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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

10-Gigabit-capable passive optical networks (XG-PON): Physical media dependent (PMD) layer specification

Recommendation ITU-T G.987.2

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Recommendation ITU-T G.987.2

10-Gigabit-capable passive optical networks (XG-PON): Physical media dependent (PMD) layer specification

Summary

Recommendation ITU-T G.987.2 describes the physical layer requirements and specifications for the XG-PON physical media dependent (PMD) layer. Wavelength enhancement bands are described in Recommendation ITU-T G.987.1. The transmission convergence (TC) layer is described in Recommendation ITU-T G.987.3. The ONU management and control interface (OMCI) specifications are described in Recommendation ITU-T G.988.

Recommendation ITU-T G.987.2 describes a flexible optical fibre access network capable of supporting the bandwidth requirements of business and residential services. The G.987 series of standards allows for multiple upstream and downstream line rates. This Recommendation currently defines one type of 10-Gigabit-capable passive optical network (XG-PON) system with asymmetric nominal line rate of 9.95328 Gbit/s in the downstream direction and 2.48832 Gbit/s in the upstream direction, hereinafter referred to as XG-PON1.

This Recommendation describes a system that represents an evolutionary development from the systems described in the ITU-T G.984 series. To the greatest extent possible, this Recommendation maintains the requirements of Recommendation ITU-T G.984.1 to ensure maximal continuity with existing systems and optical fibre infrastructure.

History

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* 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>.

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

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

NOTE

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

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Recommendation ITU-T G.987.2

10-Gigabit-capable passive optical networks (XG-PON): Physical media dependent (PMD) layer specification

1 Scope

This Recommendation pertains to flexible access networks using optical fibre technology. The focus is primarily on a network supporting services with bandwidth requirements ranging from that of voice to data services running at up to 10 Gbit/s. Also included are broadcast services.

This Recommendation describes characteristics of the physical medium dependent (PMD) layer of an optical access network (OAN) with the capability of transporting various services between the user-network interface and the service node interface.

The OAN dealt with in 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 ODN considered is based on a point-to-multipoint tree and branch option.

2 References

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

- [ITU-T G.652] Recommendation ITU-T G.652 (2009), *Characteristics of a single-mode optical fibre and cable*.
- [ITU-T G.657] Recommendation ITU-T G.657 (2012), *Characteristics of a bending loss insensitive single mode optical fibre and cable for the access network*.
- [ITU-T G.783] Recommendation ITU-T G.783 (2006, as amended), *Characteristics of synchronous digital hierarchy (SDH) equipment functional blocks*.
- [ITU-T G.825] Recommendation ITU-T G.825 (2000, as amended), *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 (2016), *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.984.1] Recommendation ITU-T G.984.1 (2008, as amended), *Gigabit-capable passive optical networks (GPON): General characteristics*.
- [ITU-T G.984.2] Recommendation ITU-T G.984.2 (2003, as amended), *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 (2010), *10 Gigabit-capable passive optical network (XG-PON): General requirements*.
- [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 (2012), *ONU management and control interface (OMCI) specification*.
- [ITU-T G-Sup.39] ITU-T G-series Recommendations – Supplement 39 (2016), *Optical system design and engineering considerations*.
- [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.987].

4 Abbreviations and acronyms

See clause 4 of [ITU-T G.987].

5 Conventions

See clause 5 of [ITU-T G.987].

6 Architecture of the optical access network

See [ITU-T G.984.1]. For convenience, Figure 1 of [ITU-T G.984.2] is reproduced below.

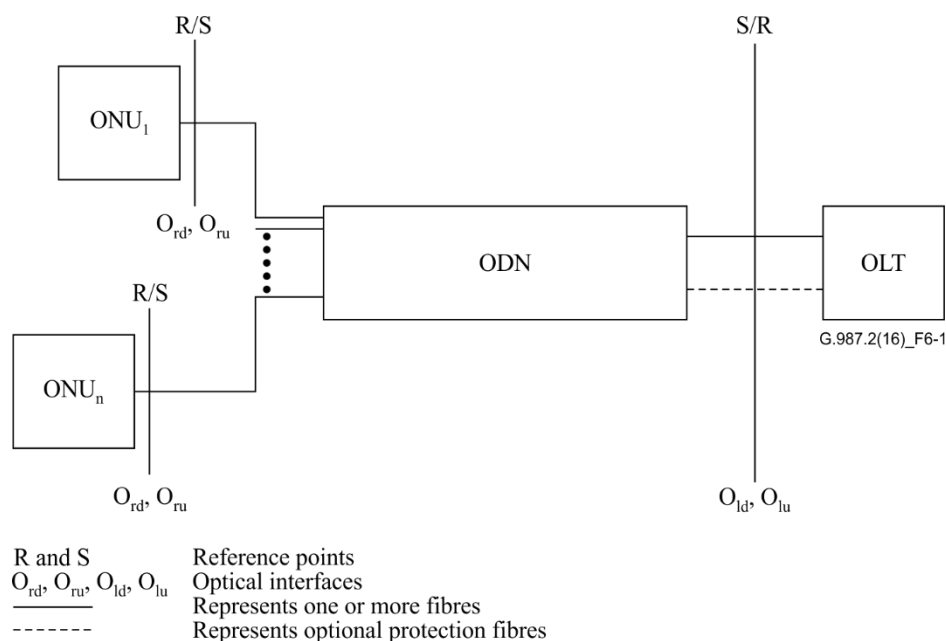


Figure 6-1 – Generic physical configuration of the optical distribution network (reproduced from Figure 1 of [ITU-T G.984.2])

The following reference points are defined in Figure 6-1:

- S: Point on the optical fibre just after the OLT[Downstream]/ONU[Upstream] optical connection point (i.e., optical connector or optical splice).
- R: Point on the optical fibre just before the ONU[Downstream]/OLT[Upstream] optical connection point (i.e., optical connector or optical splice).
- S/R, R/S: Combination of points S and R existing simultaneously in a single fibre, when operating in bidirectional mode.
- Oru, Ord: Optical interface at the reference point R/S between the ONU and the ODN for the upstream and downstream directions respectively.
- Olu, Old: Optical interfaces at the reference point S/R between the OLT and the ODN for the upstream and downstream directions respectively.

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 on the same fibre and components (duplex/duplex configuration).

6.1 Classes for optical path loss

Recommended classes for optical path loss are shown in Table 6-1.

Table 6-1 – Classes for optical path loss defined in this Recommendation

	Nominal1 class (N1 class)	Nominal2 class (N2 class)	Extended1 class (E1 class)	Extended2 class (E2 class)
Minimum loss	14 dB	16 dB	18 dB	20 dB
Maximum loss	29 dB	31 dB	33 dB	35 dB

For single-star architectures, the absence of optical branching devices may result in optical path losses of less than 5 dB. In such a case, the ODN must contain additional optical attenuators guaranteeing minimum channel insertion loss for the given class to prevent potential damage to receivers.

6.2 Categories for fibre differential distance

Categories for fibre differential distance

Recommended categories for fibre differential distance (DD) are shown in Table 6-2.

Table 6-2 – Categories for fibre differential distance defined in G.987.2

	DD20	DD40
Maximum differential distance	20 km	40 km

7 Services

See clause 7 of [ITU-T G.987.1].

8 User network interface and service node interface

See Appendix I of [ITU-T G.987.1].

9 Optical network requirements

9.1 Layered structure of optical network

See clause 5.2.5 of [ITU-T G.987.1].

9.2 Physical media dependent layer requirements for the XG-PON

All parameters are specified as follows, and are in accordance with Table 9-2 through Table 9-4.

There are two optical network unit (ONU) types, based on different ONU receiver sensitivity.

All parameter values specified are worst-case values, to be met over the range of standard operating conditions (i.e., temperature and humidity), and they include ageing effects. The parameters are specified relative to an optical section design objective of a bit error ratio (BER) not worse than the values specified in Table 9-3 and Table 9-4, for the extreme case of optical path attenuation and dispersion conditions.

In particular, the values given in Table 9-3 and Table 9-4 are valid for the cases of an enhancement band, as described in clause 10.

9.2.1 Line rate

The transmission line rate is a multiple of 8 kHz. The target standardized 10-gigabit-capable passive optical network (XG-PON) system supports the following variant: XG-PON1 with a downstream line rate of 9.95328 Gbit/s and an upstream line rate of 2.48832 Gbit/s.

Parameters to be defined are categorized by downstream and upstream, and the nominal line rate as shown in Table 9-1.

Table 9-1 – Relation between parameter categories and tables

Variant	Transmission direction	Nominal line rate [Gbit/s]	Reference table
XG-PON1	Downstream	9.95328	Table 9-3
	Upstream	2.48832	Table 9-4

9.2.1.1 Downstream accuracy

When the optical trunk line (OLT) and the end office 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.

