
Maximum downstream WNE-PSD	dBm (15 GHz)	FFS	
Minimum extinction ratio (Note 1)	dB	6	
Tolerance to reflected optical power	dB	–15	
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), 0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)	
Minimum side mode suppression ratio (at S/R-CP) (Note 3)	dB	30	
Maximum downstream per channel out-of-band optical PSD (Note 6)	dBm (15 GHz)	–49.2	
Maximum downstream per channel out-of-channel optical PSD (Note 7)	dBm (15 GHz)	–61.2	
Jitter generation	–	See clause C.1.8.3	

Table C.7 – Optical interface parameters for line rate class 3 (from 6.144 Gbit/s to 11.09 Gbit/s) downstream direction

Item	Unit	Value	
ONU receiver (optical interface R)			
Maximum OPP (Note 4) – with Raman effects	dB	2.5 (without FEC)	
		2.5 (with FEC ON)	
Maximum reflectance of equipment at R/S, measured at receiver wavelength	dB	–20	
Rx wavelength channel tuning time		See Table 9-2	
Maximum tuning granularity	GHz	CS/20	
ODN Class		L1	L2
Sensitivity (at R/S) @ BER=10^{-12}	dBm	–23.5	–23.5
Sensitivity (at R/S) @ BER=10^{-3} (Note 5)	dBm	–25.5	–25.5
Overload (at R/S) @ BER=10^{-12}	dBm	–1	–1
Overload (at R/S) @ BER=10^{-3} (Note 5)	dBm	–3	–3
In-band crosstalk tolerance	dB (15 GHz)	–38.2	
Consecutive identical digit immunity	bit	72	
Jitter tolerance	–	See clause C.1.8.3	

NOTE 1 – A lower extinction ratio must be compensated by a larger transmitter launch power within the limits of the mean launch power MAX value.

NOTE 2 – This formula (see clause 6.10 of [ITU-T G.652]) is used instead of the worst case value due to the large variation of dispersion within the LL 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 nanometre units, considering the spectral excursion.

NOTE 3 – For downstream, SMSR is measured on the laser output, before any filtering. This prevents a significant mode partition noise penalty.

NOTE 4 – 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application.

NOTE 5 – See clause 9.4.1 of [b-ITU-T G.Sup39] for additional details.

NOTE 6 – 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 16 PtP WDM channels (15 interferers).

NOTE 7 – 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, 16 PtP WDM channels (15 interferers).

NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].

Table C.8 – Optical interface parameters of line rate class 3 (from 6.144 Gbit/s to 11.09 Gbit/s) upstream direction

Item	Unit	Value	
ONU transmitter (optical interface S)			
Nominal line rate	Gbit/s	6.144 to 11.09	
Operating wavelength band	nm	1603-1625 (shared spectrum) 1524-1625 (expanded spectrum)	
Minimum operating channel spacing	GHz	50	
Maximum operating channel spacing	GHz	200	
Maximum tuning granularity	GHz	CS/20	
Tx 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 C.1.8.2	
Maximum reflectance of equipment at R/S, measured at transmitter wavelength	dB	–6	
Minimum ORL of ODN at R/S	dB	32	
ODN Class		L1	L2
Mean channel launch power minimum (at R/S) without FEC	dBm	–1	–1
Mean channel launch power minimum (at R/S) with FEC	dBm	–2	–2
Mean channel launch power maximum (at R/S) without FEC	dBm	4	4
Mean channel launch power minimum (at R/S) with FEC	dBm	3	3
Minimum extinction ratio (Note 1)	dB	6	
Tolerance to reflected optical power	dB	–15	
Dispersion range (Note 2)	ps/nm	0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 20$ (DD20), 0 to $\frac{0.092\times\lambda}{4}\left[1-\left(\frac{1300}{\lambda}\right)^2\right]\times 40$ (DD40)	
Minimum side mode suppression ratio (Note 3)	dB	30	
Maximum upstream out-of-band optical PSD (Note 6)	dBm (15 GHz)	–55.7	
Maximum upstream out-of-channel optical PSD – OOC1 (Note 7)	dBm (15 GHz)	–31.7 for 50 GHz CS –35.5 for 100 GHz CS –39.4 for 200 GHz CS	
Maximum upstream out-of-channel optical PSD – OOC2 (Note 7)	dBm (15 GHz)	–58.2	
Jitter transfer	–	See clause C.1.8.3	
Jitter generation	–	See clause C.1.8.3	

Table C.8 – Optical interface parameters of line rate class 3 (from 6.144 Gbit/s to 11.09 Gbit/s) upstream direction

Item	Unit	Value	
OLT receiver (optical interface R)			
Maximum OPP (Note 4) – with Raman effects	dB	2.5 (without FEC)	
		2.5 (with FEC on)	
Maximum reflectance of equipment at S/R-CG, measured at receiver wavelength	dB	–20	
ODN Class		L1	L2
Sensitivity (at S/R-CG) @ BER=10^{-12}	dBm	–20.5	–28.5
Sensitivity (at **S/R-CG**) @ BER=10^{-3} (Note 5)	dBm	–21.5	–29.5
Overload (at S/R-CG) @ BER=10^{-12}	dBm	3	–5
Overload (at **S/R-CG**) @ BER=10^{-3} (Note 5)	dBm	2	–6
In-band crosstalk tolerance	dB (15 GHz)	–37.4	
Consecutive identical digit immunity	bit	72	
Jitter tolerance	–	See clause C.1.8.3	

NOTE 1 – A lower extinction ratio must be compensated by a larger transmitter launch power within the limits of the mean launch power MAX value.

NOTE 2 – This formula (see clause 6.10 of [ITU-T G.652]) is used instead of the worst case value due to the large variation of dispersion within the LL 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 nanometre 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.

NOTE 4 – 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. Maximum OPP value assumes the use of the shared spectrum band, OPP related to Raman impacts for the expanded spectrum are determined by application.

NOTE 5 – See clause 9.4.1 of [b-ITU-T G.Sup39] for additional details.

NOTE 6 – This value is based the following assumptions: remote node is 1:16 splitter limited by the 9 dB differential loss, OOB impact from PtP WDM PON on TWDM PON can be controlled through filtering from WM, 0.1 dB penalty, TWDM PON operates with FEC and 16 PtP WDM channels (15 interferers).

NOTE 7 – This value is based the following assumptions: remote node is 1:16 splitter limited by the 9 dB differential loss, OOC in upstream can be controlled through filtering from WM, 0.1 dB penalty, PtP WDM PON operates without FEC, 16 PtP WDM channels (15 interferers).

NOTE 8 – The definition of In-band crosstalk tolerance and its implication on receiver sensitivity is defined in clause 3.2.2.10 of [ITU-T G.989].

C.1.8 Transmitter at reference point S

This clause is in accordance with clause 11.1.5, except where indicated otherwise.

C.1.8.1 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.

C.1.8.2 Mask of transmitter eye diagram

The parameters specifying the mask of the eye diagram, illustrated in Figure C.2, for both the OLT and ONU transmitters are shown in Table C.9.

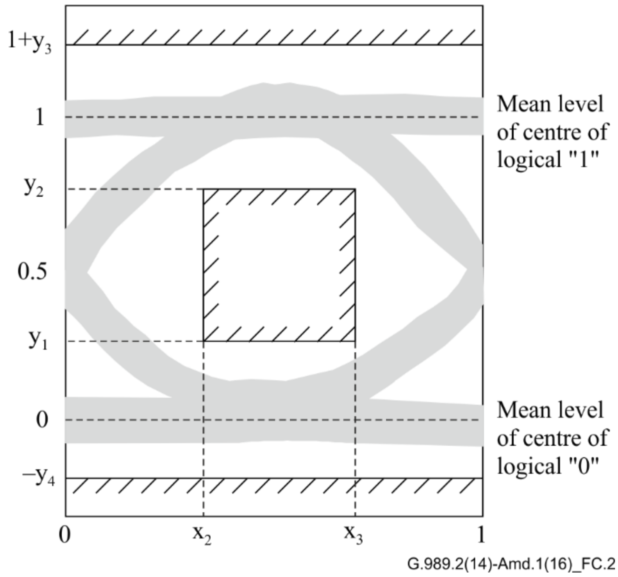


Figure C.2 – Mask of the eye diagram for OLT and ONU transmitter

Table C.9 – Mask of the eye diagram for OLT and ONU transmitters – Numeric values

Line rate class	1.2288 to 1.25 Gbit/s	2.4576 to 2.666 Gbit/s	6.144 to 11.09 Gbit/s
x3-x2 (Note 1)	0.2	0.2	0.2
y1, y3, y4	0.25	0.25	0.25
y2	0.75	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 for the classes 2 (~2.5Gbit/s) and 3 (~ 10 Gbit/s) are taken from clause 7.2.2.14 of [ITU-T G.959.1]. NOTE 3 – The values for the class 1 (~1.25 Gbit/s) are derived from clause 7.2.2.14 of [ITU-T G.959.1].			

C.1.8.3 Jitter performance

Jitter performance of PtP WDM PON is in accordance with 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:

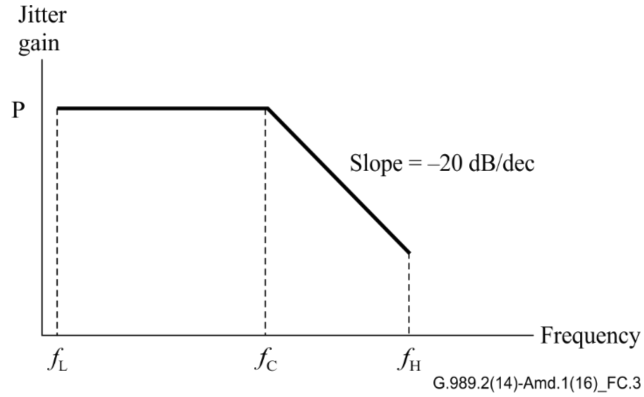


Figure C.3 – Jitter transfer for ONU

Table C.10 – Jitter transfer parameters for ONU

Line rate class	f_L (kHz)	f_C (kHz)	f_H (kHz)	P (dB)
1.2288 to 1.25 Gbit/s	10	1000	10 000	0.1
2.4576 to 2.666 Gbit/s	20	2000	20 000	0.1
6.144 to 11.09 Gbit/s	10	1000	80 000	0.1
NOTE – These values are taken or derived from clause 15 of [ITU-T G.783]				

High-band portion of sinusoidal jitter mask for jitter transfer:

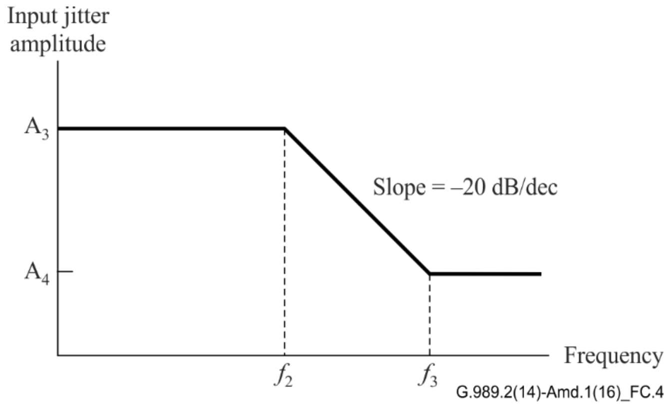


Figure C.4 – High-band portion of sinusoidal jitter mask for jitter transfer

Table C.11 – High-band portions of sinusoidal jitter mask parameters

Line rate class	A_3 (UI)	A_4 (UI)	f_2 (kHz)	f_3 (kHz)
1.2288 to 1.25 Gbit/s	1.5	0.15	50	500
2.4576 to 2.666 Gbit/s	1.5	0.15	100	1000
6.144 to 11.09 Gbit/s	1.5	0.15	400	4000
NOTE – These values are taken or derived from clause 15 of [ITU-T G.783].				

