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

Digital sections and digital line system – Digital line
systems

**Optical transport network physical layer
interfaces**

Recommendation ITU-T G.959.1



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Recommendation ITU-T G.959.1

Optical transport network physical layer interfaces

Summary

Recommendation ITU-T G.959.1 provides physical layer inter-domain interface (IrDI) specifications for optical networks which may employ wavelength division multiplexing (WDM). The IrDIs within the optical transport network (OTN) are provided by unidirectional, point-to-point, single- and multichannel line systems. Their primary purpose is to enable transversely-compatible interfaces to span the boundary between two administrative domains. The IrDI specifications include intra-office, short-haul and long-haul applications, without line amplifiers.

This version of this Recommendation includes single channel interfaces up to OTU3 (40 Gbit/s) rate and multichannel interfaces suitable for OTL4.4 (OTU4 striped across four physical lanes).

Source

Recommendation ITU-T G.959.1 was approved on 13 November 2009 by ITU-T Study Group 15 (2009-2012) under Recommendation ITU-T A.8 procedures.

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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NOTE

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Recommendation ITU-T G.959.1

Optical transport network physical layer interfaces

1 Scope

This Recommendation provides physical layer inter-domain interface (IrDI) specifications for optical networks which may employ wavelength division multiplexing (WDM). These interfaces may also be employed, where appropriate, as intra-domain interfaces (IaDI). The physical layer specifications are valid for non-OTN IrDIs, while also allowing application on OTN IrDIs according to [ITU-T G.709]. In the case of a non-OTN IrDI, OTN management capabilities are not required. The IrDIs within the optical transport network (OTN) are provided by unidirectional, point-to-point, single- and multichannel line systems. Their primary purpose is to enable transversely compatible interfaces to span the boundary between two administrative domains. The IrDI specifications include intra-office, short-haul and long-haul applications, without line amplifiers.

NOTE – For the purposes of this Recommendation, the term "administrative domain" is understood to mean the extent of resources which belong to a single player such as a network operator, a service provider or an end-user. Administrative domains of different players do not overlap among themselves.

The specifications are organized according to application codes, which take into account the many possible combinations of channel counts, optical tributary signal types, span distances, fibre types and system configurations. The reference configuration and application codes form the foundation for specifying the optical networking physical layer parameters.

In this Recommendation, the use of an optical supervisory channel has not been considered. Future versions and other new ITU-T Recommendations will further address this aspect of the OTN, possibly involving an arrangement of optical network elements on either side of an optical subnetwork interface that is more complex than point-to-point. For these applications, different parameters beyond those specified for a point-to-point configuration may be required.

This Recommendation presumes that the optical tributary signals transported within optical channels are digital rather than analogue. Specifications for systems enabling transport of analogue optical tributary signals are for further study.

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 (2005), *Characteristics of a single-mode optical fibre and cable.*

[ITU-T G.653] Recommendation ITU-T G.653 (2006), *Characteristics of a dispersion-shifted single-mode optical fibre and cable.*

[ITU-T G.655] Recommendation ITU-T G.655 (2006), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable.*

[ITU-T G.664] Recommendation ITU-T G.664 (2006), *Optical safety procedures and requirements for optical transport systems.*

- [ITU-T G.691] Recommendation ITU-T G.691 (2006), *Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers.*
- [ITU-T G.692] Recommendation ITU-T G.692 (1998), *Optical interfaces for multichannel systems with optical amplifiers.*
- [ITU-T G.693] Recommendation ITU-T G.693 (2005), *Optical interfaces for intra-office systems.*
- [ITU-T G.694.1] Recommendation ITU-T G.694.1 (2002), *Spectral grids for WDM applications: DWDM frequency grid.*
- [ITU-T G.707] Recommendation ITU-T G.707/Y.1322 (2003), *Network node interface for the synchronous digital hierarchy (SDH).*
- [ITU-T G.709] Recommendation ITU-T G.709/Y.1331 (2003), *Interfaces for the Optical Transport Network (OTN).*
- [ITU-T G.872] Recommendation ITU-T G.872 (2001), *Architecture of optical transport networks.*
- [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.8251] Recommendation ITU-T G.8251 (2001), *The control of jitter and wander within the optical transport network (OTN).*
- [IEC 60825-1] IEC 60825-1 (2001), *Safety of laser products – Part 1: Equipment classification and requirements.*
<<http://webstore.iec.ch/webstore/webstore.nsf/artnum/037864?opendocument>>
- [IEC 60825-2] IEC 60825-2 (2005), *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS).*
<<http://webstore.iec.ch/webstore/webstore.nsf/artnum/037463?opendocument>>

3 Terms and definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

- 3.1.1 3R regeneration:** [ITU-T G.872].
- 3.1.2 completely standardized OTUk (OTUk):** [ITU-T G.709].
- 3.1.3 inter-domain interface (IrDI):** [ITU-T G.872].
- 3.1.4 intra-domain interface (IaDI):** [ITU-T G.872].
- 3.1.5 optical channel (OCh):** [ITU-T G.872].
- 3.1.6 optical multiplex section (OMS):** [ITU-T G.872].
- 3.1.7 optical supervisory channel (OSC):** [ITU-T G.692].
- 3.1.8 optical transmission section (OTS):** [ITU-T G.872].

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

- 3.2.1 non-OTN:** This term refers to systems not compliant with the suite of OTN Recommendations indicated in [b-ITU-T G.871]. In particular, non-OTN systems may rely on

client-specific overhead information for performance monitoring, management and protection switching/restoration of the single-channel client signals.

3.2.2 optical transmission section of order 1 (OTS1): A single channel signal that provides transport of an optical channel between two optical network elements.

3.2.3 optical transmission section of order n (OTS_n): A multichannel signal that provides transport of an optical multiplex section, which in turn provides transport of up to n ($n > 1$) optical channels between two optical network elements.

3.2.4 optical tributary signal: A single channel signal that is placed within an optical channel for transport across the optical network.

3.2.5 optical tributary signal class NRZ 1.25G: Applies to continuous digital signals with non-return to zero line coding, from nominally 622 Mbit/s to nominally 1.25 Gbit/s. Optical tributary signal class NRZ 1.25G includes a signal with STM-4 bit rate according to [ITU-T G.707].