9.2.1.2 Upstream accuracy

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

9.2.2 FEC code selection for XG-PON

See clause 10.3 of [ITU-T G.987.3].

9.2.3 Physical media and transmission method

9.2.3.1 Transmission medium

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

9.2.3.2 Transmission direction

The signal is transmitted both upstream and downstream through the transmission medium.

9.2.3.3 Transmission methodology

Bidirectional transmission is accomplished by use of wavelength division multiplexing (WDM) technique on a single fibre.

9.2.4 Line code

The scrambling method is defined in [ITU-T G.987.3].

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.

9.2.4.1 Downstream

Downstream line coding for XG-PON1: NRZ.

9.2.4.2 Upstream

Upstream line coding for XG-PON1: NRZ.

9.2.5 Operating wavelength

9.2.5.1 Downstream wavelength allocation

The operating wavelength range for XG-PON1 for the downstream direction is defined in Table 9-3.

9.2.5.2 Upstream wavelength allocation

The operating wavelength range for XG-PON1 for the upstream direction is defined in Table 9-4.

9.2.6 XG-PON PMD parameters

9.2.6.1 XG-PON compatible ODN

XG-PON shall operate over an ODN whose parameters are described by Table 9-2.

Table 9-2 – Physical parameters of a simple ODN (ODS)

Item	Unit	Specification
Fibre type (Note)	–	[ITU-T G.652], or compatible
Attenuation range (as defined in clause 6.1)	dB	N1 class: 14 – 29 N2 class: 16 – 31 E1 class: 18 – 33 E2 class: 20 – 35
Maximum fibre distance between S/R and R/S points	km	DD20: 20 DD40: 40
Minimum fibre distance between S/R and R/S points	km	0
Bidirectional transmission	–	1-fibre WDM
Maintenance wavelength	nm	See [ITU-T L.313]
NOTE – See clause 9.2.3.1		

9.2.6.2 Optical interface parameters of 9.95328 Gbit/s downstream direction

Table 9-3 – Optical interface parameters of 9.95328 Gbit/s downstream direction

Item	Unit	Value					
OLT transmitter (optical interface O _{ld})							
Nominal line rate	Gbit/s	9.95328					
Operating wavelength (Note 1)	nm	1575 – 1580					
Line code	–	NRZ					
Mask of the transmitter eye diagram	–	see clause 9.2.7.6.1					
Maximum reflectance at S/R, measured at transmitter wavelength	dB	NA					
Minimum ORL of ODN at O _{lu} and O _{ld} (Notes 2 and 3)	dB	more than 32					
ODN Class		N1	N2		E1	E2	
			N2a	N2b		E2a	E2b
Mean launched power MIN	dBm	+2.0	+4.0	+10.5	+6	+8	+14.5
Mean launched power MAX	dBm	+6.0	+8.0	+12.5	+10	+12	+16.5
Launched optical power without input to the transmitter	dBm	NA					
Minimum extinction ratio	dB	8.2					
Transmitter tolerance to reflected optical power (Note 7)	dB	more than –15					
Dispersion Range	ps/nm	0-400 (DD20) 0-800 (DD40)					
Minimum side mode suppression ratio	dB	30					
Maximum differential optical path loss	dB	15					
Jitter generation	–	see clause 9.2.9.7.3					

Table 9-3 – Optical interface parameters of 9.95328 Gbit/s downstream direction

Item	Unit	Value					
ONU receiver (optical interface O _{rd})							
Maximum optical path penalty (Note 6)	dB	1.0					
Maximum reflectance at R/S, measured at receiver wavelength	dB	less than −20					
Bit error ratio reference level	–	10 ^{−3} (Note 4)					
ODN Class		N1	N2		E1	E2	
			N2a	N2b		E2a	E2b
Minimum sensitivity at BER reference level (Note 5)	dBm	−28.0	−28.0	−21.5	−28.0	−28.0	−21.5
Minimum overload at BER reference level	dBm	−8.0	−8.0	−3.5	−8.0	−8.0	−3.5
Consecutive identical digit immunity	bit	more than 72					
Jitter tolerance	–	see clause 9.2.9.7.2					
Receiver tolerance to reflected optical power (Note 8)	dB	less than 10					
NOTE 1 – In the case of outdoor OLT deployment, it is allowed for the operating wavelength to span between 1575 – 1581 nm.							
NOTE 2 – There are optional cases where the "minimum ORL of ODN at O _{lu} and O _{ld} " can be as low as 20 dB. (see [b-ITU-T G.983.1] Appendix I)							
NOTE 3 – The value of ONU transceiver reflectance corresponding to the "minimum ORL of ODN at O _{lu} and O _{ld} " is −20 dB. (see [b-ITU-T G.983.1] Appendix II)							
NOTE 4 – See [ITU-T G.Sup39], clause 9.4.1 for additional details.							
NOTE 5 – This sensitivity shall be met in the presence of G-PON and video overlay on the same ODN. If either G-PON, or video overlay, or both of them are absent, the sensitivity may be different (precise value is FFS).							
NOTE 6 – The specified penalty must be met by optics complying with the specified launch power range. If a transmitter exhibits a higher penalty, it can still comply if it equally increases the minimum launch power while remaining under the maximum launch power. In no case should the OPP exceed 2 dB.							
NOTE 7 – Parameter known in [ITU-T G.984.2] as "Tolerance to the transmitter incident light power".							
NOTE 8 – Parameter known in [ITU-T G.984.2] as "Tolerance to the reflected optical power".							

9.2.6.3 Optical interface parameters of 2.48832 Gbit/s upstream direction

Table 9-4 – Optical interface parameters of 2.48832 Gbit/s upstream direction

Item	Unit	Value			
ONU transmitter (optical interface O _{ru})					
Nominal line rate	Gbit/s	2.48832			
Operating wavelength	nm	1260 – 1280			
Line code	–	NRZ			
Mask of the transmitter eye diagram	–	see clause 9.2.7.6.2			
Maximum reflectance at R/S, measured at transmitter wavelength	dB	less than –6			
Minimum ORL of ODN at O _{ru} and O _{rd} (Notes 1 and 2)	dB	more than 32			
ODN Class		N1	N2	E1	E2
Mean launched power MIN	dBm	+2.0	+2.0	+2.0	+2.0
Mean launched power MAX	dBm	+7.0	+7.0	+7.0	+7.0
Launched optical power without input to the transmitter (Note 3)	dBm	less than "Minimum sensitivity at BER reference level" – 10			
Maximum Tx enable (Note 3)	bits	32			
Maximum Tx disable (Note 3)	bits	32			
Minimum extinction ratio	dB	8.2			
Transmitter tolerance to reflected optical power (Note 8)	dB	more than –15			
Dispersion Range (Note 4, Note 5)	ps/nm	0 to –140 (DD20) 0 to –280 (DD40)			
Minimum side mode suppression ratio	dB	30			
Jitter transfer	–	see clause 9.2.9.7.1			
Jitter generation	–	see clause 9.2.9.7.3			
OLT receiver (optical interface O _{lu})					
Maximum optical path penalty (Note 7)	dB	0.5			
Maximum reflectance at S/R, measured at receiver wavelength	dB	less than –20			
Bit error ratio reference level	–	10 ^{–4} (Note 6)			
ODN Class		N1	N2	E1	E2
Minimum sensitivity at BER reference level	dBm	–27.5	–29.5	–31.5	–33.5
Minimum overload at BER reference level	dBm	–7.0	–9.0	–11	–13
Consecutive identical digit immunity	bit	more than 72			
Jitter tolerance	–	see clause 9.2.9.7.2			
Receiver tolerance to reflected optical power (Note 9)	dB	less than 10			
NOTE 1 – There are optional cases where the "minimum ORL of ODN at O _{ru} and O _{rd} " can be as low as 20 dB. (see [b-ITU-T G.983.1] Appendix I)					
NOTE 2 – The value of ONU transceiver reflectance corresponding to the "minimum ORL of ODN at O _{ru} and O _{rd} " is –20 dB. (see [b-ITU-T G.983.1] Appendix II)					

Table 9-4 – Optical interface parameters of 2.48832 Gbit/s upstream direction

NOTE 3 – As defined in clause 9.2.7.3.1.

NOTE 4 – Dispersion range is considered to be the most appropriate method of specifying a laser's spectral characteristic. These values are considered to be compatible with the older method of specifying values using maximum –20 dB width, for line rates below 2.5 Gbit/s.

NOTE 5 – The equivalent maximum –20 dB width value is specified as less than 1 nm.

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

NOTE 7 – The specified penalty is valid up to a 40 km link distance.