Jitter tolerance mask:

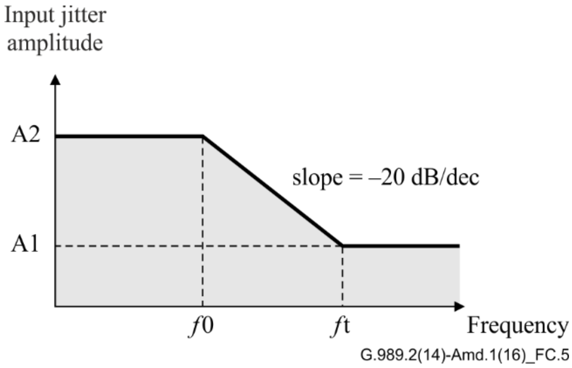


Figure C.5 – Jitter tolerance mask

Table C.12 – Jitter tolerance mask parameters

Line rate class	f_t [kHz]	f_0 [kHz]	A1 [UIp-p]	A2 [UIp-p]
1.2288 to 1.25 Gbit/s	500	50	0.075	0.75
2.4576 to 2.666 Gbit/s	1000	100	0.075	0.75
6.144 to 11.09 Gbit/s	4000	400	0.075	0.75
NOTE – These values are scaled to 10 Gbit/s from the values in clause 8.2.8.9 of [ITU-T G.984.2].				

Annex D

ONU power levelling

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

D.1 Interaction between NG-PON2 PMD layer and TC layer

Power levelling is defined to allow the ONU's mean launch power level to be attenuated in order to meet certain criteria. This levelling can be initiated by the OLT, or managed completely by the ONU. The ONU can activate at its highest attenuation level, gradually adjusting its attenuation level to achieve steps of higher mean launch power, until the ONU initially ranges on the PON. In this annex, the focus is on ONU autonomous optical power levelling, providing an example of how it can be used.

D.2 Power levelling (PL) mechanism at ONU transmitter

The introduction of multi-wavelengths in PON, in combination with the large differential optical path loss of the ODN, results in several difficult to meet optical parameters, namely:

1) Out of band PSD
2) Out of channel PSD
3) Wavelength multiplexer isolation
4) OLT receiver overload

While a number of potential mechanisms exist to meet the various parameters, the use of PL is able to mitigate all of these effects with a single mechanism. However, to obtain the latter two benefits of WM isolation and OLT receiver overload relaxation all ONUs on the ODN must employ the same PL mechanism. Described in this Annex are the details of the mechanism which shall be used if PL is applied.

PL can be realized in at least two different ways. First, the laser current can be adjusted to achieve a modest reduction in optical out, but only in the main mode of the laser (i.e., broadband side mode and amplified spontaneous emission (ASE) power are not impacted). As a result, this mechanism is only useful in addressing WM isolation and OLT Rx overload. A second approach is the use of a variable optic attenuator (VOA) function that attenuates all of the light from the ONU transmitter which then addresses all four of the optical parameters listed above. This annex focuses on using the VOA method to control PL.

Further, the PL mechanism can also be realized via autonomous and/or directed command mechanisms.

D.3 ONU autonomous power levelling

It is possible for the ONU to autonomously control its output power based on the received signal strength indication (RSSI) value, which is an approximation of the actual received downstream power from the OLT via the ODN. Therefore the RSSI is an approximate indication of the ODN loss. Note that the RSSI includes the variability of the OLT laser power which is 4 dB. However autonomous PL can still be effective in reducing the impact of the ODN dynamic range as long as it does not have to eliminate the entire dynamic range but rather reduce it. The following mechanism for autonomous PL will take advantage of the ITU-T G.989.2 PMD requirements that define the highest allowed optical power expected at the ONU. When the highest optical power is received the ODN should be at minimum allowed attenuation (for a given ODN class) and the OLT Tx power should be at the maximum allowed transmit power (for a given ODN class). If the downstream is at the minimum allowed attenuation then the upstream must also be at the minimum allowed attenuation, except for the difference in the optical attenuation for the upstream vs. downstream wavelengths. The differential attenuation due to wavelength difference is well under 1 dB even for a 40 km ODN and is not considered in this annex.

The following example will examine the relationship between the downstream RSSI and the appropriate PL setting as well as the magnitude of mitigation of the ODN dynamic range that may be obtained autonomously by the ONU using PL.

Example:

Tables 11-5 and 11-7 for 10G downstream and upstream type A links contain the following relevant parameters:

- OOC2 PSD = −45.7 dBm/15 GHz;
- ONU Rx Sensitivity = −28 dBm;
- ONU Rx Overload = −7 dBm;
- ONU Tx Maximum Power = +9 dBm.

Additionally, Appendix II and Table 6-1, contain, respectively, the following parameters:

- ONU RSSI accuracy = +/−3 dB;
- ODN maximum differential optical path loss = 15 dB.

If the ONU RSSI reading were considered absolutely accurate and the reading was −7 dBm this would indicate that the ODN is at the minimum loss with the OLT Tx at maximum power. This would allow the transmitter power to be reduced by 15 dB using PL. However due to the +/3 dB accuracy error of the RSSI, the allowed PL is reduced by 3 dB to only 12 dB. It is assumed in this analysis that the inaccuracy of the PL attenuation is negligible. As the downstream RSSI decreases, the PL must eventually be reduced until the PL = 0 and the laser reaches full power to ensure minimum upstream optical power is obtained over the entire ODN attenuation range.

While it is possible to determine the approximate laser power using optical line supervision parameters at the ONU, the tolerance of that reading is no better than the RSSI. So the only useful information available to the ONU is the downstream RSSI and it must be assumed that the ODN loss is increasing rather than the OLT Tx power is decreasing as RSSI falls.

To avoid falling below the OLT minimum receive power level, the ONU must begin to reduce the PL from 12 dB when the RSSI falls below –7 dBm.

Assuming the minimum step size is 3 dB the following rules would apply (other steps, for example 1 dB, are also possible):

1) If the ONU RSSI is greater than or equal to –7 dBm, then PL of 12 dB is applied.
2) If the ONU RSSI is less than –7 and greater than or equal to –10 dBm, then PL of 9 dB is applied.
3) If the ONU RSSI is less than –10 and greater than or equal to –13 dBm, then PL of 6 dB is applied.
4) If the ONU RSSI is less than –13 and greater than or equal to –16 dBm, then PL of 3 dB is applied.
5) If the ONU RSSI is less than –16 then PL of 0 dB is applied.

The PL procedure reduces the apparent differential optical path loss of the ODN and, hence, the optical dynamic range at the OLT, at least for ONUs with PL. If all ONUs implement PL then all of the four optical parameters (OOC, OOB, isolation, overload) could be relaxed. However if there is a mix of ONUs with and without PL, then only the PSD requirements (OOC and OOB) will be able to be relaxed for the ONUs employing PL.

D.4 OOC and OOB PSD relaxation

The PSD requirements in Tables 11-6 and 11-7 are based on the worst case dynamic range of upstream bursts as received at the S/R-CG point. If the apparent differential optical path loss of the ODN can be reduced, then the PSD levels may be relaxed, for ONUs with PL.

In this example, it is possible to effectively reduce the apparent differential optical path loss of the ODN by up to 12 dB (15 dB ideal, minus 3 dB accuracy).

Considering the maximum OOC2 PSD requirement of −45.7 dBm/15 GHz and considering that the maximum ONU Tx power is +9 dBm then the out of channel side mode suppression ratio (SMSR) requirement without PL is +9 dBm – (−45.7 dBm) = 54.7 dB. Therefore the 12 dB PL allows a relaxation of SMSR to 42.7 dB. Note that OOB PSD benefits in the same way from this technique.

Upon completion of autonomous PL, the ONU should send a message to the OLT after ranging to indicate it is operating PL mode and the level of PL it is using.

D.5 OLT directed ONU power levelling

The directed mode applies only to ONUs that are capable of PL in excess of 12 dB, or if more precise control of PL is needed. If the PL values possible with the ONU autonomous method are insufficient for the laser being used, then an additional 6-9 dB of mitigation is possible via control by the OLT using the mechanisms provided in [ITU-T G.989.3].

The directed PL mechanism requires functionalities belonging to the TC layer, such as the ONU capability to increase/reduce the transmitted power on the basis of downstream messages sent by the OLT. Such functionalities, as well as the capability to perform PL during initialization or as well as during operation, are for further study.

D.6 ONU troubleshooting considerations

Without power levelling it is possible to determine whether an ONU is transmitting outside of PMD launch power requirements by locally measuring the optical power from the ONU using a PON power meter. For ONUs with PL this becomes somewhat more complicated. Conceivably, one might troubleshoot by measuring both the downstream and upstream powers at the ONU to determine if the ONU is transmitting outside of the range of the PMD tables for ONUs without PL. The downstream optical power measurement could be used to check if it is compliant with the PL rules described above. However, due to the limitations on accuracy of the RSSI reading at the ONU, there is scope for a significant difference in what the PON power meter will be detecting and what the ONU determines is being received. Furthermore, it is possible that, near the cross-over points of the ranges defined in clause D.3, that the insertion loss of the power meter could cause the ONU's RSSI signal to drop to the next range and result in the ONU Tx level being driven 3 dB higher. The above factors should be taken into account by network operators and system designers when designing troubleshooting procedures.

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 in Figure I.1 to provide an understanding of the considerations when coexisting with NG-PON2.