3.2.6 optical tributary signal class NRZ 2.5G: Applies to continuous digital signals with non-return to zero line coding, from nominally 622 Mbit/s to nominally 2.67 Gbit/s. Optical tributary signal class NRZ 2.5G includes a signal with STM-16 bit rate according to [ITU-T G.707] and OTU1 bit rate according to [ITU-T G.709].

3.2.7 optical tributary signal class NRZ 10G: Applies to continuous digital signals with non-return to zero line coding, from nominally 2.4 Gbit/s to nominally 10.76 Gbit/s. Optical tributary signal class NRZ 10G includes a signal with STM-64 bit rate according to [ITU-T G.707], OTU2 bit rate according to [ITU-T G.709] and OTL3.4 bit rate (OTU3 striped across four physical lanes) according to [ITU-T G.709].

3.2.8 optical tributary signal class NRZ 25G: Applies to continuous digital signals with non return to zero line coding, from nominally 9.9 Gbit/s to nominally 28 Gbit/s. Optical tributary signal class NRZ 25G includes a signal with OTL4.4 bit rate (OTU4 striped across four physical lanes) according to [ITU-T G.709].

3.2.9 optical tributary signal class NRZ 40G: Applies to continuous digital signals with non-return to zero line coding, from nominally 9.9 Gbit/s to nominally 43.02 Gbit/s. Optical tributary signal class NRZ 40G includes a signal with STM-256 bit rate according to [ITU-T G.707] and OTU3 bit rate according to [ITU-T G.709].

3.2.10 optical tributary signal class RZ 40G: Applies to continuous digital signals with return to zero line coding, from nominally 9.9 Gbit/s to nominally 43.02 Gbit/s. Optical tributary signal class RZ 40G includes a signal with STM-256 bit rate according to [ITU-T G.707] and OTU3 bit rate according to [ITU-T G.709].

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

2R	(Regeneration) Re-amplification, Reshaping
3R	(Regeneration) Re-amplification, Reshaping, Retiming
APD	Avalanche Photodiode
ATM	Asynchronous Transfer Mode
BER	Bit Error Ratio
DC	Dispersion Compensation
DGD	Differential Group Delay
DWDM	Dense Wavelength Division Multiplexing

EX	Extinction ratio
FEC	Forward Error Correction
FFS	For Further Study
FWHM	Full-Width at Half-Maximum
IaDI	Intra-Domain Interface
IP	Internet Protocol
IrDI	Inter-Domain Interface
MLM	Multi-Longitudinal Mode
MPI	Main Path Interface
MPI-R	Single channel Receive Main Path Interface reference point
MPI-R _M	Multichannel Receive Main Path Interface reference point
MPI-S	Single channel Source Main Path Interface reference point
MPI-S _M	Multichannel Source Main Path Interface reference point
NA	Not Applicable
NE	Network Element
NRZ	Non-Return to Zero
OA	Optical Amplifier
OADM	Optical Add-Drop Multiplexer
OCh	Optical Channel
OD	Optical Demultiplexer
OEO	Optical-to-Electrical-to-Optical
OM	Optical Multiplexer
OMS	Optical Multiplex Section
ONE	Optical Network Element
OSC	Optical Supervisory Channel
OTL	Optical channel Transport Lane
OTN	Optical Transport Network
OTS	Optical Transmission Section
OTS1	Optical Transmission Section of level 1
OTSn	Optical Transmission Section of level n
OTUk	Completely standardized optical channel Transport Unit – k
PIN	P type-intrinsic-n type
PMD	Polarization Mode Dispersion
RM	Multichannel Receive reference point (for line OAs)
RMS	Root Mean Square
RS	Single channel Receive reference point
RS-M	Single channel (to Multichannel) Receive reference point

RZ	Return to Zero
SDH	Synchronous Digital Hierarchy
SLM	Single-Longitudinal Mode
SM	Multichannel Source reference point (for line OAs)
SM-S	Single channel (from Multichannel) Source reference point
SONET	Synchronous Optical Network
SS	Single channel Source reference point
WDM	Wavelength Division Multiplexing

5 Classification of optical interfaces

5.1 Applications

This Recommendation addresses single- and multichannel optical systems and provides optical interface parameters and values for a range of inter-domain interface applications.

The majority of the application codes in this Recommendation apply to a range of optical tributary signals with bit rates within the relevant optical tributary signal class (these are termed "plural" application codes and contain the letter P). For example, the code P1I1-2D2 applies to a signal with STM-64 bit rate according to [ITU-T G.707] and also to a signal with OTU2 bit rate according to [ITU-T G.709].

As described in [ITU-T G.872], a standardized interconnection is required for interconnecting administrative domains in a point-to-point configuration.

Interworking between different administrative domains also requires the specification of the characteristic information that is transferred across the inter-domain interface (IrDI) as described in [ITU-T G.707] and [ITU-T G.709] or other specifications. The definition of this characteristic information, which includes signal bit rate, format and byte assignment, is outside the scope of this Recommendation.

From the transmission viewpoint, an optical connection shows analogue behaviour (e.g., the optical transmission impairments due to attenuation, dispersion, fibre non-linearity, amplified spontaneous emission, etc., accumulate in a manner similar to the accumulation of noise and other impairments in analogue networks). Within digital networks, mitigation of such impairments is achieved at 3R regeneration points, located in the transmission path according to engineering guidelines designed to achieve the required link error performance objective. Similarly, within the OTN, 3R regeneration is required at certain locations to maintain the OTN error performance objectives. Currently, the 3R process typically relies on electro-optic conversion. The use of 2R regeneration, as an alternative solution to 3R regeneration for particular applications in IrDIs is left for further study. The use of all-optical 2R/3R regeneration is also for further study.

The IrDI may be realized as either a single-channel interface or a multichannel interface. Multichannel IrDIs require additional wavelength multiplexing and demultiplexing equipment and possibly optical amplifiers but use fewer fibres as compared with multiple single-channel IrDIs having equivalent optical channel capacity. Figure 5-6 indicates a single-channel IrDI. Figures 5-3, 5-4 and 5-5 indicate three types of multichannel IrDI.