NOTE 8 – Parameter known in [ITU-T G.984.2] as "Tolerance to the transmitter incident light power".

NOTE 9 – Parameter known in [ITU-T G.984.2] as "Tolerance to the reflected optical power".

9.2.7 Transmitter at O_{ld} and O_{ru}

All parameters are specified as follows, and are in accordance with Table 9-3 and Table 9-4.

9.2.7.1 Source type

Considering the attenuation/dispersion characteristics of the target fibre channel, feasible 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 the XG-PON systems both for the downstream and upstream links.

The use of multi-longitudinal mode (MLM) lasers is not contemplated in this Recommendation, due to their practical distance/line rate limitations.

9.2.7.2 Spectral characteristics

For SLM lasers, the laser is specified as 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 side-mode suppression ratio is specified. The actual spectral characteristics are limited by the maximum amount of optical path penalty (OPP) produced with the worst-case optical dispersion in the data channel.

The use of MLM lasers is not contemplated in this Recommendation.

9.2.7.3 Mean launched power

The mean launched power at O_{ld} and O_{ru} is the average power of a pseudo-random data sequence coupled into the fibre by the transmitter. It is given 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 launched power at the O_{ru} optical interface must take into account the bursty nature of the upstream traffic transmitted by the ONUs.

9.2.7.3.1 Launched optical power without input to the transmitter

In the upstream direction, the ONU transmitter should ideally launch 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 launched power without input to the transmitter is allowed during bursts which are not assigned to that ONU. During the Tx Enable bit period immediately preceding the assigned burst, which may be used for laser pre-bias, and during the Tx Disable bit period immediately following the assigned burst,

the maximum launched power level allowed is the zero level corresponding to the extinction ratio specified in Table 9-3 and Table 9-4.

The specification of the maximum number of Tx Enable and Tx Disable bit periods is provided in Table 9-3 and Table 9-4.

The relationship between ONU power levels and burst times is shown in Figure 9-1.

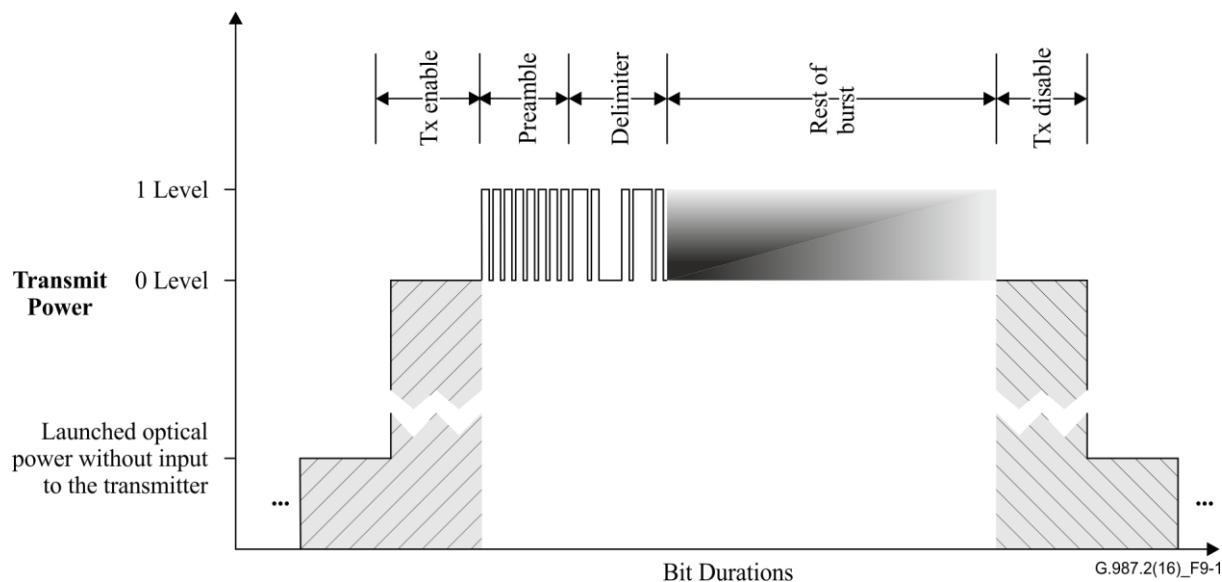


Figure 9-1 – Relationship between ONU power levels and burst times

9.2.7.4 Minimum extinction ratio

The extinction ratio (ER) is defined as:

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

where A is the average optical power level at the centre of the binary 1 and B is the average optical power level at the centre of the binary 0.

The extinction ratio 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.

9.2.7.5 Maximum reflectance of equipment, measured at transmitter wavelength

Reflections from equipment (ONU/OLT) back to the cable plant are specified by the maximum permissible reflectance of equipment measured at O_{ld}/O_{ru} , in accordance with Table 9-3 and Table 9-4.

9.2.7.6 Mask of transmitter eye diagram

In this Recommendation, general transmitter pulse shape characteristics including rise time, fall time, pulse overshoot, pulse undershoot, and ringing, all of which should be controlled to prevent excessive degradation of the receiver sensitivity, are specified in the form of a mask of the transmitter eye diagram at O_{ld}/O_{ru} . 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.

9.2.7.6.1 OLT transmitter

The parameters specifying the mask of the eye diagram (see Figure 9-2) for the OLT transmitter are shown in Table 9-5. The test set-up for the measurement of the mask of the eye diagram is shown in Figure 9-3.

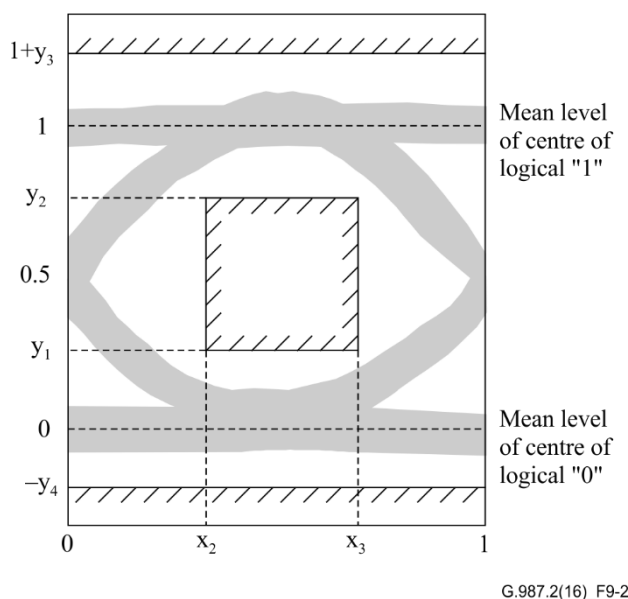
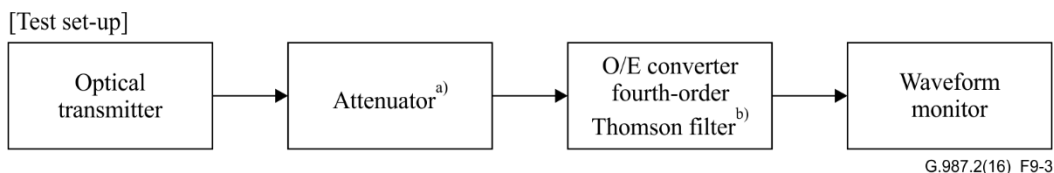


Figure 9-2 – Mask of the eye diagram for OLT transmitter

Table 9-5 – Mask of the eye diagram for OLT transmitter – Numeric values

	9.95328 Gbit/s
$x_3 - x_2$ (Note 1)	0.2
y_1	0.25
y_2	0.75
y_3	0.25
y_4	0.25

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.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 9-3 – Test set-up for mask of the eye diagram for OLT transmitter

9.2.7.6.2 ONU transmitter

The parameters specifying the mask of the eye diagram (see Figure 9-4) for the ONU transmitter are shown in Table 9-6. The test set-up for the measurement of the mask of the eye diagram is shown in Figure 9-5.