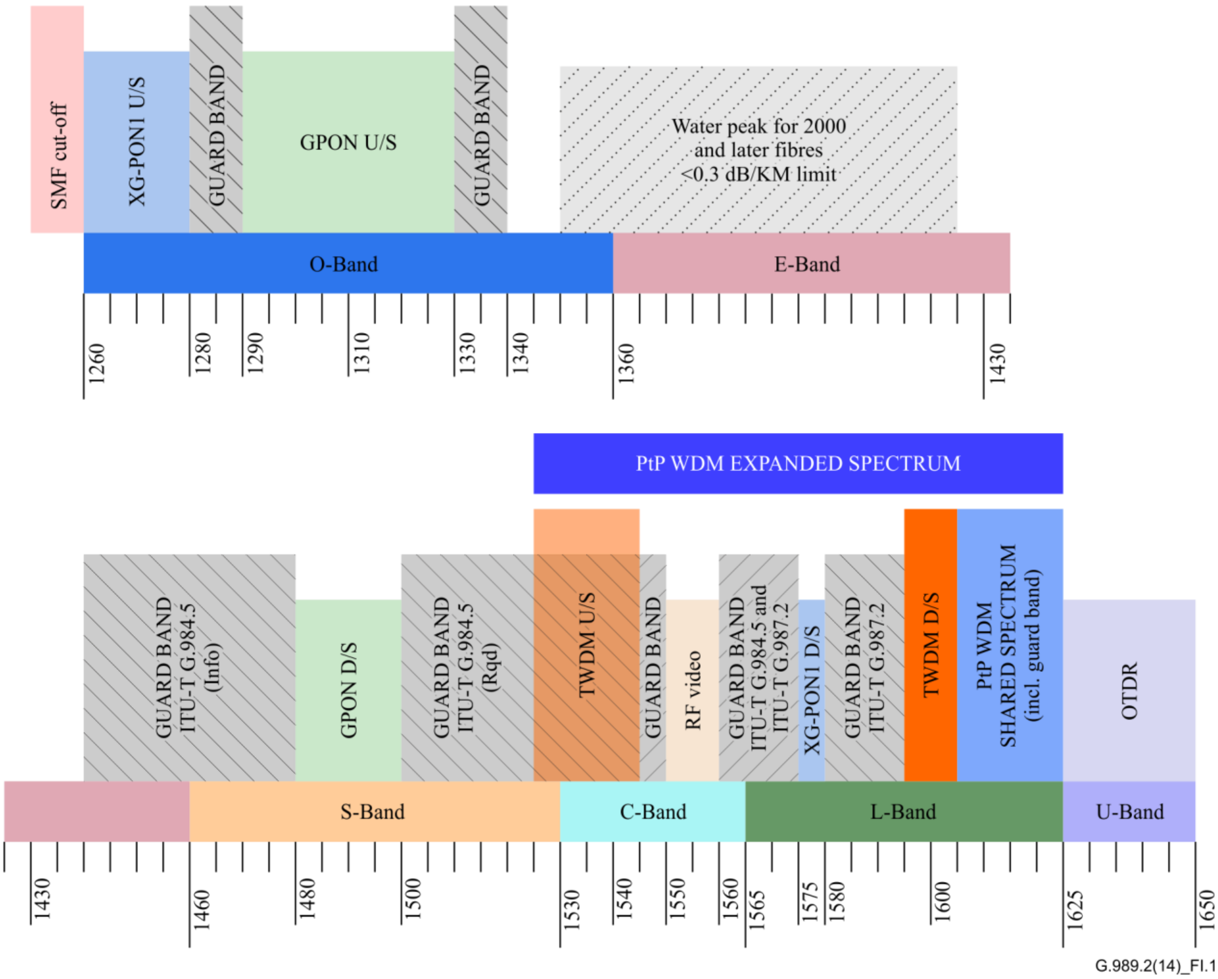


Figure I.1 – NG-PON2 wavelength plan – Coexistence representation

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 appendix. 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
V				V
0	=	1e3		0x02 0x9A
0.0065	=	1.0015e3		0x02 0x9B
V				V
+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
V				V
–27.972	=	1.595	=	0x01 0x3F
–27.959	=	1.600	=	0x01 0x40
–27.945	=	1.605	=	0x01 0x41
V				V
–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 physical layer overhead time (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.

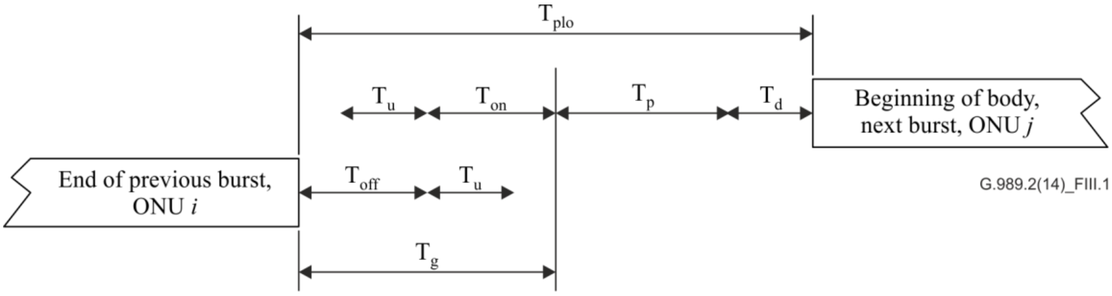


Figure III.1 – Timing relationship between the various physical layer overhead times

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:

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

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:

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

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	**Transmitter disable**	**Total time, T_{plo}**	**Guard time, T_g**	**Preamble time, T_p**	**Delimiter time, T_d**
2.48832 **Gb/s** ***Worst case*** in bit times (ns)	320 (128.6)	320 (128.6)	2048 (823.1)	512 (205.8)	1472 (610.9)	64 (25.7)
2.48832 **Gb/s** ***Objective*** in bit time (ns)	64 (25.7)	64 (25.7)	512 (205.8)	128 (51.4)	320 (128.6)	32 (12.8)
9.95328 **Gb/s** ***Worst case*** in bit times (ns)	1280 (128.6)	1280 (128.6)	8192 (823.1)	2048 (205.8)	6080 (610.9)	64 (6.4)
9.95328 **Gb/s** ***Objective*** in bit times (ns)	256 (25.7)	256 (25.7)	2048 (205.8)	512 (51.4)	1280 (128.6)	32 (3.2)

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 for further study. 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.

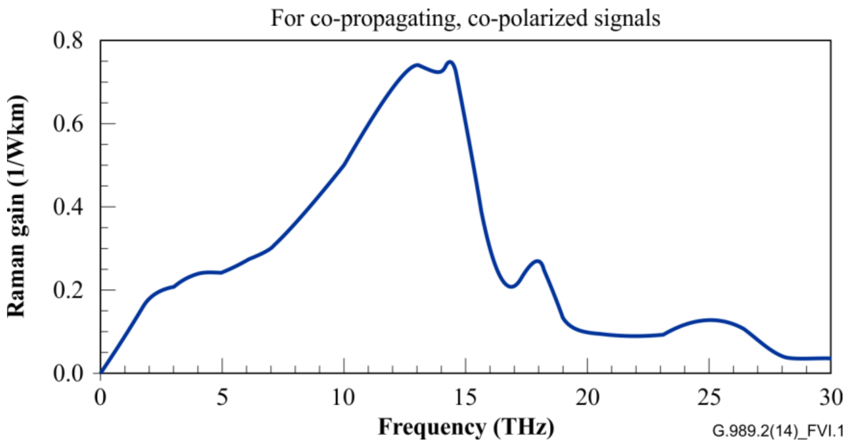


Figure VI.1 – Raman gain curve example for ITU-T G.652 type of fibre

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.

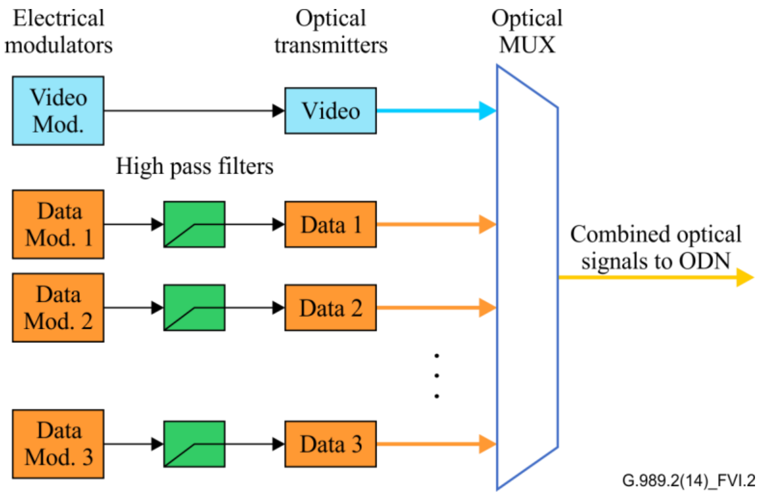


Figure VI.2 – HighPassRF – Raman crosstalk suppression scheme utilizing RF high-pass filtering of the data modulation

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.

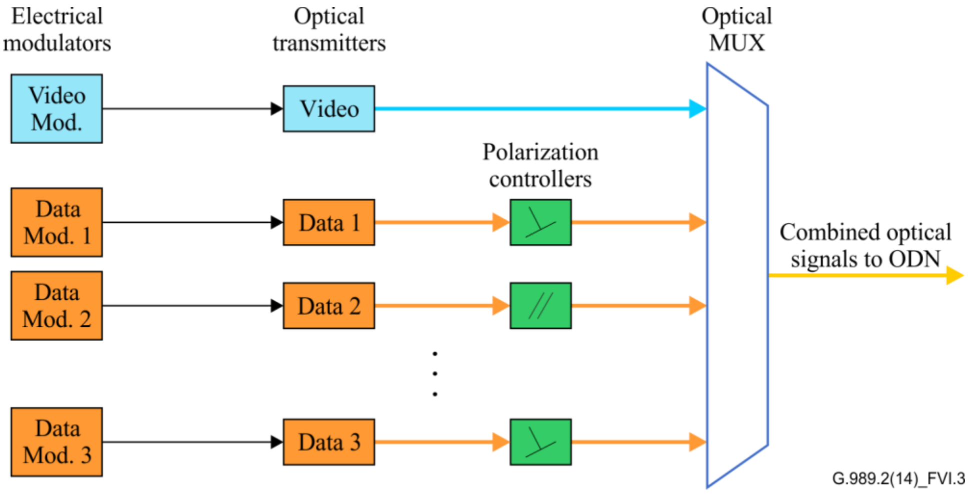


Figure VI.3 – DoP0 – Raman crosstalk suppression scheme utilizing alternating orthogonal polarization states to create a mixed state with a composite degree of polarization equal to zero

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.