This Recommendation provides the physical layer parameters and values for application codes corresponding both to the single-channel and multichannel IrDIs with 3R regenerators on both sides of the interface as shown in Figures 5-3, 5-4, 5-5 and 5-6.

The specification method used in this Recommendation is a "black-box" approach, which means that within the scope of this Recommendation, only the optical interfaces to the IrDI are specified. It

is not intended to restrict or specify the internal elements and/or the connections between the elements within the black-box. There are, however, functional requirements for the black-box, the most important being the inclusion of 3R regeneration.

Specifications are given for single-channel inter-domain interfaces with the following characteristics: channel bit rates corresponding to NRZ 2.5G, NRZ 10G and NRZ 40G, intra-office, short-haul and long-haul span distances, and unidirectional transmission. In the future, specifications are also anticipated for single channel IrDIs with a bit rate/line coding of RZ 40G. Information concerning these possible future applications can be found in Appendix VI.

Appendix I contains a further description of single-channel client interfaces.

Specifications are also given for a multichannel inter-domain interface. This interface accommodates up to 16 channels with central frequencies conforming to the ITU-T G.694.1 grid, with channel bit rates corresponding to NRZ 2.5G and NRZ 10G, intra-office and short-haul (40 km) optical multiplex section single span distances, unidirectional transmission, and point-to-point configuration.

In the future, specifications are anticipated for a further multichannel application. It accommodates up to 16 channels with central frequencies conforming to the ITU-T G.694.1 grid, with channel bit rates corresponding to NRZ 2.5G and NRZ 10G, a long-haul (80 km) optical multiplex section span distance without line amplifiers, unidirectional transmission, and point-to-point configuration.

5.2 Reference points

A set of "generic" reference points for optical network elements (ONEs) in the future OTN can be found in Appendix II.

For the purpose of this Recommendation, the relevant reference points applicable to the multichannel IrDI and the single-channel IrDI are shown in Figures 5-1 and 5-2, respectively.

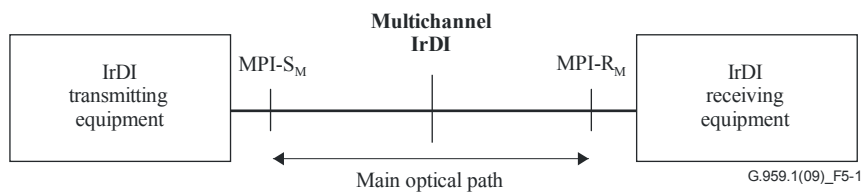


Figure 5-1 – Multichannel IrDI reference configuration

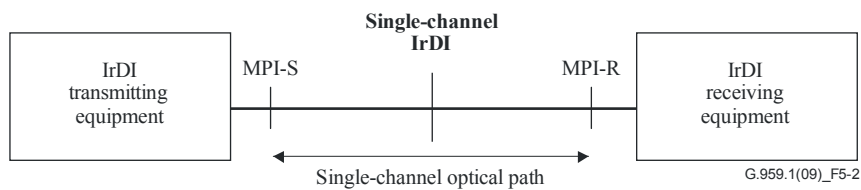


Figure 5-2 – Single-channel IrDI reference configuration

The reference points in Figures 5-1 and 5-2 are defined as follows:

- MPI-S is a (single channel) reference point just after each of the optical network element tributary interface output optical connectors.
- MPI-R is a (single channel) reference point on the optical fibre just before each of the optical network element tributary interface input optical connectors.
- MPI-S_M is a (multichannel) reference point on the optical fibre just after the optical network element transport interface output optical connector.

- MPI-R_M is a (multichannel) reference point on the optical fibre just before the optical network element transport interface input optical connector.

A clarification of the use of the set of generic reference points that apply to both the IrDI and IaDI, as specified in [ITU-T G.872], is given in Appendix III.

5.3 Nomenclature

The application code identifies the network, implementation and architectural characteristics of an application.

The application code notation is constructed as follows:

$$PnW_x-ytz$$

where:

- **P** when present, indicates a "plural" application code applying to an IrDI. Plural codes apply to any optical tributary signal within the defined class.
- **n** is the maximum number of channels supported by the application code.
- **W** is a letter indicating the span distance/attenuation, such as:
 - **I** indicating intra-office (up to 7 dB span attenuation);
 - **S** indicating short-haul (11 dB span attenuation);
 - **L** indicating long-haul (22 dB span attenuation);
 - **V** indicating very long-haul (33 dB span attenuation);
 - **U** indicating ultra long-haul (44 dB span attenuation).
- **x** is the maximum number of spans allowed within the application code.
- **y** indicates the highest class of optical tributary signal supported:
 - **1** indicating NRZ 2.5G;
 - **2** indicating NRZ 10G;
 - **9** indicating NRZ 25G;
 - **3** indicating NRZ 40G;
 - **7** indicating RZ 40G.

Appendix V contains an explanation of how these numbers have been allocated.

- **t** is a letter indicating power level assumptions for the application code, such as:
 - **A** indicating power levels suitable for a booster amplifier in the originating ONE and power levels suitable for a pre-amplifier in the terminating ONE;
 - **B** indicating power levels suitable for a booster amplifier only are used;
 - **C** indicating power levels suitable for a pre-amplifier only are used;
 - **D** indicating power levels suitable for operation with no amplifiers are used.
- **z** is the source and fibre type, as follows:
 - **1** indicating nominally 1310 nm sources on ITU-T G.652 fibre;
 - **2** indicating nominally 1550 nm sources on ITU-T G.652 fibre;
 - **3** indicating nominally 1550 nm sources on ITU-T G.653 fibre;
 - **5** indicating nominally 1550 nm sources on ITU-T G.655 fibre.

In this version of this Recommendation, only physical parameter values of single span IrDIs (i.e., for $x = 1$) have been defined.

A bidirectional system, if introduced, will be indicated by the addition of the letter B at the front of the application code. For an OTN application this would be:

BnWx-ytz

For some application codes, a suffix is added to the end of the code. Six suffixes are defined as follows:

- **F** to indicate that this application requires FEC bytes as specified in [ITU-T G.709] to be transmitted.
- **D** to indicate that this application includes adaptive dispersion compensation.
- **E** to indicate that this application requires the use of a receiver which is capable of dispersion compensation.