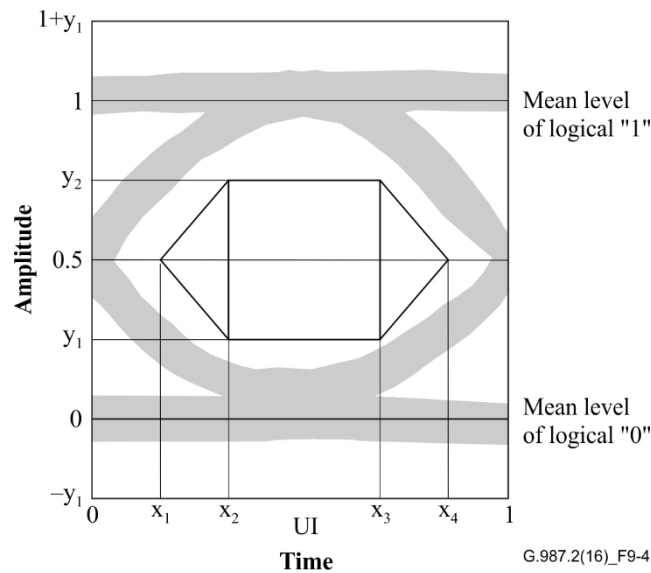
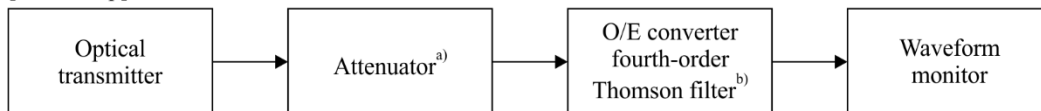


Figure 9-4 – Mask of the eye diagram for ONU transmitter

Table 9-6 – Mask of the eye diagram for ONU transmitter – numeric values

	2.48832 Gbit/s
$x_3 - x_2$	0.2
y_1	0.25
y_2	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.	

[Test set-up]



G.987.2(16)_F9-5

^{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 9-5 – Test set-up for mask of the eye diagram for ONU transmitter

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.

9.2.7.7 Transmitter tolerance to reflected optical power

The specified transmitter performance must be met in the presence of the optical reflection level at reference point S specified in Table 9-3 and Table 9-4.

9.2.8 Optical path between O_{ld}/O_{ru} and O_{rd}/O_{lu}

9.2.8.1 Attenuation range

Four classes of attenuation ranges are specified in clause 6.1.

Attenuation specifications are assumed to be worst-case values at all wavelengths specified in Table 9-3 and Table 9-4 including losses due to splices, connectors, optical attenuators (if used) or other passive optical devices, and any additional cable margin to cover allowances for:

- 1) future modifications to the cable configuration (additional splices, increased cable lengths, etc.);
- 2) fibre cable performance variations due to environmental factors; and
- 3) degradation of any connector, optical attenuators (if used) or other passive optical devices between points S and R, when provided.

9.2.8.2 Minimum optical return loss of the cable plant at point R/S, including any connectors

Overall minimum optical return loss (ORL) specification at point R/S in the ODN is specified in Table 9-3 and Table 9-4.

Optionally, minimum ORL specification at point S in the ODN is specified in Note 2 of Table 9-3 and Table 9-4.

NOTE – The overall reflectance at the S/R point for an ODN model is dominated by the optical connectors at the optical distribution frame (ODF). The maximum reflectance of a single discrete element within [ITU-T G.982] is –35 dB. The reflectance from the two ODF connectors leads to a figure of –32 dB. However, based on another network model, the overall reflectance may become worse than –20 dB.

9.2.8.3 Maximum discrete reflectance between points S and R

All discrete reflectances in the ODN shall be better than –35 dB as defined in [ITU-T G.982].

9.2.8.4 Dispersion

Systems considered limited by dispersion have maximum values of dispersion (ps/nm) specified in Table 9-3 and Table 9-4. These values are consistent with the maximum optical path penalties specified. They take into account the specified transmitter type, and the fibre dispersion coefficient over the operating wavelength range.

9.2.9 Receiver at O_{rd} and O_{lu}

All parameters are specified as follows, in accordance with Table 9-3 and Table 9-4.

9.2.9.1 Receiver sensitivity

Receiver sensitivity is defined in [ITU-T G.987]. The values are specified in Table 9-3 and Table 9-4. Receiver sensitivity takes into account power penalties caused by the use of a transmitter under standard operating conditions with worst-case values of extinction ratio, pulse rise and fall times, optical return loss at point R/S, receiver connector degradation and measurement tolerances. The receiver sensitivity does not include power penalties associated with dispersion, jitter, or reflections from the optical path; these effects are specified separately in the allocation of maximum optical path penalty.

9.2.9.2 Receiver overload

Receiver overload is defined in [ITU-T G.987]. The values are specified in Table 9-3 and Table 9-4, accordingly. The receiver should have a certain robustness against increased optical power level due to start-up or potential collisions during ranging, for which the BER, specified in Table 9-3 and Table 9-4, is not guaranteed.

9.2.9.3 Maximum optical path penalty

Optical path penalty is defined in [ITU-T G.987]. The receiver is required to tolerate an optical path penalty not exceeding the value specified in Table 9-3 and Table 9-4.

9.2.9.4 Maximum reflectance at R/S, measured at receiver wavelength

Reflections from equipment (ONU/OLT) back to the cable plant are specified by the maximum permissible reflectance of equipment measured at O_{rd} and O_{lu} . It shall be in accordance with Table 9-3 and Table 9-4.

9.2.9.5 Differential optical path loss

Differential optical path loss means the optical path loss difference between the highest and lowest optical path loss in the same ODN. The maximum differential optical path loss is defined in Table 9-3 and Table 9-4.

9.2.9.6 Clock extraction capability

NOTE – 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.

9.2.9.7 Jitter performance

This clause deals with jitter requirements for optical interfaces of XG-PON.

9.2.9.7.1 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 9-6, when input sinusoidal jitter up to the mask level in Figure 9-7 is applied, with the parameters specified in this figure for each line rate.