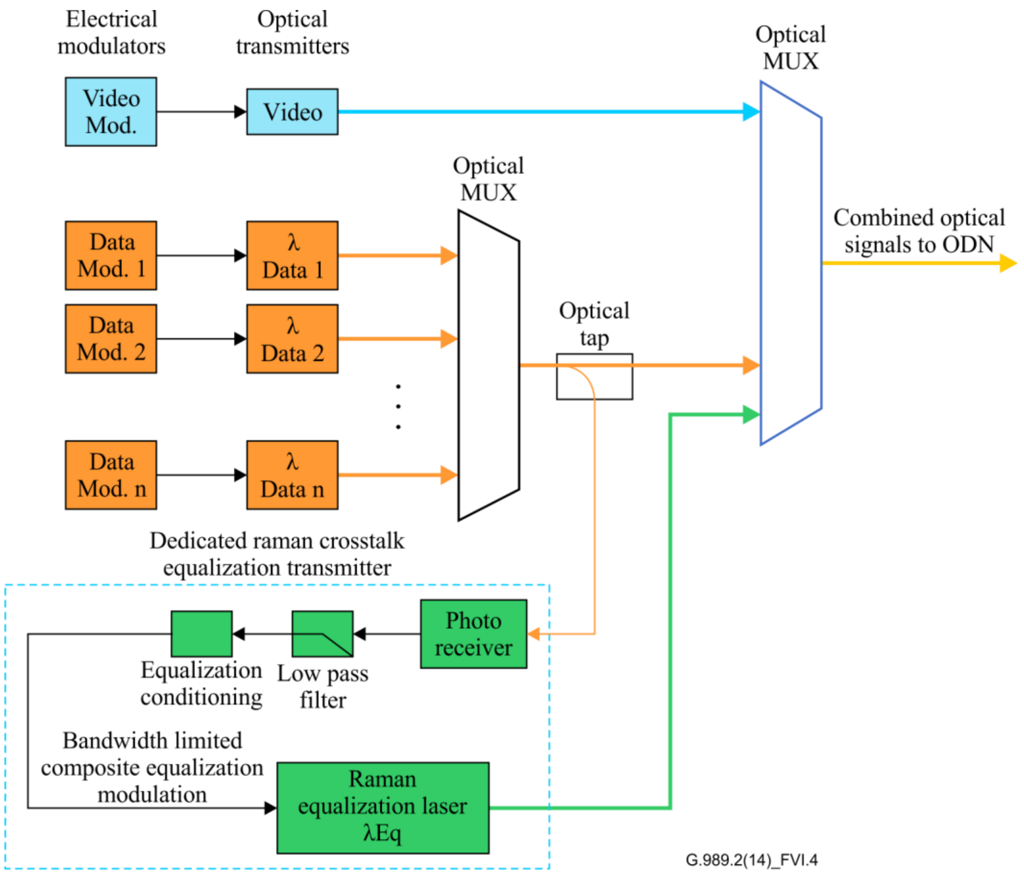


Figure VI.4 – DedicatedTx – Raman crosstalk cancellation scheme utilizing a dedicated crosstalk mitigation transmitter

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.

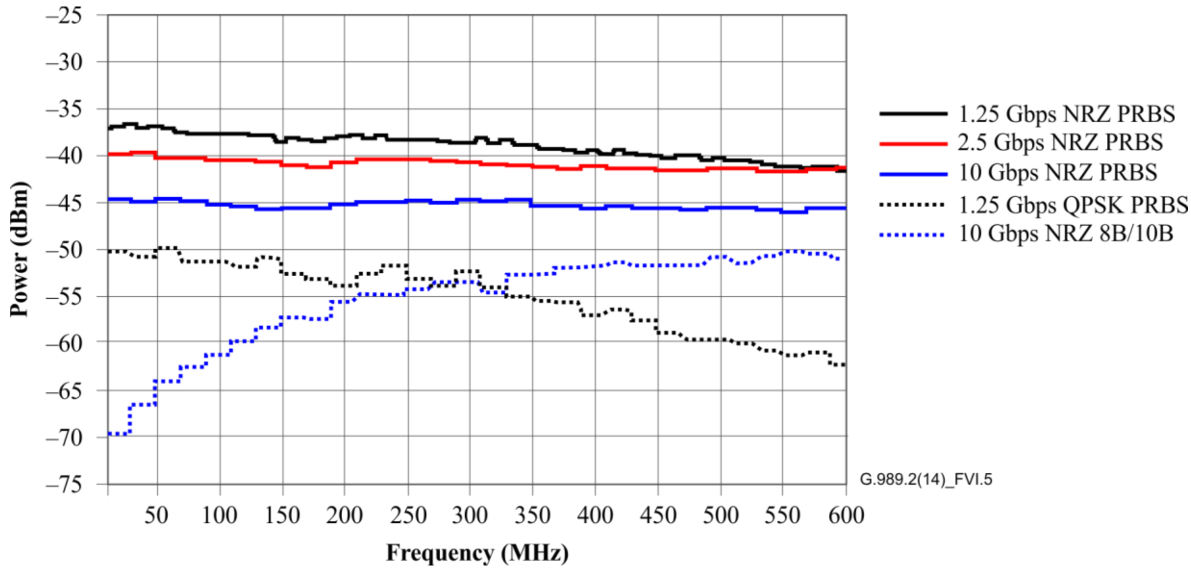


Figure VI.5 – Measured RF spectrum of several data rates, modulation formats and codings

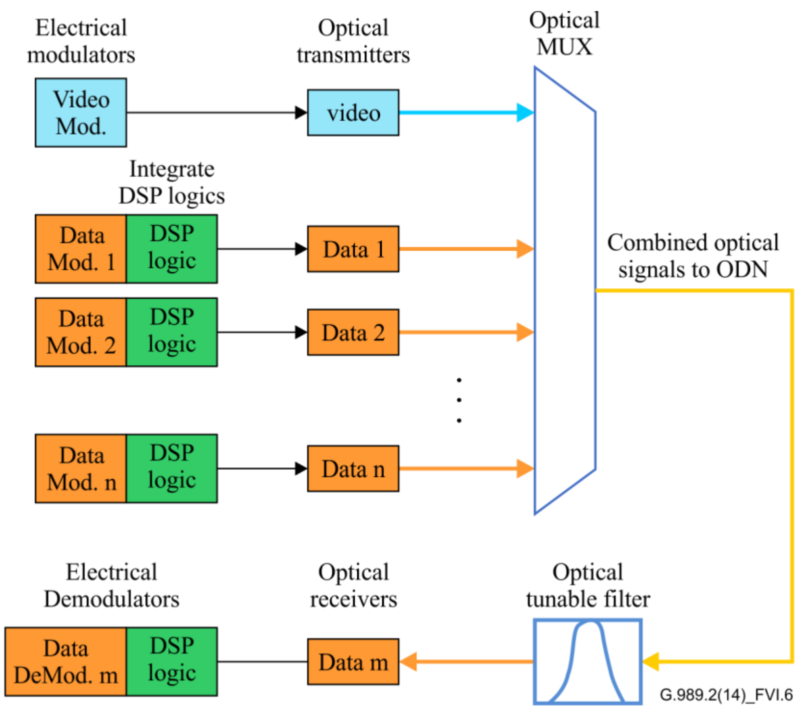


Figure VI.6 – PDS shaping scheme utilizing integrated DSP logic architecture

Appendix VII

Cyclic AWG channel grid design examples

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

This appendix has been deprecated.

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)