NOTE – This may be electronic dispersion compensation.

- **r** to indicate a reduced target distance. These application codes are dispersion limited. The same target distances can also be achieved by means of other technical solutions, which are for further study (e.g., parallel interface approach).
- **a** to indicate that this code has transmitter power levels appropriate to APD receivers.
- **b** to indicate that this code has transmitter power levels appropriate to PIN receivers.

This notation level may have to be augmented when other architectural and implementation alternatives are identified. Table 5-1 provides examples of application codes.

Table 5-1 – Application code examples

Example application code	Plural code?	Maximum number of channels	Maximum span attenuation	Maximum number of spans	Highest class of optical tributary signal	Power levels suitable for ONE type	Fibre type
P111-1D1	Yes	1	6 dB	1	NRZ 2.5G	No amplifiers	G.652
P16S1-2C5	Yes	16	11 dB	1	NRZ 10G	Pre-amplifier only	G.655
16S1-2B5	No	16	11 dB	1	NRZ 10G (OTU2)	Booster only	G.655

5.4 Multichannel inter-domain interfaces

The multichannel IrDI interfaces in this Recommendation are intended to enable transverse (multi-vendor) compatibility. These interfaces may operate on ITU-T G.652, ITU-T G.653 or ITU-T G.655 fibre, simultaneously transporting up to 32 optical channels, using either NRZ 2.5G, NRZ 10G or NRZ 25G optical tributary signals, depending on the particular application code. The same optical parameters apply to all the application codes listed in each individual column of Tables 8-1 to 8-5.

Further requirements related to transverse compatibility can be found in clause 6.

Tables 5-2 to 5-4 summarize the multichannel IrDI application codes, which are structured according to the nomenclature in clause 5.3.

**Table 5-2 – Classification of multichannel inter-domain interfaces
for intra-office applications**

Application	Intra-office (I)			
Source nominal wavelength (nm)	1310 (G.694.1 grid) (Note 2)	1550 (G.694.1 grid) (Note 2)		
Type of fibre	G.652	G.652	G.653	G.655
Target distance (km) (Note 1)	10	20	2	20
Optical tributary signal class NRZ 2.5G	–	–	–	–
Parameters given in:	–	–	–	–
Optical tributary signal class NRZ 10G	–	P16I1-2D2 P32I1-2D2	P16I1-2D3	P16I1-2D5 P32I1-2D5
Parameters given in:	–	Table 8-2	Table 8-2	Table 8-2
Optical tributary signal class NRZ 25G	4I1-9D1F	–	–	–
Parameters given in:	Table 8-5	–	–	–
NOTE 1 – These target distances are for classification and not for specification.				
NOTE 2 – See Table 8-2 or 8-5.				

**Table 5-3 – Classification of multichannel inter-domain interfaces
for short-haul applications**

Application	Short-haul (S)		
Source nominal wavelength (nm)	1550 (G.694.1 grid) (Note 2)		
Type of fibre	G.652	G.653	G.655
Target distance (km) (Note 1)	40	40	40
Optical tributary signal class NRZ 2.5G	P16S1-1D2 P32S1-1D2	–	P16S1-1D5 P32S1-1D5
Parameters given in:	Table 8-1	–	Table 8-1
Optical tributary signal class NRZ 10G	P16S1-2B2 P16S1-2C2 P32S1-2B2 P32S1-2C2	P16S1-2C3	P16S1-2B5 P16S1-2C5 P32S1-2B5 P32S1-2C5
Parameters given in:	Table 8-3	Table 8-3	Table 8-3
NOTE 1 – These target distances are for classification and not for specification.			
NOTE 2 – See Table 8-1 or 8-3.			

Table 5-4 – Classification of multichannel inter-domain interfaces for long-haul applications

Application	Long-haul (L)		
	Source nominal wavelength (nm)	1310 (G.694.1 grid) (Note 2)	1550 (G.694.1 grid) (Note 2)
Type of fibre	G.652	G.652	G.655
Target distance (km) (Note 1)	40	80	80
Optical tributary signal class NRZ 2.5G	–	P16L1-1A2	P16L1-1A5
Parameters given in:	–	Table 8-4	Table 8-4
Optical tributary signal class NRZ 10G	–	P16L1-2A2	P16L1-2A5
Parameters given in:	–	Table 8-4	Table 8-4
Optical tributary signal class NRZ 25G	4L1-9C1F	–	–
Parameters given in:	Table 8-5	–	–
NOTE 1 – These target distances are for classification and not for specification.			
NOTE 2 – See Table 8-4 or 8-5.			

Applications with power levels appropriate to pre-amplifiers only contain the letter C in the application code and are illustrated in Figure 5-3.

Applications with power levels appropriate to booster amplifiers only contain the letter B in the application code and are illustrated in Figure 5-4.

Applications with power levels suitable for operation with no amplifiers contain the letter D in the application code and are illustrated in Figure 5-5.