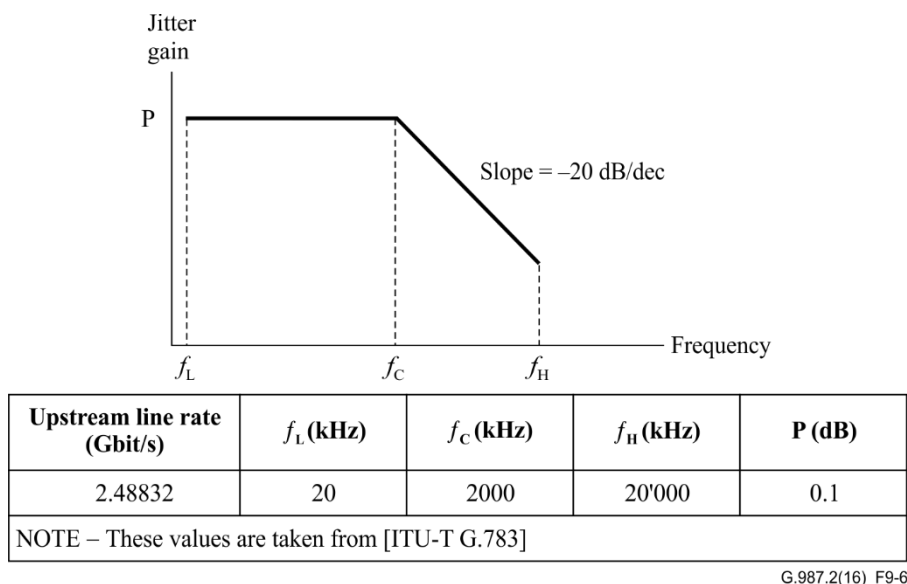


Figure 9-6 – Jitter transfer for ONU

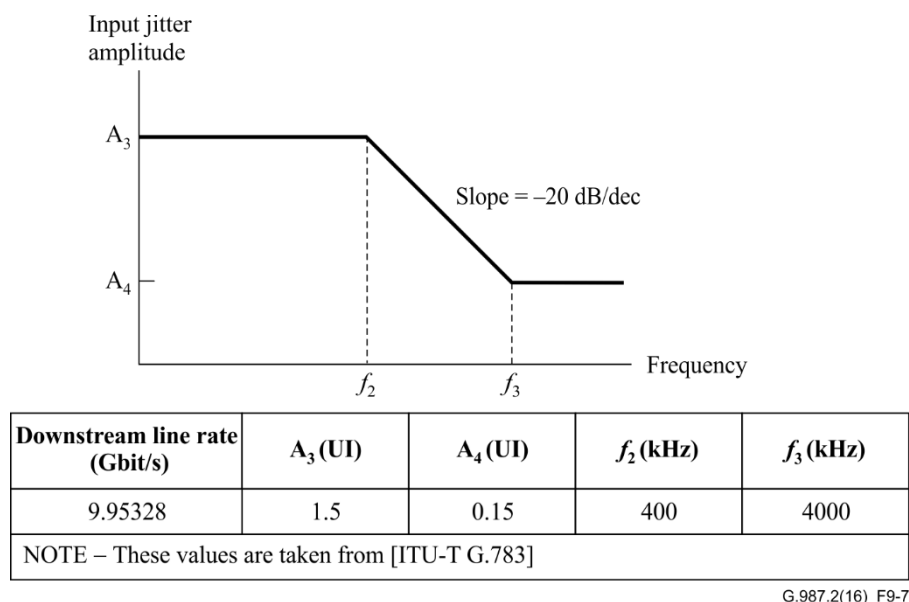


Figure 9-7 – High-band portion of sinusoidal jitter mask for jitter transfer

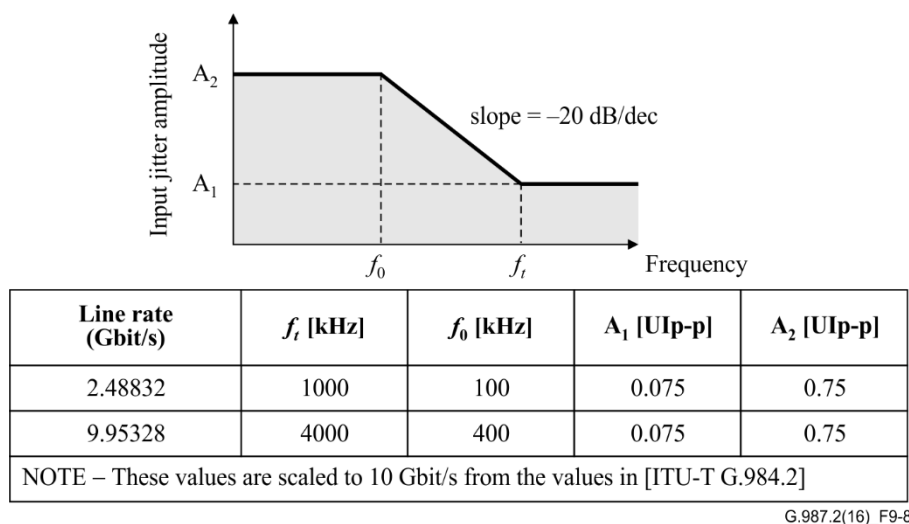


Figure 9-8 – Jitter tolerance mask

9.2.9.7.2 Jitter tolerance

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

The ONU shall tolerate, as a minimum, the input jitter applied according to the mask in Figure 9-8, with the parameters specified in that figure for the downstream line rate. The OLT should tolerate, as a minimum, the input jitter applied according to the mask in Figure 9-8, 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.

9.2.9.7.3 Jitter generation

An ONU shall not generate a peak-to-peak jitter amplitude more than shown in Table 9-7 at a line rate of 2.48832 Gbit/s, with no jitter applied to the downstream input and with a measurement bandwidth as specified in Table 9-7. An OLT shall not generate a peak-to-peak jitter amplitude more than shown in Table 9-7 at a line rate of 9.95328 Gbit/s, with no jitter applied to its timing reference input and with a measurement bandwidth as specified in Table 9-7.

Table 9-7 – Jitter generation requirements for XG-PON1

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
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].			

9.2.9.8 Consecutive identical digit (CID) immunity

The OLT and the ONU shall have a CID immunity as specified in the series of Table 9-3 and Table 9-4.

9.2.9.9 Receiver tolerance to reflected power

The receiver tolerance to reflected power is the allowable ratio of optical input average power of O_{rd} and O_{lu} to reflected optical average power when multiple reflections are regarded as a noise light at O_{rd} and O_{lu} respectively.

The receiver tolerance to reflected power is defined at minimum receiver sensitivity.

9.2.9.10 Transmission quality and error performance

To avoid system down time or failures, the frame structure should be robust in the presence of transmission BER up to the values defined in Table 9-3 and Table 9-4.

The average BER on individual links across the entire PON system will typically be lower than the values defined in Table 9-3 and Table 9-4. Optical components should provide BER better than the values defined in Table 9-3 and Table 9-4 when conditions allow.

10 X/S tolerance of XG-PON ONU

The minimum optical sensitivity of an XG-PON ONU must be met in the presence of interference signals. Interference signals are caused by other services such as G-PON and/or video signals in the enhancement band specified in [ITU-T G.987.1]. To minimize the effect of interference signals, XG-PON ONUs need to isolate them using an appropriate wavelength blocking filter (WBF) and WDM filter. This Recommendation does not specify the isolation characteristics of the WBF and WDM filters directly, but specifies the X/S tolerance of the XG-PON ONU. Here, S is the optical power of the XG-PON signal, and X is that of the interference signal(s). Both are measured at the ONU reference point R/S, corresponding to the ONU reference point IF_{XGPON} specified in [ITU-T G.987.1].

The interference signal format for measuring X/S tolerance is an NRZ pseudo-random code with the same line rate as the XG-PON downstream signal or a lower line rate within the bandwidth of the XG-PON receiver.

10.1 Versatile WDM configuration

This clause describes the X/S tolerance of XG-PON ONUs. This tolerance can be used to design a variety of WDM configurations at the ONU. It makes no definite assumption about additional services using the enhancement band specified in [ITU-T G.987.1]. Figure 10-1 shows the X/S tolerance mask that should not cause the XG-PON receiver to fail to meet its sensitivity requirements. Implementers need to specify the isolation characteristics of the WBF and WDM filters to obtain enough isolation of the interference signal(s). This allows the XG-PON sensitivity requirement to be met in the presence of this level of interference. The wavelengths and total optical launch power of additional services must fall beneath the mask of Figure 10-1 to allow coexistence with XG-PON.

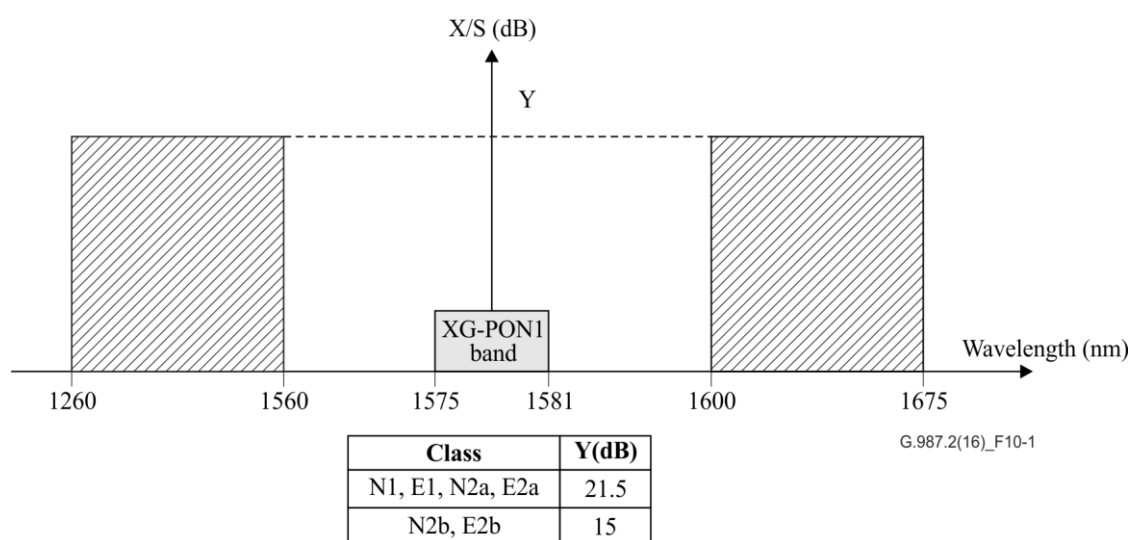


Figure 10-1 – X/S tolerance mask for ONU (Versatile WDM configuration)

S: Received power of basic band

X: Maximum total power of additional services received in the blocking wavelength range.

X/S: In the mask (hatching area) should not cause the XG-PON receiver to fail to meet its sensitivity requirements

11 Upstream physical layer overhead

The XG-PON frame structure is described in [ITU-T G.987.3], which is devoted to the specification of the TC layer. However, upstream bursts must be preceded by suitable physical layer overhead, which is used to accommodate several physical processes. Table 11-1 shows the length of the physical layer overhead for the upstream line rate specified in this Recommendation.

Table 11-1 – XG-PON upstream physical layer overhead

Upstream line rate	Overhead bits
2.48832 Gbit/s	256

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

Appendix I

Examples of wavelength allocation for XG-PON, G-PON and video distribution services

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

See Appendix II of [ITU-T G.984.5] for a generic consideration of wavelength allocation for XG-PON, G-PON and video distribution services.

Appendix II

Physical layer measurements required to support optical layer supervision

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

See Appendix IV in Amendment 2 of [ITU-T G.984.2].

Appendix III

Allocation of the physical layer overhead time

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

The physical layer overhead time (T_{plo}) 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.

T_{plo} 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 (T_g), the preamble time (T_p) and the delimiter time (T_d). During T_g , the ONU will transmit no more power than the nominal zero level. During T_p , 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 T_d , the ONU will transmit a special data pattern with optimal autocorrelation properties that enable the OLT to find the beginning of the burst. Table III. 2 gives recommended values for T_g , T_p , T_d , and T_{plo} . Figure III. 1 shows the timing relationship between the various physical layer overhead times.