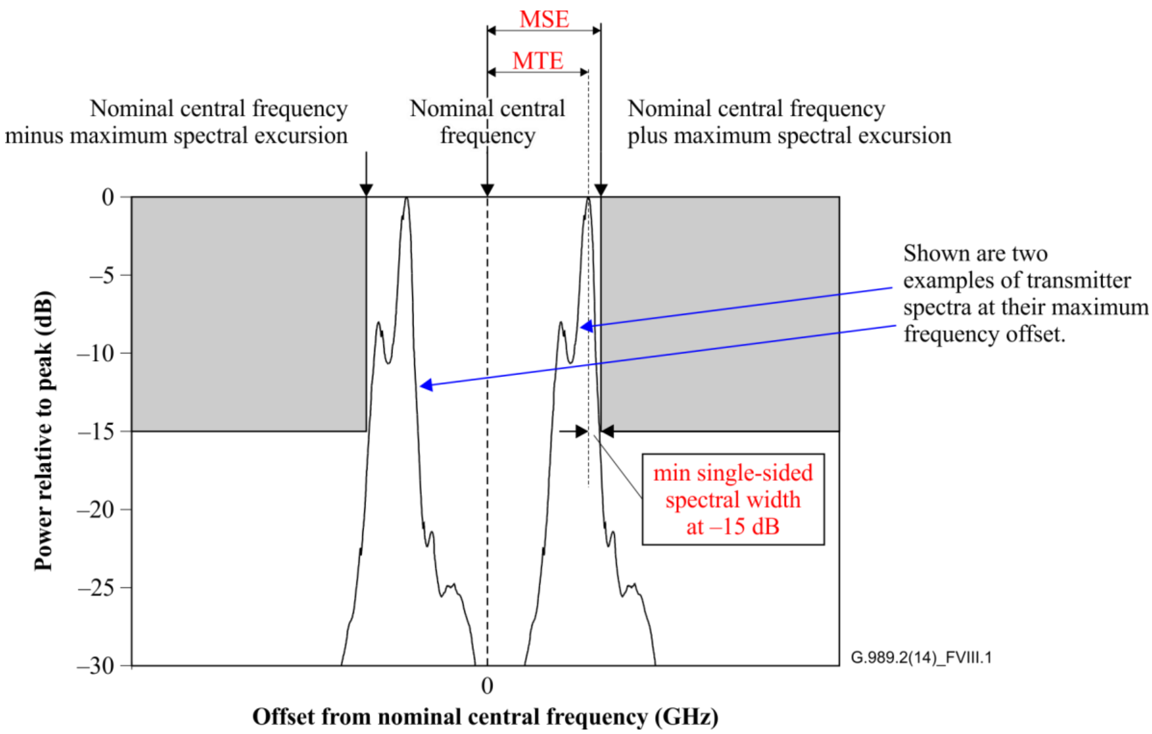


Figure VIII.1 – Relationship between MTE and MSE

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[2] 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[3], 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 1 dB, 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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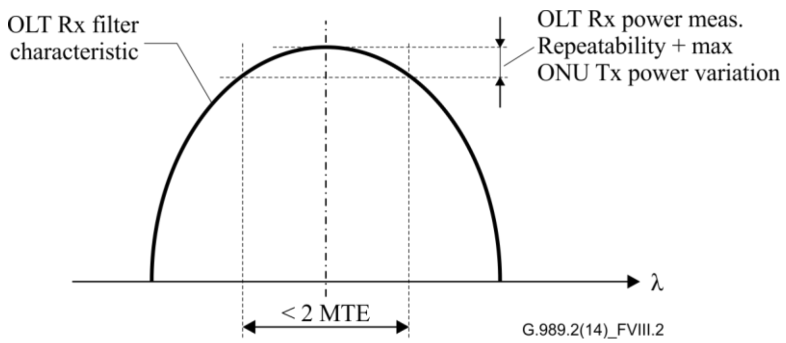
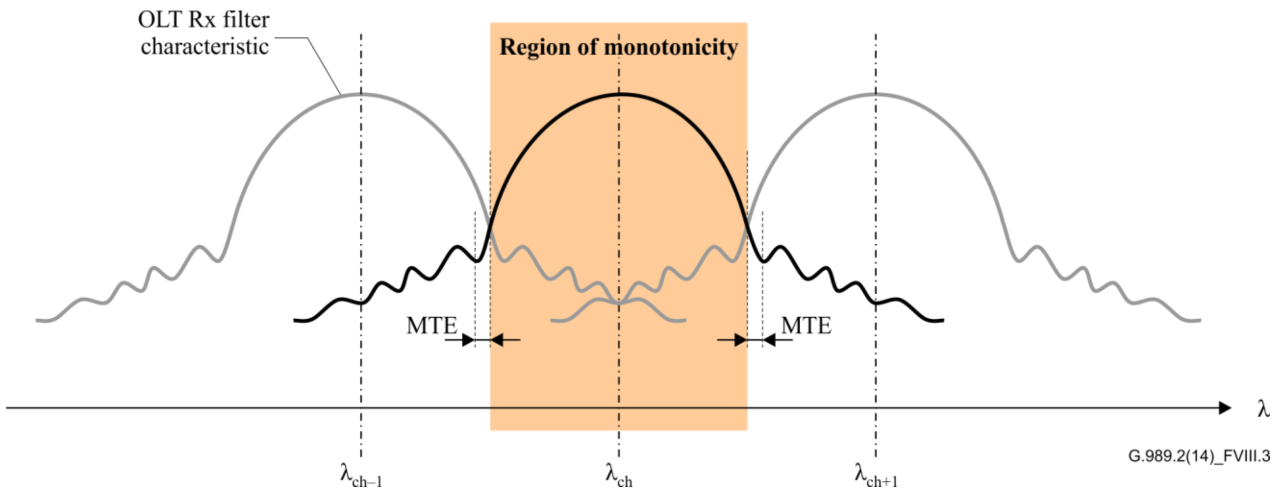
[2] Or, equivalently, the incremental loss caused by any wavelength deviation from the nominal channel wavelength greater than MTE must be greater than the OLT receive power measurement repeatability, which equals ±0.5 dB (see Table VIII.2), plus the ONU power variation, which equals the transmitter power wavelength dependency.

[3] 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.

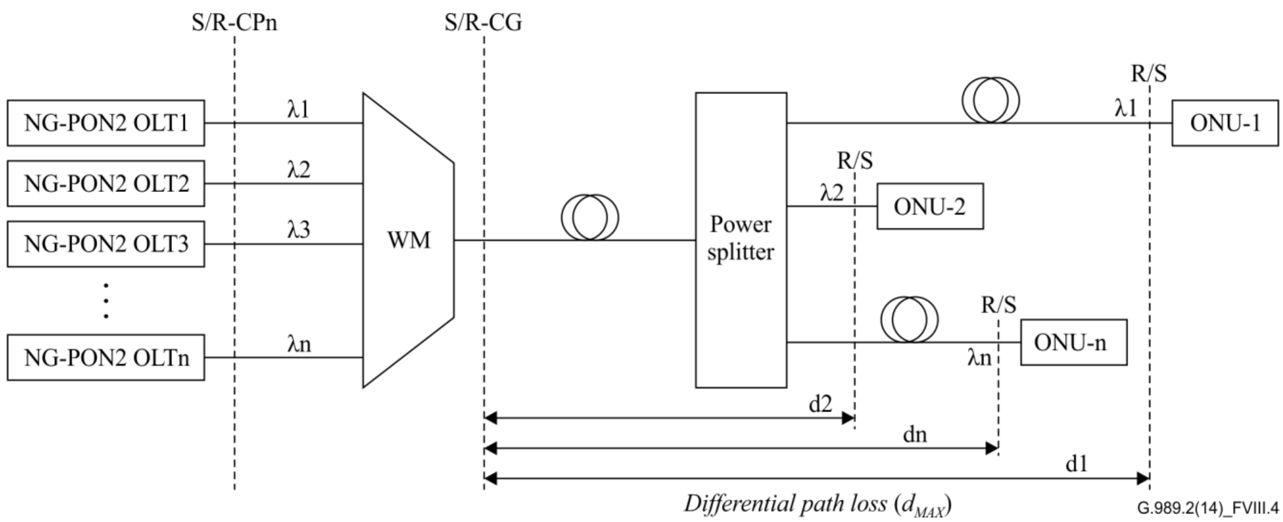


Figure VIII.4 – Reference diagram for inter-channel crosstalk calculation

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.

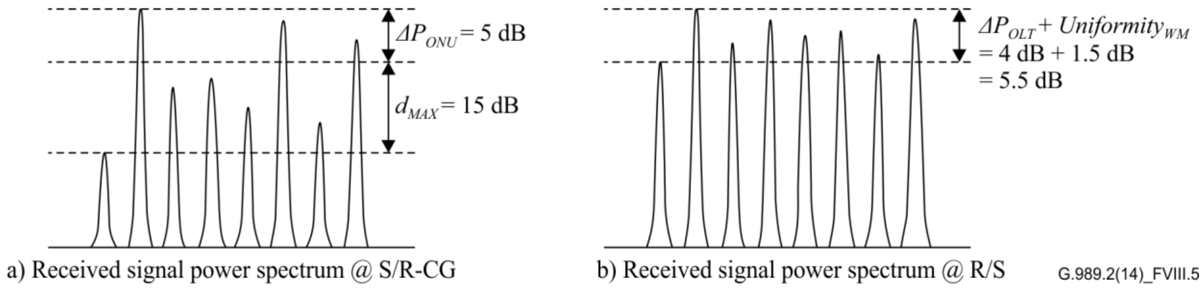


Figure VIII.5 – Signal power spectrum (a) at S/R-CG point and (b) at R/s point

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 an upstream BER of 10^{-4} as specified in Table 11-6, Q = 3.72. The induced optical penalty at a linear extinction ratio of 0.16 (8 dB) is plotted against inter-channel crosstalk for the cases of total number of channel N = 4 and N = 8 in Figure VIII.6.

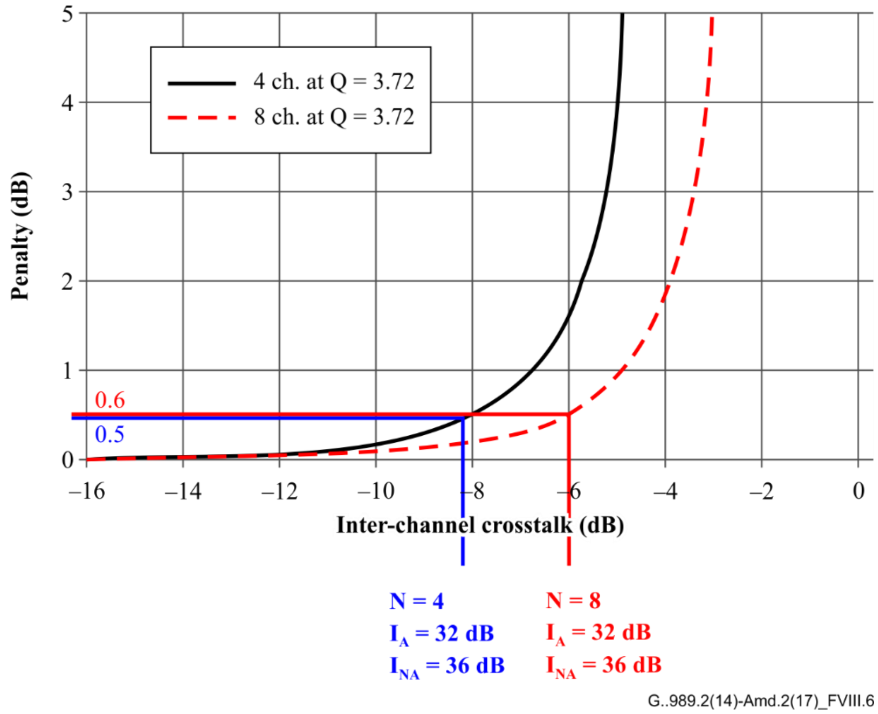


Figure VIII.6 – Optical penalty against inter-channel crosstalk for N = 4 and N = 8

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.

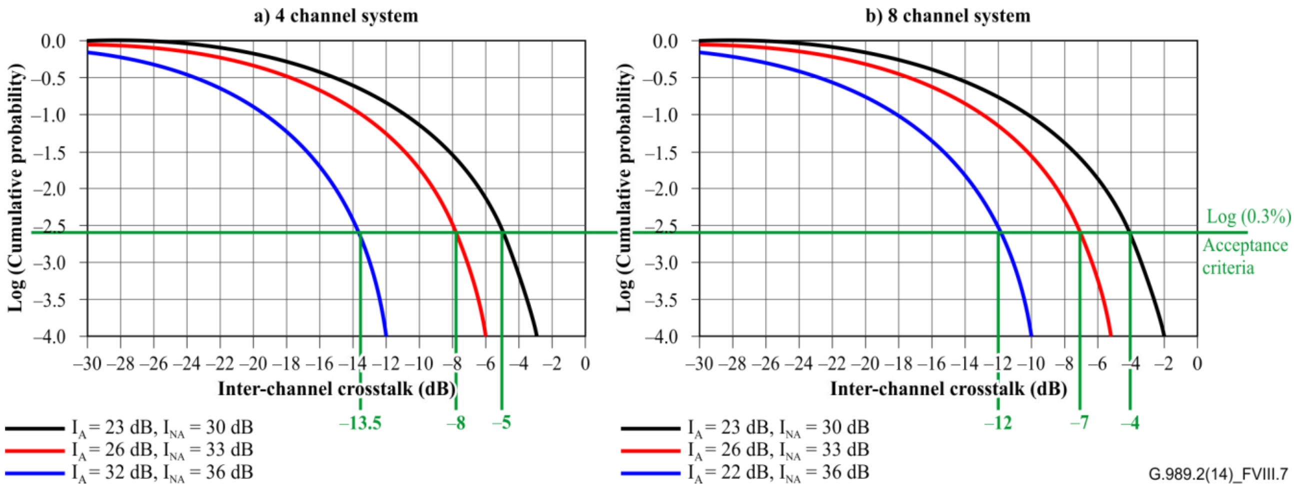


Figure VIII.7 – Monte Carlo simulation for the probability of inter-channel crosstalk for the cases (a) four channel system and (b) eight channel system

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, a probability threshold for system acceptance of 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 arrayed waveguide grating (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.