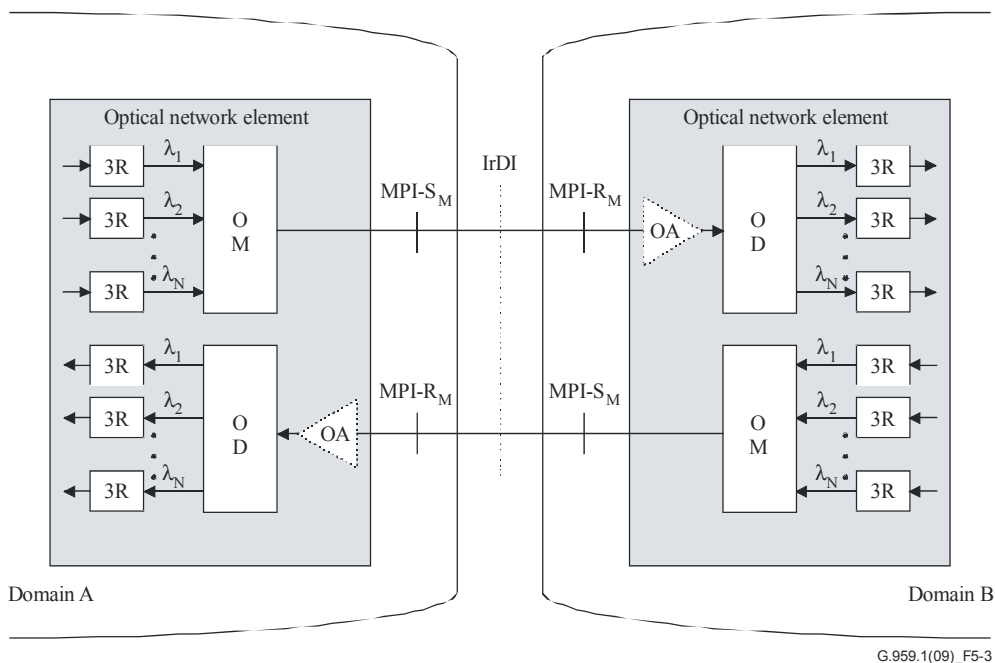


Figure 5-3 – Multichannel IrDI applications using pre-amplifiers

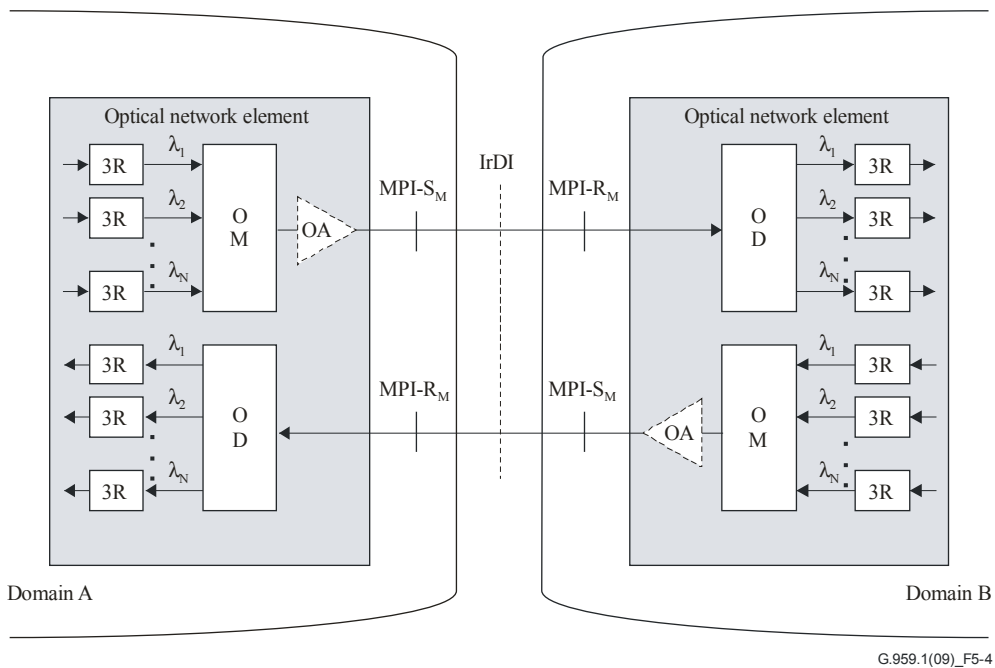


Figure 5-4 – Multichannel IrDI applications using booster amplifiers

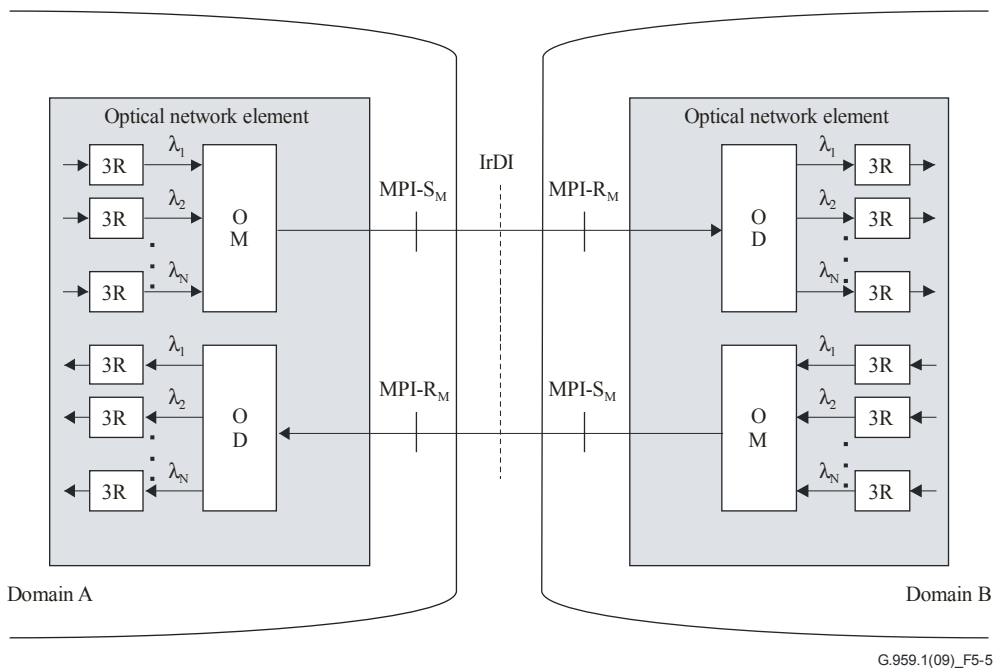
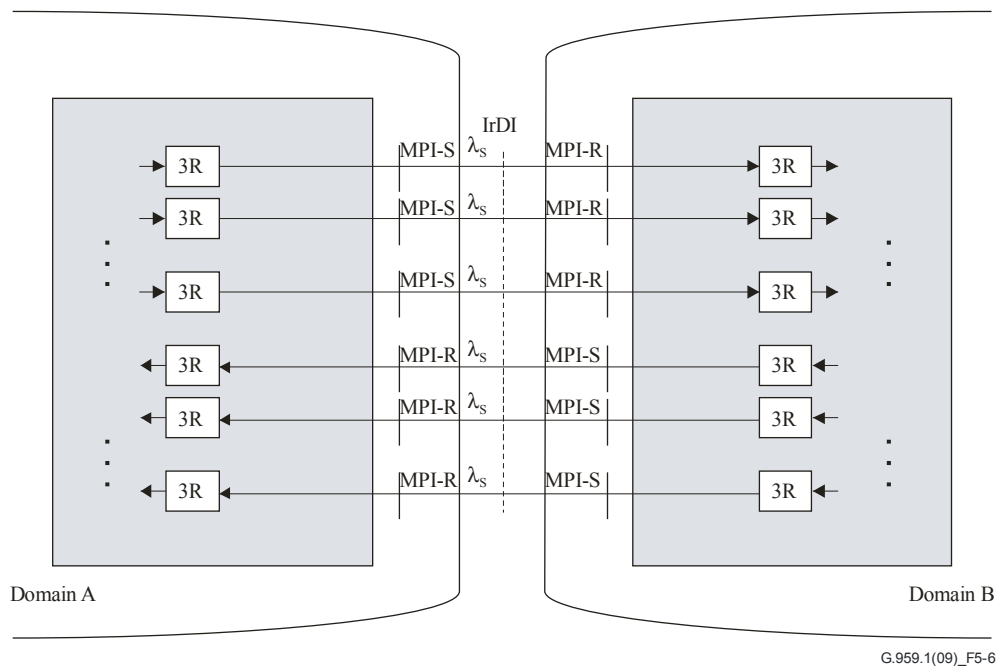