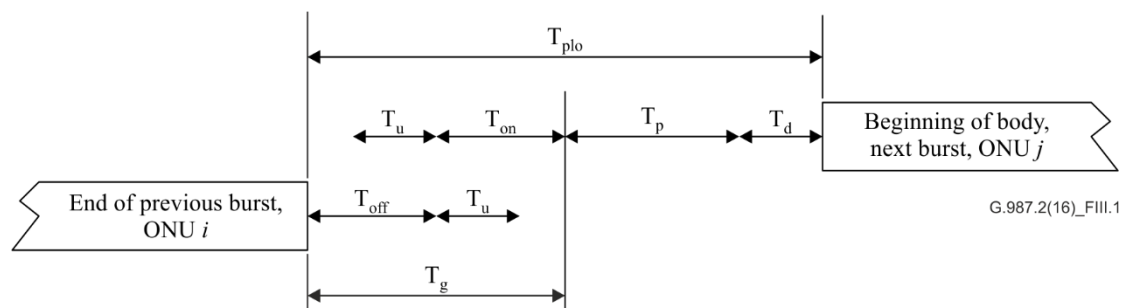


Figure III.1 – Timing relationship between the various physical layer overhead times

An additional parameter of the control logic on the PON is the total peak-to-peak timing uncertainty (T_u). This uncertainty arises from variations of the time of flight caused by the fibre and component variations with temperature and other environmental factors.

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

$$T_g > T_{on} + T_u, \text{ and}$$

$$T_g > T_{off} + T_u$$

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.

T_p 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 gets to configure the details of the preamble that is transmitted by the ONU. This is part of the burst profile discussion below.

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

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

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 $D = \text{int}(N/2) - 1$; yielding the error tolerance shown.

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

$$P_{seb} = \binom{N}{E+1} BER^{E+1} \quad (\text{III-2})$$

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

$$P_{seb} = \binom{N}{\text{int}(N/4)} BER^{\text{int}(N/4)} \quad (\text{III-3})$$

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 Tx enable time and Tx 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 XG-PON1 OLT functions**

	Tx enable	Tx disable	Total time	Guard time	Preamble time	Delimiter time
Worst-case (bit times)	32	32	2048	128	1856	64
Objective (bit times)	32	32	256	64	160	32

In addition to the design dependent aspects of the burst overhead, there can be operationally dependent factors. For example, detecting an ONU's ranging burst is a more difficult problem than receiving an ONU's regular transmission. For another example, some ONUs may have higher power and be 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 should be 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 should use 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 should be balanced and they should 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 are described in [ITU-T G.987.3], the XG-PON XGTC layer.

Appendix IV

Jitter budget specifications

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

IV.1 The concept of jitter budget

Figure IV.1 describes the overall concept of the jitter specification and shows the place of the jitter budget in it.

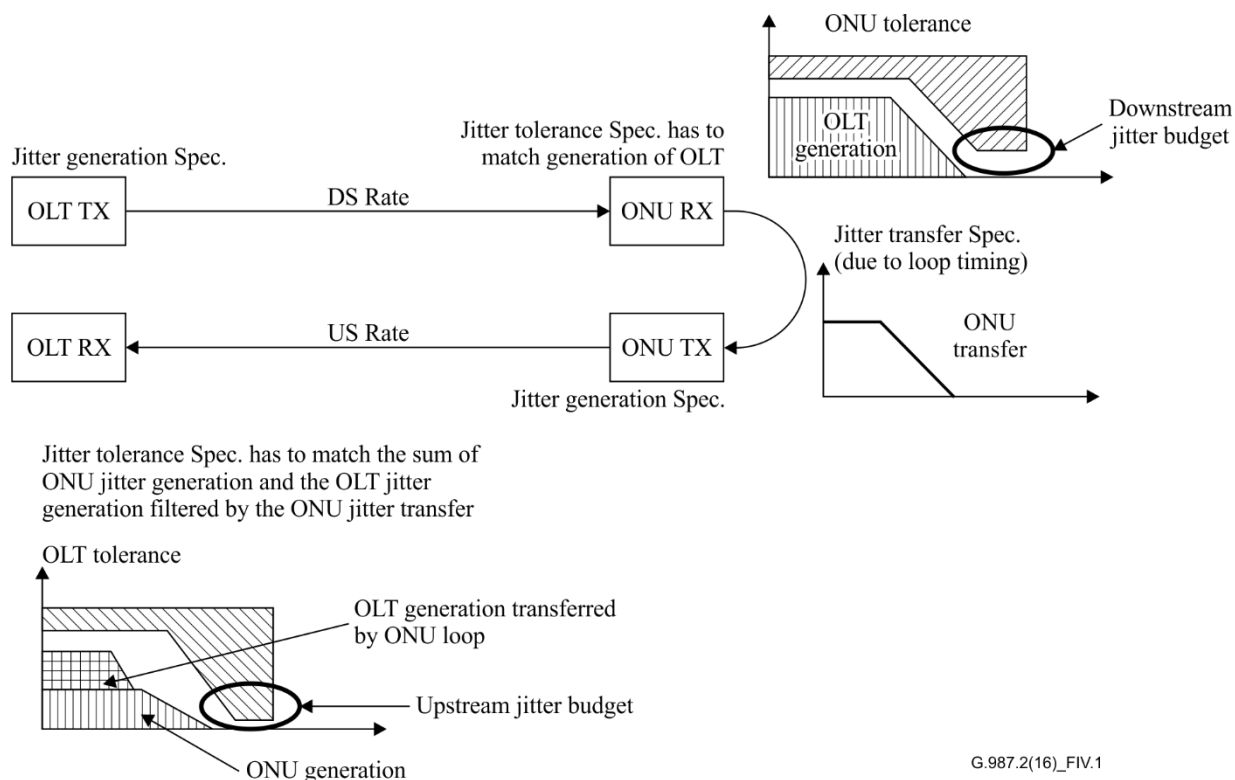


Figure IV.1 – The place of the jitter budget in the overall jitter specification

The jitter budget specifies jitter components that are not covered by the low frequency jitter specifications. All jitter components accounted for in the jitter budget are integrated over the frequency domain that starts from the upper corner frequency (f_i) of the jitter tolerance mask (see clause 9.2.9.7.2).

The jitter budget is based on the dual Gaussian jitter model. In this model, the jitter components are classified into deterministic jitter (DJ) and random jitter (RJ). The DJ components are modelled as a bimodal distribution and the RJ components as a Gaussian distribution. In addition, the duty-cycle distortion (DCD), which is a DC component, is included into the DJ specification of the jitter budget. The basic assumptions of the model are as follows:

- 1) jitter is represented assuming the DJ has an equi-probable bimodal distribution and the RJ has a Gaussian distribution;
- 2) all sources of random jitter are assumed independent; therefore RJ RMS values can be added by squares;
- 3) all sources of DJ are assumed to be correlated (this is a worst-case assumption, meaning that all DJ components are either together at maximum value or together at minimum value, with equal probability for the minimum and the maximum to occur).

Under these assumptions, the total jitter is defined at each given BER by:

$$TJ_{@BER} = DJ + RJ_{RMS} \cdot 2 \cdot Q^{-1}(BER)$$

where $Q^{-1}(BER)$ is the inverse of the Q function. For a very rigorous definition of jitter methodologies, refer to [b-ANSI MJSQ].

IV.2 Definition of test points

In order to build a consistent jitter budget, test points need to be defined at which the jitter components are to be measured. It is important to notice that between the optical module and the SERDES component (whether it is a stand-alone component connected to the MAC through a parallel interface or whether it is integrated inside the MAC ASIC) there is a non-negligible electrical channel.

The test points of the jitter budget are defined in Figure IV.2 and Table IV.1.