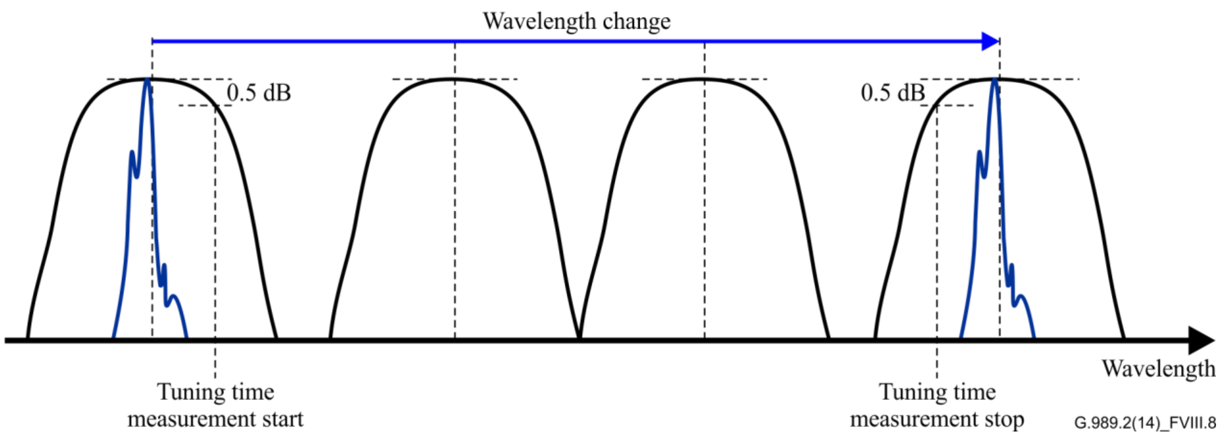


Figure VIII.8 – Illustration of laser tuning across the operating band

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.

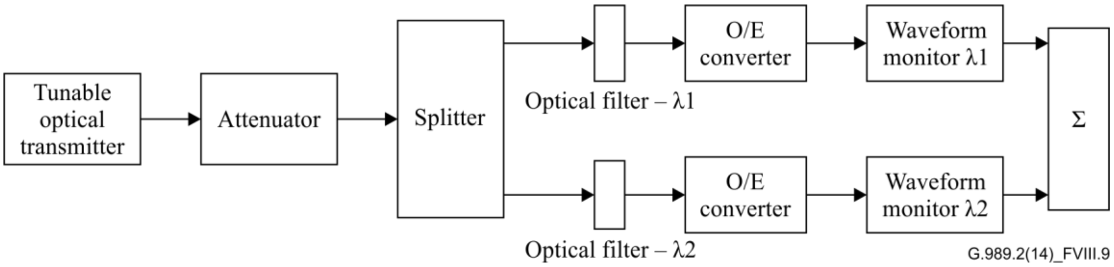


Figure VIII.9 – Test set-up for tuning time of ONU transmitter

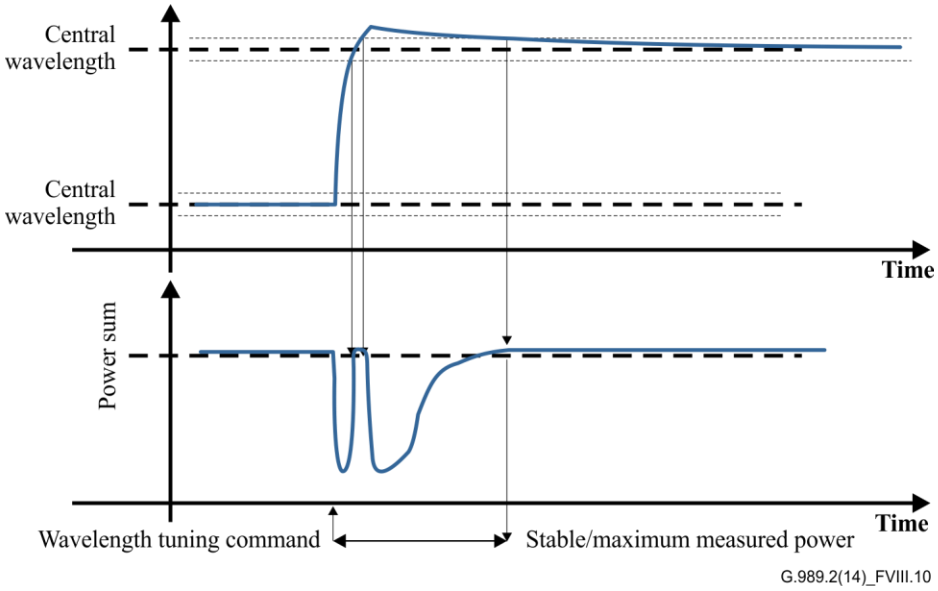


Figure VIII.10 – Optical power vs. time from summation of waveform monitors

The test set up attenuator is set such that the optical received power at the optical-to-electrical (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., common layer interface (CLI) or element management system (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 examples

Two upstream channel grid examples are provided: an on-grid example an off-grid example. The off-grid example supports a single bi-directional AWG at the wavelength mux, a potentially desirable feature.

Table VIII.5 shows examples of the TWDM PON on-grid upstream channel assignments which contain eight channels with 50 GHz, 100 GHz and 200 GHz channel spacing. The examples are sub-wavelength bands from the ITU-T grid, which is described in clause 6 of [ITU-T G.694.1].

Table VIII.5 – TWDM PON upstream channel on-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

Table VIII.6 shows examples of the TWDM PON off-grid upstream channel assignments which contain 8 channels with 50 GHz, 100 GHz and 200 GHz channel spacing. The examples are off grid of the sub-wavelength bands from the ITU-T grid. Note that the frequencies are exact, wavelengths are approximate.

Table VIII.6 – TWDM PON upstream channel off-grid example

	51.2 GHz CS		**104.2 GHz CS**		**208.4 GHz CS**	
Channel	**Frequency (THz)**	**Wavelength (nm)**	**Frequency (THz)**	**Wavelength (nm)**	**Frequency (THz)**	**Wavelength (nm)**
1	195.226	1535.619	195.591	1532.756	196.112	1528.684
2	195.174	1536.029	195.486	1533.573	195.903	1530.310
3	195.122	1536.439	195.382	1534.391	195.695	1531.940
4	195.069	1536.849	195.278	1535.210	195.486	1533.574
5	195.017	1537.260	195.174	1536.030	195.278	1535.211
6	194.965	1537.671	195.069	1536.851	195.069	1536.852
7	194.913	1538.082	194.965	1537.672	194.861	1538.496
8	194.861	1538.494	194.861	1538.495	194.652	1540.143

VIII.5 Detail of OOC near the channel band edge

In NG-PON2, the ONU transmitter is subject to the out of channel (OOC) requirement. Namely, there are two levels of OOC: OOC1 is determined by the incoherent crosstalk that will occur when the interfering light is outside the victim channel bandwidth, and OOC2 is determined by the coherent crosstalk that will occur when the interfering light is within the victim channel bandwidth. This is shown in Figure 9-1, which is reproduced below as Figure VIII.11.

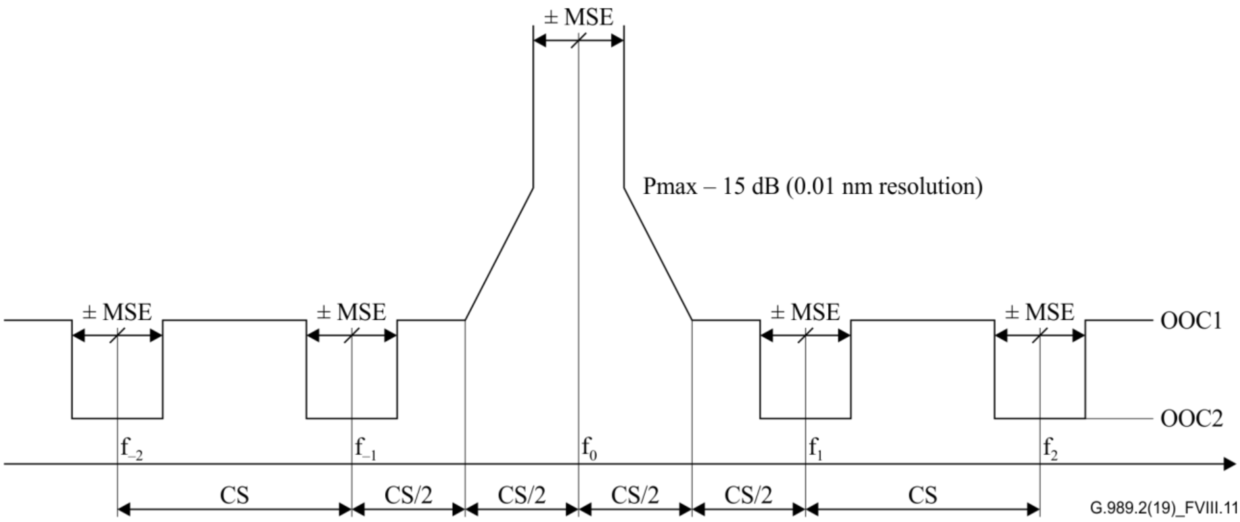


Figure VIII.11 – OOC-PSD mask definition

One will note that the edges between the OOC1 and OOC2 are perfectly sharp. The transition from coherent to incoherent crosstalk would be sharp only with a perfectly monochromatic signal; however, our signals are modulated which leads to their spectrum being broadened. This will have the effect of softening the edges between the two cases.

The signal that is being interfered with is a NRZ waveform intensity modulated on an optical carrier. The NRZ waveform classically is a sinc(f) function. However, to make the calculation simpler, we can model the spectrum as a rect(f) function that is 15 GHz wide (for a 7.5 GHz electrical bandwidth). Assuming a close to perfect extinction ratio, half the power goes into modulation, and the other half is the optical carrier, which is represented by a delta(f) function. This can be written:

$$PSD(f) = 1/2\ \delta(f–f_0) + 1/2\ 1/15\ \text{GHz}\ rect((f–f_0)/15\ \text{GHz}).$$

The worst case carrier placement is when the f_0 is 7.5 GHz (or more) from the band edge. Then, the allowed interference power at any frequency can be calculated by integrating over every part of the PSD that is within 7.5 GHz of the interference frequency. Also keep in mind that the incoherent crosstalk is always present also, and so much be added (linearly) to the result.