Figure 5-5 – Non-amplified multichannel IrDI applications

5.5 Single-channel inter-domain interfaces

Single-channel inter-domain interfaces are illustrated in Figure 5-6.



G.959.1(09)_F5-6

Figure 5-6 – Single-channel IrDI applications

These interfaces are intended to enable transverse (multi-vendor) compatibility and may operate on ITU-T G.652, ITU-T G.653 or ITU-T G.655 fibres using either NRZ 2.5G, NRZ 10G or NRZ 40G optical tributary signals, depending on the particular application code.

The applications do not cover all possible combinations of distance category, optical tributary signal class, nominal source wavelength and fibre type. The included applications are intended to satisfy a broad range of network requirements with low-cost implementations. Tables 5-5 to 5-9 summarize the single-channel IrDI application codes, which are structured according to the nomenclature in clause 5.3.

Parameter values for intra-office, short-haul, long haul, very long-haul and ultra long-haul applications are given in clause 8.2. For optical tributary signal class NRZ 2.5G applications, in most instances the values in clause 8.2 are similar to or the same as values for applications found in [ITU-T G.957], except that the ITU-T G.957 values have been modified, where necessary, to achieve a bit error ratio of less than or equal to 10^{-12} . For optical tributary signal class NRZ 10G applications, in most instances the values in clause 8.2 are the same as values for applications previously found in [ITU-T G.691].

**Table 5-5 – Classification of single-channel inter-domain interfaces
for intra-office applications**

Application	Intra-office (I)					
	1310		1550			
Type of fibre	G.652		G.652	G.653	G.655	
Optical tributary signal class NRZ 2.5G	–	P1I1-1D1	–	–	–	–
Target distance for class NRZ 2.5G (km) (Note)	–	2	–	–	–	–
Parameters given in:	–	Table 8-6	–	–	–	–
Optical tributary signal class NRZ 10G	P1I1-2D1r	P1I1-2D1	P1I1-2D2r	P1I1-2D2	P1I1-2D3	P1I1-2D5
Target distance for class NRZ 10G (km) (Note)	0.6	2	2	25	25	25
Parameters given in:	[ITU-T G.693]	[ITU-T G.693]	[ITU-T G.693]	Table 8-9	Table 8-9	Table 8-9
As code:	VSR600-2R1	VSR2000-2R1	VSR2000-2L2			
Optical tributary signal class NRZ 40G	–	P1I1-3D1 1I1-3D1F				
Target distance for class NRZ 40G (km) (Note)	–	10				
Parameters given in:	–	Table 8-15				
NOTE – These target distances are for classification and not for specification.						

**Table 5-6 – Classification of single-channel inter-domain interfaces
for short-haul applications**

Application	Short-haul (S)			
	1310	1550		
Type of fibre	G.652	G.652	G.653	G.655
Optical tributary signal class NRZ 2.5G	P1S1-1D1	P1S1-1D2	–	–
Target distance for class NRZ 2.5G (km) (Note)	20	40	–	–
Parameters given in:	Table 8-6	Table 8-6	–	–
Optical tributary signal class NRZ 10G	P1S1-2D1	P1S1-2D2a,b 1S1-2D2bF	P1S1-2D3a,b 1S1-2D3bF	P1S1-2D5a,b 1S1-2D5bF
Target distance for class NRZ 10G (km) (Note)	20	40	40	40
Parameters given in:	Table 8-10	Table 8-10	Table 8-11	Table 8-11

**Table 5-6 – Classification of single-channel inter-domain interfaces
for short-haul applications**

Application	Short-haul (S)			
Optical tributary signal class NRZ 40G	P1S1-3D1 1S1-3D1F	P1S1-3C2	P1S1-3C3	P1S1-3C5
Target distance for class NRZ 40G (km) (Note)	20	40	40	40
Parameters given in:	Table 8-16	Table 8-17	Table 8-17	Table 8-17
NOTE – These target distances are for classification and not for specification.				

**Table 5-7 – Classification of single-channel inter-domain interfaces
for long-haul applications**

Application	Long-haul (L)			
Source nominal wavelength (nm)	1310	1550		
Type of fibre	G.652	G.652	G.653	G.655
Optical tributary signal class NRZ 2.5G	P1L1-1D1	P1L1-1D2 1L1-1D2F	–	–
Target distance for class NRZ 2.5G (km) (Note)	40	80	–	–
Parameters given in:	Table 8-7	Table 8-7	–	–
Optical tributary signal class NRZ 10G	P1L1-2D1	P1L1-2D2 1L1-2D2F P1L1-2D2E 1L1-2D2FE		
Target distance for class NRZ 10G (km) (Note)	40	80		
Parameters given in:	Table 8-12	Table 8-12 Table VII.1		
Optical tributary signal class NRZ 40G	P1L1-3C1 1L1-3C1F	P1L1-3A2 1L1-3C2F 1L1-3C2FD	P1L1-3A3 1L1-3C3F 1L1-3C3FD	P1L1-3A5 1L1-3C5F 1L1-3C5FD
Target distance for class NRZ 40G (km) (Note)	40	80	80	80
Parameters given in:	Table 8-16	Table 8-17	Table 8-17	Table 8-17
Optical tributary signal class RZ 40G	–	P1L1-7A2	P1L1-7A3	P1L1-7A5
Target distance for class RZ 40G (km) (Note)	–	80	80	80
Parameters given in:	–	Table VI.1	Table VI.1	Table VI.1
NOTE – These target distances are for classification and not for specification.				