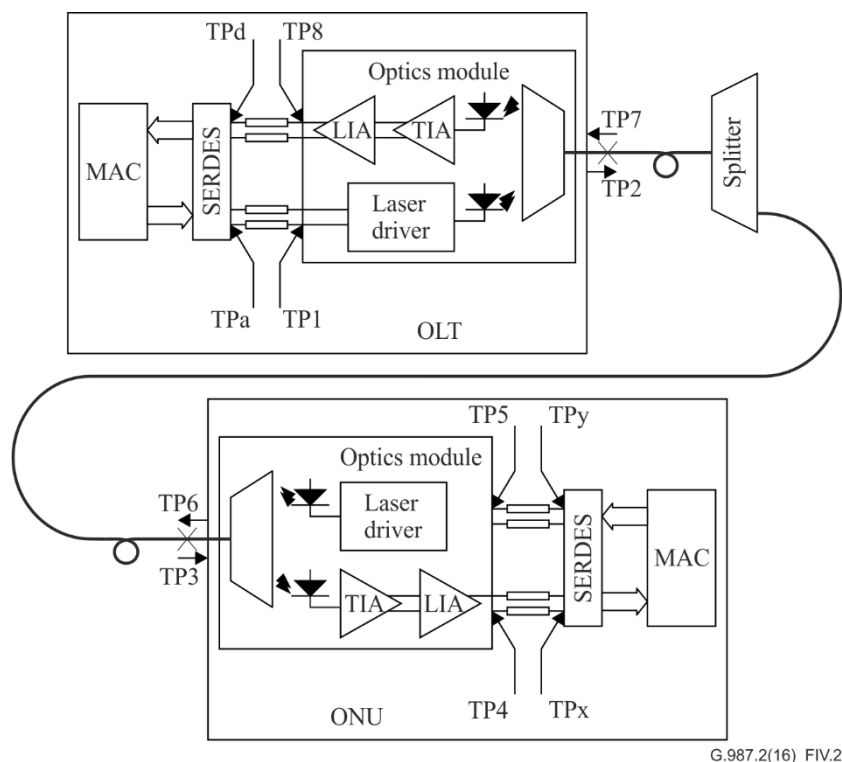


Figure IV.2 – Test points of the jitter budget

Table IV.1 – Description of test points for jitter budget

Test Point	Description
TPa	Electrical test point at the TX output pins of OLT SERDES
TP1	Electrical test point at the TX input pins of OLT optical module
TP2	Optical test point at output of OLT (downstream)
TP3	Optical test point at input of ONU (downstream)
TP4	Electrical test point at the RX output pins of ONU optical module
TPx	Electrical test point at the RX input pins of ONU SERDES
Tpy	Electrical test point at the TX output pins of ONU SERDES
TP5	Electrical test point at the TX input pins of ONU optical module
TP6	Optical test point at output of ONU (upstream)

Table IV.1 – Description of test points for jitter budget

Test Point	Description
TP7	Optical test point at input of OLT (upstream)
TP8	Electrical test point at the RX output pins of OLT optical module
TPd	Electrical test point at the RX input pins of OLT SERDES

IV.3 Jitter budget specification for XG-PON1

The proposed values of the jitter components at the different test points are presented in Table IV.2.

All jitter values are indicated as peak-to-peak values at the BER that corresponds to the respective test point. Jitter at all test points except TP4, TPx, TP8, and TPd is defined at $BER=10^{-12}$, which is the target BER of the system and also the default BER used by the test instruments. RJ at receiver is calculated at a power level equal to the sum of the minimum sensitivity and the maximum OPP, as defined in Table 9-3 for the downstream direction and Table 9-4 for the upstream direction. Jitter at TP4 and TPx is defined at $BER=10^{-3}$, and jitter at TP8 and TPd is defined at $BER=10^{-4}$, since the system relies on FEC to reach the system target BER.

Table IV.2 – Jitter budget for XG-PON1

Downstream jitter budget				
Test Point	DJ [Uipp]	RJ [Uipp]	TJ [Uipp]	BER
Tpa	0.10	0.14	0.24	10 ⁻¹²
TP1	0.12	0.14	0.26	
TP2	0.21	0.18	0.38	
TP3	0.26	0.18	0.43	
TP4	0.41	0.27	0.67	10 ⁻³
TPx	0.50	0.27	0.77	
Upstream jitter budget				
Test Point	DJ [Uipp]	RJ [Uipp]	TJ [Uipp]	BER
Tpy	0.07	0.09	0.17	10 ⁻¹²
TP5	0.10	0.09	0.20	
TP6	0.24	0.10	0.35	
TP7	0.24	0.10	0.35	
TP8	0.40	0.19	0.59	10 ⁻⁴
TPd	0.43	0.19	0.62	
NOTE – The values in Table IV.2 are for further study and subject to change.				

IV.4 Jitter measurements for compliance to budget

A set-up that can be used to measure the jitter components at the test points defined in Table IV.1 and verify their compliance to the values given in Table IV.2 is presented in Figure IV.3.

The set-up contains an OLT and an ONU. The ONU is configured to transmit in continuous mode and a PRBS31 pattern is recommended.

If measurement of jitter at optical test-points is required, optical splitters have to be added to the set-up to permit connection of the O2E probe. If the measurement is to include the dispersion from the optical fibre, then a 20 km spool has to be added to the set-up.

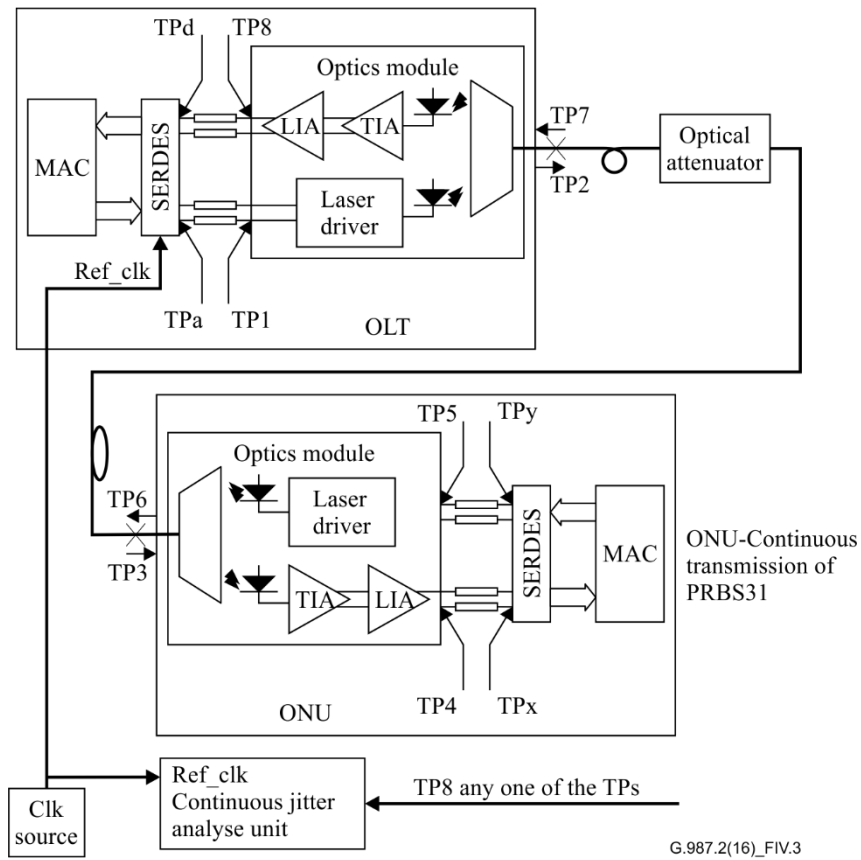


Figure IV.3 – Measurement set-up for jitter budget compliance

Appendix V

Measurement of burst mode acquisition time and burst mode eye opening at OLT

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

One of the major challenges for the burst mode CDR implementation is the need to cope with the transient effects causing additional eye closure at the beginning of the burst. The burst mode CDR has to acquire the phase information exactly on the preamble portion of the incoming data stream, hence it would be reasonable to require the optical module to preserve signal good quality. The better the performance of the optics, the shorter the preamble required for correct system operation.

We define the burst mode eye opening as the opening of the eye pattern that is collected starting from an offset X from the beginning of the burst. The burst mode acquisition time is defined as the shortest offset X from the beginning of the burst that will render a compliant eye pattern. A compliant eye pattern means an eye opening that meets the jitter budget and correct logical signal levels.

A set-up for measuring burst mode acquisition time and burst mode eye opening occurring at the beginning of each burst is presented in Figure V.1.