The figure below gives a representative calculation of the allowable out of channel PSD as a function of frequency difference from the band edge. In this case, we are looking at a left edge of a channel. This assumes that the OOC1 is –40.4 dBm and the OOC2 is –41.6 dBm. The OOC requirement starts at the OOC1 value, and starting at 7.5 GHz from outside the band edge, the OOC declines linearly to one quarter of the difference between the levels. Then there is a step down to three quarters of the difference – this is due to the optical carrier coming into range. Then the crosstalk continues its decline until it reaches the OOC2 value at 7.5 GHz inside the band. One can see that just inside the band, the allowed power is about 0.3 dB higher (easier) than the OOC2 level. However, just outside the band, the crosstalk is about 0.3 dB lower (harder) than the OOC1 level. This means that the OOC1 must be tightened by that amount.

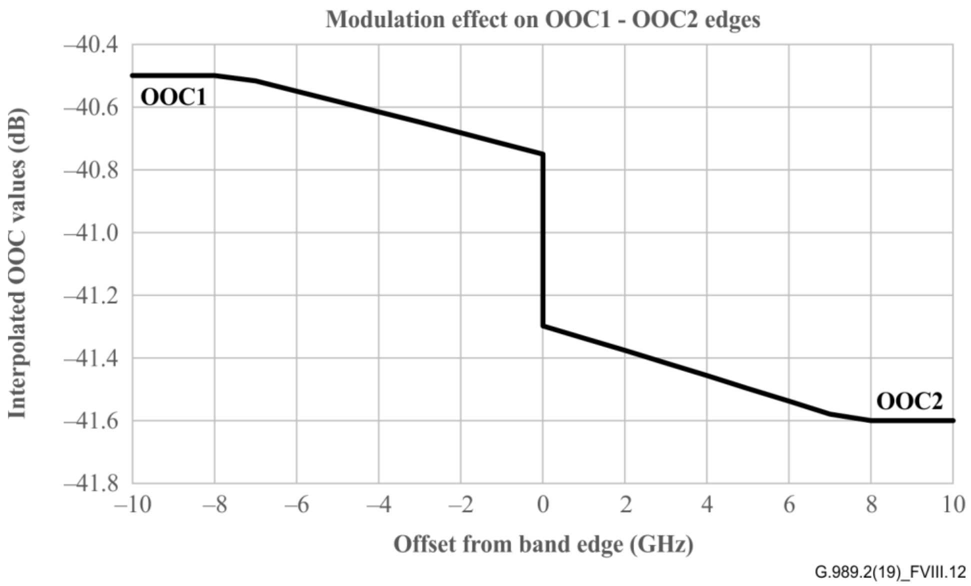


Figure VIII.12 – The modulation effect on OOC band edges

As a practical matter, the difference between the two OOC values is not as high as first calculated. Therefore, the impact of this interpolation between the two values is not big, and most likely could be ignored to first order in any testing.

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.

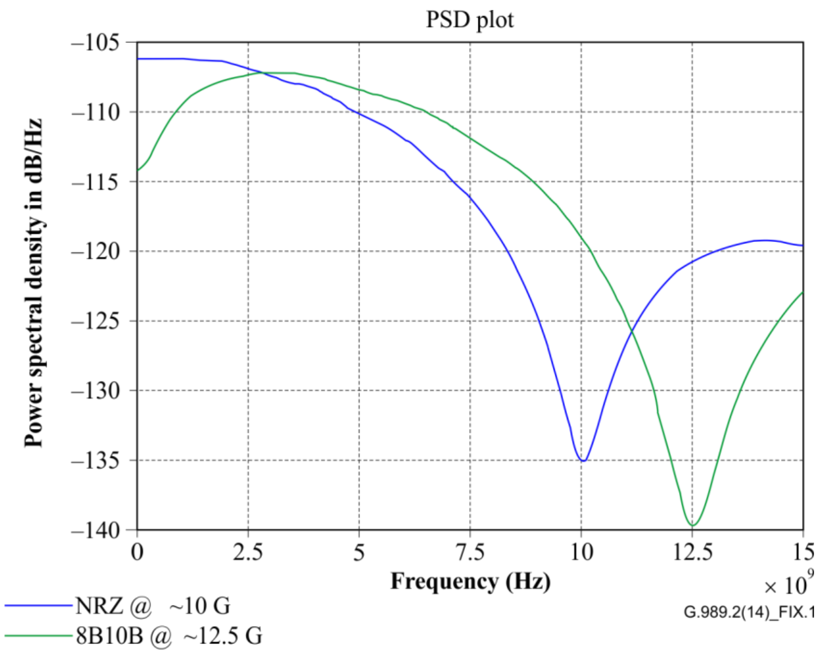


Figure IX.1 – Power spectral density of NRZ and 8B10B codes

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 shown in 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 is 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 and 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.

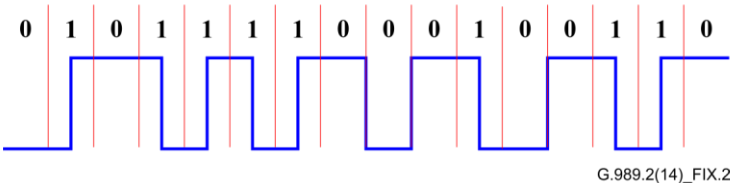


Figure IX.2 – Miller code

IX.2.1 Modified definitions for Miller code

IX.2.1.1 Minimum extinction ratio

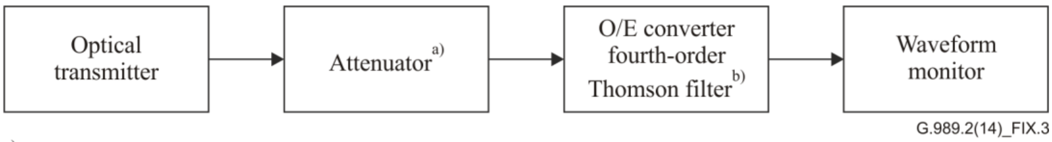
With respect to a Miller code signal generated by an optical transmitter, the ER is defined as the average optical power level at the centre of the high level (A) to the average optical power level at the centre of the low level (B):

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

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 modelled 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.

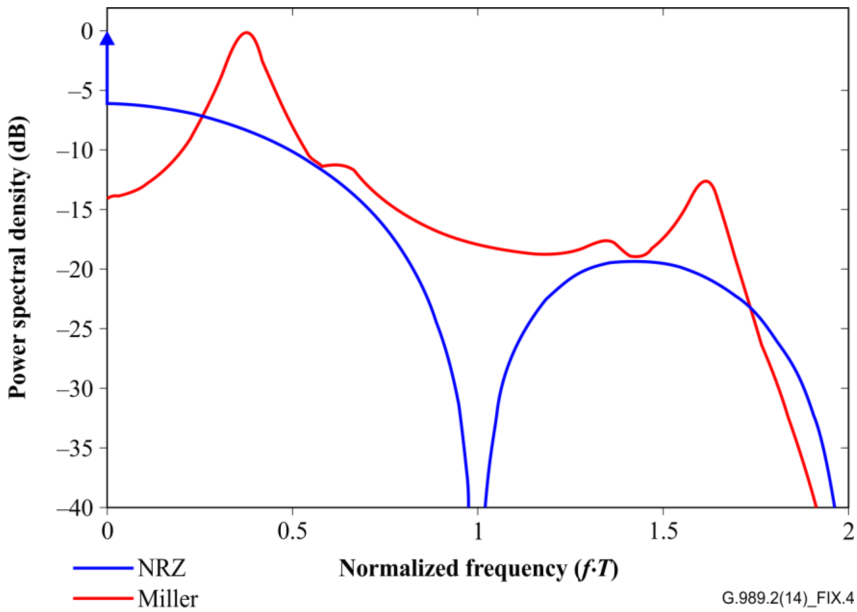


Figure IX.4 – Power spectral density of NRZ and Miller codes

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.

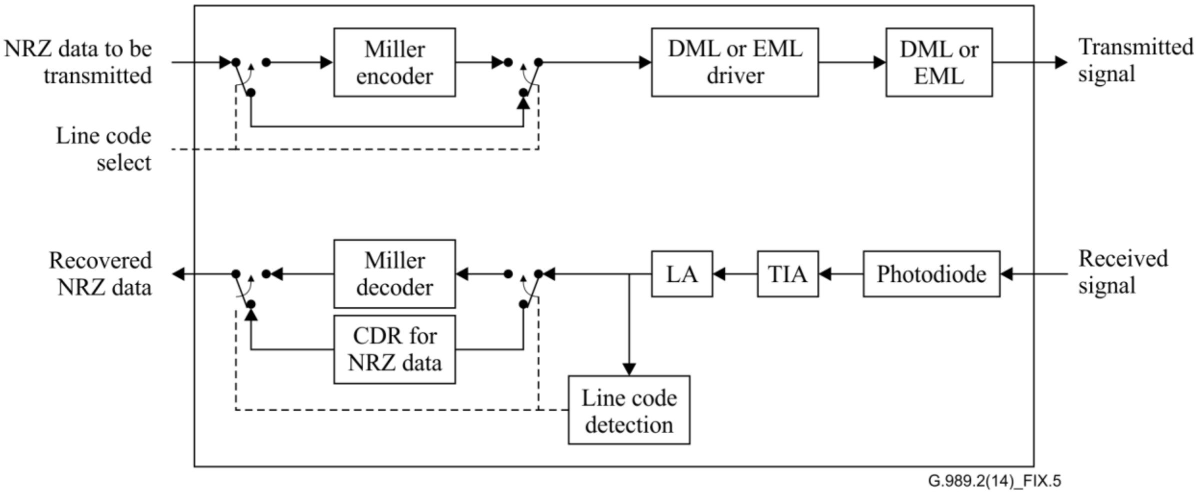


Figure IX.5 – Optical transceiver for NRZ and Miller codes

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.

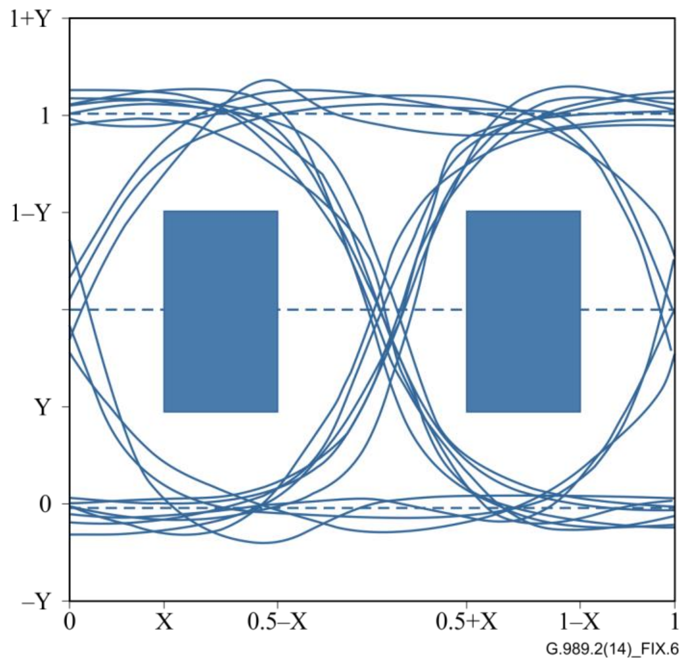


Figure IX.6 – Miller encoded eye mask

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			

Appendix X

Upstream PMD examples for TWDM PON

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

This appendix provides examples of the single-rate PMD sublayer and the single data path dual-rate coexistence PMD sublayer of NG-PON2. Note that dual rate is not explicitly mentioned in the requirements of [ITU-T G.989.1] and are shown below as examples only.