**Table 5-8 – Classification of single-channel inter-domain interfaces
for very long-haul applications**

Application	Very long-haul (V)		
Source nominal wavelength (nm)	1550		
Type of fibre	G.652	G.653	G.655
Optical tributary signal class NRZ 10G	P1V1-2C2 1V1-2C2F P1V1-2B2E 1V1-2B2FE	–	P1V1-2B5 1V1-2B5F
Target distance for class NRZ 10G (km) (Note)	120	–	120
Parameters given in:	Table 8-13 Table VII.1	–	Table 8-13
NOTE – These target distances are for classification and not for specification.			

**Table 5-9 – Classification of single-channel inter-domain interfaces
for ultra long-haul applications**

Application	Ultra long-haul (U)		
Source nominal wavelength (nm)	1550		
Type of fibre	G.652	G.653	G.655
Optical tributary signal class NRZ 2.5G	P1U1-1A2 1U1-1B2F	P1U1-1A3 1U1-1B3F	P1U1-1A5 1U1-1B5F
Target distance for class NRZ 2.5G (km) (Note)	160	160	160
Parameters given in:	Table 8-8	Table 8-8	Table 8-8
NOTE – These target distances are for classification and not for specification.			

5.6 Management signal implementations

Although no overhead implementation is required of the current IrDI, the need for signals to manage the optical channel, optical multiplex section and optical transmission section layers is foreseen for the future OTN realization. Considerations for physical implementations of such signals are presented in Appendix IV.

6 Transverse compatibility

The goal for the IrDI in this Recommendation is to specify parameters in order to enable transverse (i.e., multi-vendor) compatible line systems for short-haul and long-haul point-to-point applications.

Inter-domain interfaces are intended to interconnect two different administrative domains. Such domains may consist of equipment from two different vendors. The two administrative domains may also belong to two different network operators.

- Transverse (multi-vendor) compatibility is enabled for all IrDIs having exactly the same application code nWx-ytz. As an example, a P16S1-2B2 interface from one vendor, implemented in domain A, can be connected with a P16S1-2B2 interface of another vendor, installed in domain B. Care must also be taken to match the optical tributary signal bit rate and format.

- Interconnection of interfaces with different application codes is a matter of joint engineering. Care must be taken particularly with respect to critical parameters that must be matched, e.g., MPI-S_M output power, MPI-R_M power levels, maximum dispersion, minimum/maximum attenuation, etc. As an example, an interface P16S1-2B2 (booster amplifier power levels) in domain A should not be interconnected with an interface P16S1-2C2 (pre-amplifier power levels) in domain B without additional measures, e.g., adding an attenuator. In this example, the booster amplifier type interface output power may be +15 dBm (see Table 8-3) and the attenuation may be 0 dB. Thus, the input power to the pre-amplifier type interface is +15 dBm. However, the maximum receiver input power of the pre-amplifier type interface must not exceed +5 dBm (see Table 8-3) and the receiver is overloaded by up to 10 dB. Care must also be taken to match the optical tributary signal bit rate and format.

7 Parameter definitions

7.1 System operating wavelength range

The operating wavelength ranges for multichannel applications within this Recommendation are not necessarily restricted to those found within [ITU-T G.692]. Specifically, operating wavelength ranges may exceed those found in [ITU-T G.692] (e.g., 1525-1625 nm).

In addition, future use of the 1285-1330 nm amplification range should not be precluded.

The operating wavelength ranges for single channel applications within this Recommendation are not necessarily restricted to those found within [ITU-T G.957] or [ITU-T G.691].

7.2 Parameters

The parameters in Table 7-1 are defined at the interface points, and definitions are provided in the clauses below.

Table 7-1 – Physical layer parameters for single-channel and multichannel IrDIs

Parameter	Units	For Tables 8-1 to 8-5 defined in:	For Tables 8-6 to 8-16 defined in:	For Table 8-17 defined in:	For Table VI.1 defined in:
General information					
Maximum number of channels	–	7.2.1.1	7.2.1.1	7.2.1.1	7.2.1.1
Bit rate/line coding of optical tributary signals	–	7.2.1.2	7.2.1.2	7.2.1.2	7.2.1.2
Maximum bit error ratio	–	7.2.1.3	7.2.1.3	7.2.1.3	7.2.1.3
Fibre type	–	7.2.1.4	7.2.1.4	7.2.1.4	7.2.1.4
Interface at point MPI-S_M or MPI-S					
Maximum mean (channel) output power	dBm	7.2.2.1	7.2.2.1	7.2.2.1	7.2.2.1
Minimum mean (channel) output power	dBm	7.2.2.1	7.2.2.1	7.2.2.1	7.2.2.1
Maximum mean total output power	dBm	7.2.2.2	NA	NA	NA
Central frequency	THz	7.2.2.3	7.2.2.3	7.2.2.3	7.2.2.3
Channel spacing	GHz	7.2.2.4	NA	NA	NA