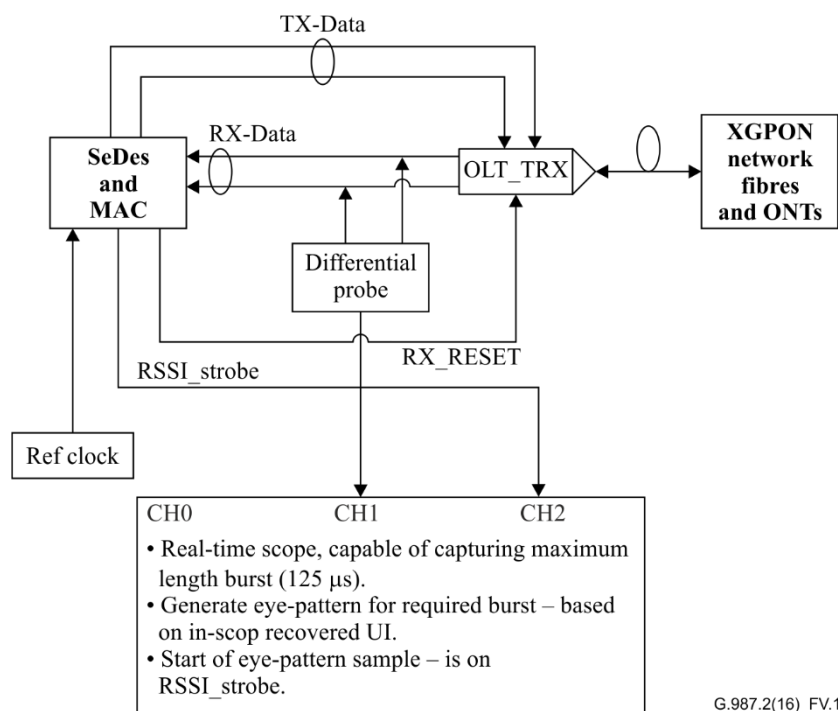


Figure V.1 – Set-up for measurement of burst mode acquisition time and burst mode eye opening

The following is a list of recommendations related to measurement of burst mode acquisition time and burst mode eye opening compliance:

- Use a real time sampling scope capable of 40 GS/s or more and a memory depth that can cover at least 125 µs (5M samples) for capturing the eye pattern.
- In order to separate the eye pattern that corresponds to a single given ONU, the oscilloscope is triggered on RSSI-strobe signal [b-ITU-T G-Sup.48]. The timing diagram for this signal is presented in Figure V.2.

- The burst mode eye diagram is built from the data collected during the sampling window defined in Figure V.3.
- The eye pattern is built using a unit interval (UI) based on an average unit interval (UI) calculated from the collected data.
- The differential probe can be placed to perform measurement at either TP8 (module pins) or at TPd (SERDES pins) (see Figure IV.2).
- The Pass/Fail condition should be a burst mode eye opening in excess of 0.38 UI at TPd and correct logical signal levels. Note that 0.38 UI is equal to 1-TJ for test point TPd in Table IV.2.

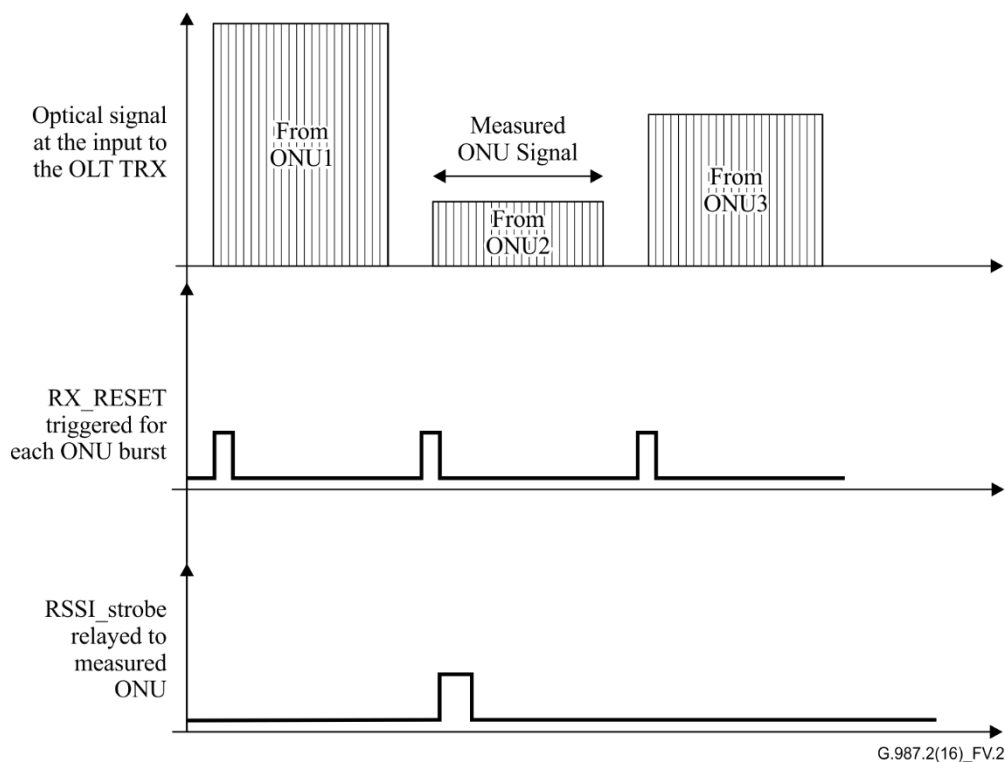


Figure V.2 – RSSI_strobe timing relative to selected burst source

The test set-up shown in Figure V.1 can be used to determine the burst mode acquisition time of a given set of optics. The eye pattern measurement is repeated for different values of the parameter X (defined in Figure V.3) and the minimum setting of X for which the (horizontal) burst mode eye opening at TPd is better than 0.38 UI determines the burst mode acquisition time of the system. Note that 0.38 UI is equal to 1-TJ for test point TPd in Table IV.2.

The system will perform correctly for settings of the preamble length that are longer than the burst mode acquisition time.

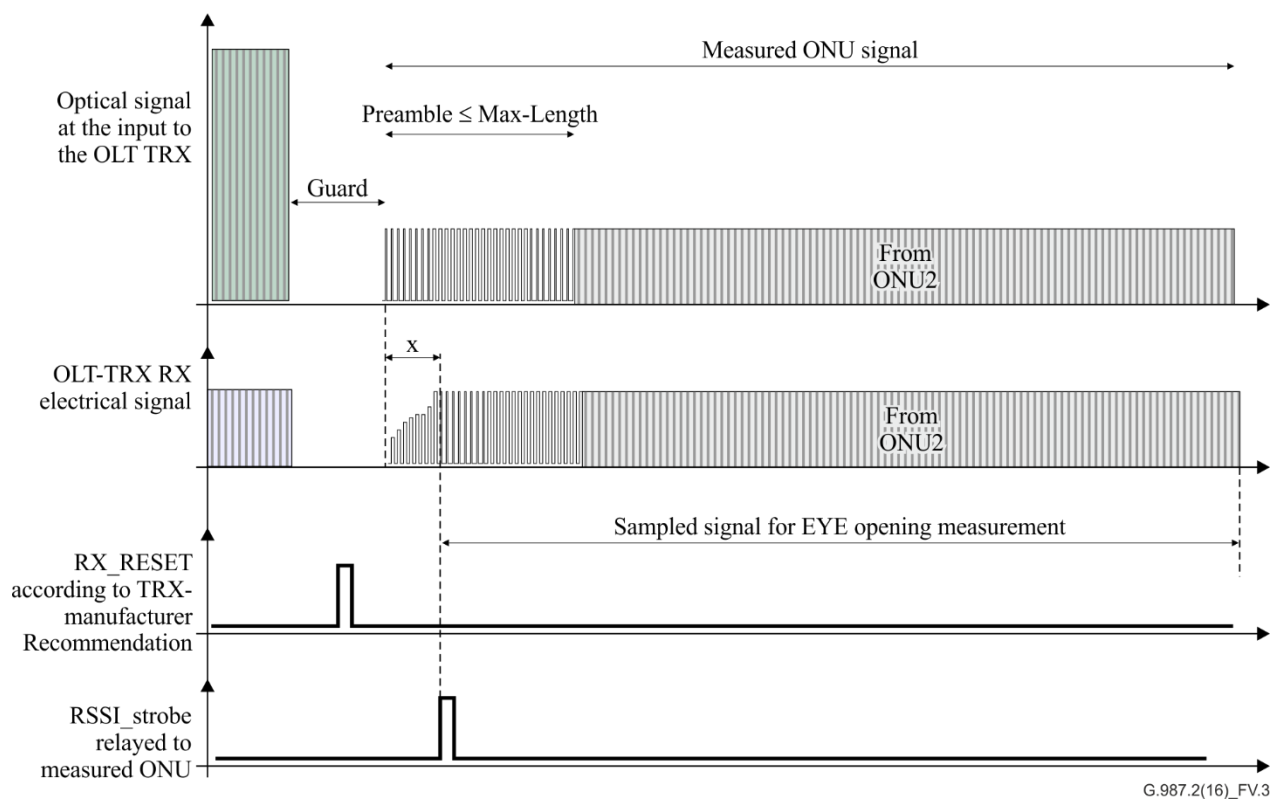


Figure V.3 – Timing diagram of the sampling window for burst mode acquisition time and burst mode eye opening measurements

Bibliography

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- [b-ANSI MJSQ] ANSI-T11.2/Project 1316-DT, *Fibre Channel – Methodologies for Jitter and Signal Quality Specification – MJSQ*. <<http://ece.wpi.edu/analog/resources/mjsq.pdf>>

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