The topology for single-rate PMD sublayer is shown in Figure X.1. Optical signals transmitted to PMD sublayer are received by the single rate receiver, then transmitted through a single rate transimpedance amplifier (TIA) to a single rate limiting amplifier. The output of the limiting amplifier is then sent on to the PMA interface.

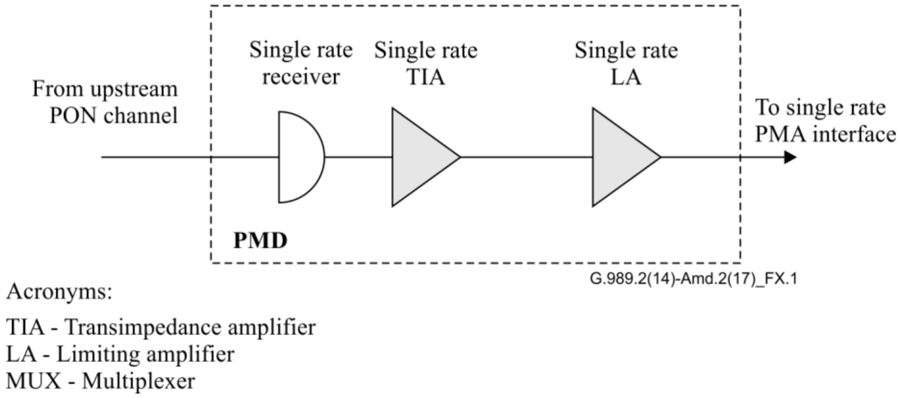


Figure X.1 – Example of single-rate PMD data path

There are two types of topologies for the reference design of dual-rate transceivers in the OLT upstream direction. As shown in Figure X.2, from a topological point of view, optical signals transmitted to the PMD layer are received by a dual rate receiver, then transmitted through a dual rate TIA. For the signals which are the output of the dual rate TIA, there exist two different processing methods as described below:

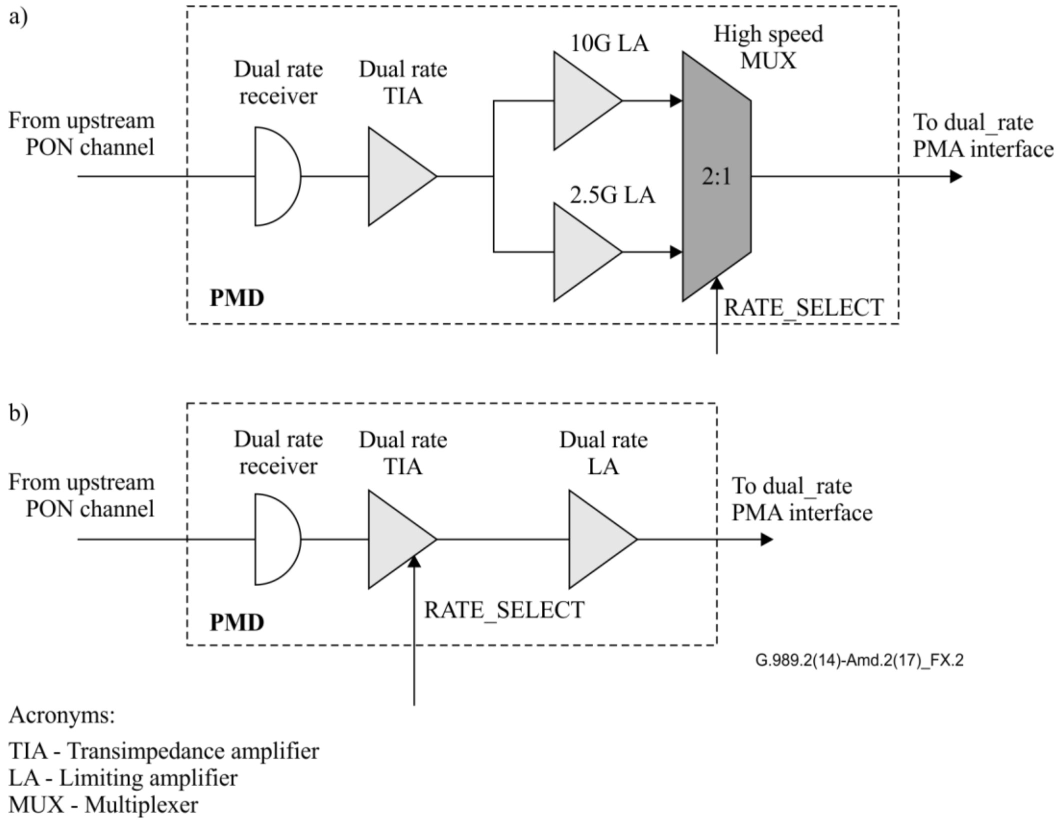


Figure X.2 – Example of dual-rate coexistence PMD implementation with single data path

One processing method is shown in Figure X.2-a. The output signal from the TIA is transmitted to the 10G LA and 2.5G LA separately, then through two different limiting amplifiers. The outputs of the limiting amplifiers are transmitted to a high speed MUX which selects the 2.5G LA or the 10G LA input signal by means of the RATE_SELECT signal. An additional time parameter, Multiplexer switch time T(sm), is introduced here – it is the switching time from one input channel to the other. This switching process could cause an additional overhead to the data transmission. However, with an appropriate design of dynamic bandwidth assignment (DBA) grant, it would have only a slight impact on the upstream bandwidth.

The RATE_SELECT signal could be generated by the TWDM TC sublayer. In the upstream direction, the dual-rate OLT CT supports the coexistence of 10G ONU and 2.5G ONUs via TDMA. OLT CT arbitrates 10G ONU and 2.5G ONU data according to the DBA grant window. It can be known which time slice is allocated to the 2.5G or the 10G stream by the calculation of DBA on the TWDM TC sublayer. As a result, the switching process of the MUX can start at the laser off time in the guard time of the DBA grant window.

Another processing method is shown in Figure X.2-b. The dual rate LA device is used for generating the output signal. The dual rate LA adapts the dual path amplification for the input signals at the different frequencies as follows:

The dual-rate LA features a low data rate path and a high data rate path, allowing for overall transmission optimization. Data path selection is controlled by the RATE_SELECT signal. The processing of the RATE_SELECT signal is the same as for the design in the first example. The low data rate path further features a low pass filter that provides optimization for high frequency noise suppression, which could increase the optical signal receive sensitivity for the 10G stream.

Appendix XI

Optical parameter specification for the S/R-CP reference point

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

The primary method of optical parameter specification is in reference to the S/R point for channel group (S/R-CG reference point of the Figure 6-1 for the individual wavelength channels). This method is used in the PMD tables appearing in the Clause 11 of this Recommendation. An alternative informative optical parameter specification method is in reference to the S/R point for channel pair (S/R-CP reference point of the Figure 6-1). The alternative method is applicable in the situations when the primary reference point, S/R-CG, is not practical or not accessible for performing measurements or it is desirable to provide a simple sensitivity specification to an OLT transceiver vendor. The alternative method is given in this appendix.

This appendix provides informative optical parameter specification of the OLT and ONU in reference to the S/R-CP point of the NG-PON2 reference logical architecture (see Figure 6-1) for the symmetric nominal line rate option (9.95328/9.95328 Gb/s in downstrea/upstream), Type A optical link and N1/N2 ODN classes. For the N2 ODN class, an optical split ratio of 1:64 or higher is assumed. The optical parameter specifications in reference to the S/R-CP point for the other nominal line rate options, Type B optical link and/or other ODN classes remain for further study.

The recommended values of optical power parameters consistent with the primary specifications of clause 11 and based on the industry best practices with respect to the WM loss and penalty parameters (see Table XI.1) are given in Table XI.2

Table XI.1 – WM loss and penalty parameters based on the industry best practices

Parameter	Notation	Unit	Value	
ODN Class			N1	N2
Minimum insertion loss	WM_{min}	dB	1.2	1.2
Maximum insertion loss	WM_{max}	dB	2.2	2.2
IBXT penalty	δ_{IBXT}	dB	0.5	0.3
WM inter-channel cross-talk penalty	δ_{ICXT}	dB	0.5	0.1
Downstream WM penalty	δ_{DS}	dB	0.0	0.0

Let P_{min}, P_{max}, S and L denote, respectively, the mean launch optical power minimum, the mean launch optical power maximum, sensitivity and overload at a respective point identified by the subscript. The optical parameters referenced to the S/R-CP point can be established using the following equations (assuming logarithmic units):

$P_{min\text{-}CP} = P_{min\text{-}CG} + WM_{max} + \delta_{DS}$;

$P_{max\text{-}CP} = P_{max\text{-}CG} + WM_{min}$;

$S_{CP} = S_{CG} - WM_{max} - (\delta_{IBXT} + \delta_{ICXT})$;

$L_{CP} = L_{CG} - WM_{min}$.

The parameters listed in Table XI.2 modify the respective optical power parameter rows in Table 11-5 and Table 11-7. The rest of the parameters of those tables remain applicable.

Table XI.2 – Optical power parameters at the S/R-CP reference point

Source	Item	Notation	Unit	Value	
	ODN class			N1	N2
Table 11-5	Mean channel launch power minimum (at S/R-CP)	$P_{min\text{-}CP}$	dBm	+5.2	+7.2
	Mean channel launch power maximum (at S/R-CP)	$P_{max\text{-}CP}$	dBm	+8.2	+10.2
Table 11-7	Sensitivity (at S/R-CP), based on DD20, four wavelength), Type A link (Note 1)	S_{CP}	dBm	–29.2	–30.6
	Overload (at S/R-CP), Type A link	L_{CP}	dBm	–6.2	–8.2

NOTE 1 – The sensitivity values specified at the S/R-CG point (e.g., Table 11-7) are to be measured with all 4 channels operating to produce crosstalk, but with no fiber. The sensitivity values specified here at the S/R-CP point are to be measured with no other channels operating and with no fiber.

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