Table 7-1 – Physical layer parameters for single-channel and multichannel IrDIs

Parameter	Units	For Tables 8-1 to 8-5 defined in:	For Tables 8-6 to 8-16 defined in:	For Table 8-17 defined in:	For Table VI.1 defined in:
Maximum spectral excursion	GHz	7.2.2.5	7.2.2.5	7.2.2.5	7.2.2.5
Operating wavelength range	nm	NA	7.2.2.6	NA	7.2.2.6
Source type		NA	7.2.2.7	7.2.2.7	7.2.2.7
Maximum duty cycle	%	NA	NA	NA	7.2.2.8
Minimum duty cycle	%	NA	NA	NA	7.2.2.8
Maximum RMS width (σ)	nm	NA	7.2.2.9	NA	NA
Maximum –20 dB width	nm	NA	7.2.2.10	NA	NA
Maximum spectral power density	mW/ 10 MHz	NA	7.2.2.11	7.2.2.11	7.2.2.11
Minimum side mode suppression ratio	dB	NA	7.2.2.12	7.2.2.12	7.2.2.12
Minimum (channel) extinction ratio	dB	7.2.2.13	7.2.2.13	7.2.2.13	7.2.2.13
Eye mask	–	7.2.2.14	7.2.2.14	7.2.2.14	7.2.2.15
Optical path (single span) from point MPI-S_M to MPI-R_M, or MPI-S to MPI-R					
Maximum attenuation	dB	7.2.3.1	7.2.3.1	7.2.3.1	7.2.3.1
Minimum attenuation	dB	7.2.3.2	7.2.3.2	7.2.3.2	7.2.3.2
Maximum chromatic dispersion at upper wavelength limit	ps/nm	7.2.3.3	7.2.3.3	7.2.3.3	7.2.3.3
Maximum chromatic dispersion at lower wavelength limit	ps/nm	7.2.3.3	7.2.3.3	7.2.3.3	7.2.3.3
Maximum chromatic dispersion deviation	ps/nm	NA	NA	7.2.3.4	7.2.3.4
Minimum optical return loss at MPI-S _M or MPI-S	dB	7.2.3.5	7.2.3.5	7.2.3.5	7.2.3.5
Maximum discrete reflectance between MPI-S _M and MPI-R _M , or MPI-S and MPI-R	dB	7.2.3.6	7.2.3.6	7.2.3.6	7.2.3.6
Maximum differential group delay	ps	7.2.3.7	7.2.3.7	7.2.3.7	7.2.3.7
Interface at point MPI-R_M or MPI-R					
Maximum mean (channel) input power	dBm	7.2.4.1	7.2.4.1	7.2.4.1	7.2.4.1
Minimum mean channel input power	dBm	7.2.4.2	NA	NA	NA
Maximum mean total input power	dBm	7.2.4.3	NA	NA	NA
Maximum channel power difference	dB	7.2.4.4	NA	NA	NA
Maximum optical path penalty	dB	7.2.4.5	7.2.4.5	7.2.4.5	7.2.4.5
Minimum equivalent sensitivity	dBm	7.2.4.6	NA	NA	NA
Maximum reflectance of optical network element	dB	7.2.4.7	7.2.4.7	7.2.4.7	7.2.4.7
Minimum sensitivity	dBm	NA	7.2.4.8	7.2.4.8	7.2.4.8

7.2.1 General information

7.2.1.1 Maximum number of channels

The maximum number of optical channels that may be simultaneously present at an interface.

7.2.1.2 Bit rate/line coding of optical tributary signals

Optical tributary signal class NRZ 2.5G applies to continuous digital signals with non-return to zero line coding, from nominally 622 Mbit/s to nominally 2.67 Gbit/s. Optical tributary signal class NRZ 10G applies to continuous digital signals with non-return to zero line coding, from nominally 2.4 Gbit/s to nominally 10.71 Gbit/s. Optical tributary signal class NRZ 40G applies to continuous digital signals with non-return to zero line coding, from nominally 9.9 Gbit/s to nominally 43.02 Gbit/s. Optical tributary signal class RZ 40G applies to continuous digital signals with return to zero line coding, from nominally 9.9 Gbit/s to nominally 43.02 Gbit/s. For OTN optical tributary signals, NRZ 2.5G includes the OTU1 bit rate, NRZ 10G includes the OTU2 bit rate and both NRZ 40G and RZ 40G include the OTU3 bit rate defined in [ITU-T G.709].

For an application that has a "P" at the beginning of the application code (one of the "plural" codes), the parameter values are the same for any bit rate within the range of the applicable optical tributary signal class. When an optical system uses one of these plural codes, therefore, it is necessary to specify both the application code and also the exact bit rate of the system. In other words, there is no requirement for equipment compliant with one of the plural codes to operate over the complete range of bit rates specified for its optical tributary signal class.

7.2.1.3 Maximum bit error ratio

The parameters are specified relative to an optical section design objective of a bit error ratio (BER) not worse than the value specified by the application code. This value applies to each optical channel under the extreme case of optical path attenuation and dispersion conditions in each application. In the case of application codes requiring FEC bytes to be transmitted (i.e., having a code with a suffix of F), the BER is required to be met only after the correction (if used) has been applied. For all other application codes, the BER is required to be met without the use of FEC.

Further information on BER in relation to FEC can be found in [b-ITU-T G-Sup.39].

7.2.1.4 Fibre type

Single mode optical fibre types are chosen from those defined in [ITU-T G.652], [ITU-T G.653] and [ITU-T G.655].

7.2.2 Interface at point MPI-S_M or MPI-S

7.2.2.1 Maximum and minimum mean (channel) output power

The mean launched power of each optical channel at reference point MPI-S_M or MPI-S is the average power of a pseudo-random data sequence coupled into the fibre from the ONE. It is given as a range (maximum and minimum) to allow for some cost optimization and to cover allowances for operation under the standard operating conditions, connector degradations, measurement tolerances and aging effects.

7.2.2.2 Maximum mean total output power

The maximum value of the mean launched optical power at point MPI-S_M.

7.2.2.3 Central frequency

The nominal single channel frequencies on which the digital coded information of the particular optical wavelength channels are modulated by use of the NRZ line code or RZ line code.

The central frequencies are based on the frequency grid given in [ITU-T G.694.1]. The allowed central frequencies for the multichannel IrDI are specified in Tables 8-1 to 8-5.

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

7.2.2.4 Channel spacing

The channel spacing is defined to be the nominal difference in frequency between two adjacent channels. All possible tolerances of actual frequencies are considered in clause 7.2.2.5.

7.2.2.5 Maximum spectral excursion

This is the maximum acceptable difference between the nominal central frequency of the channel and the -15 dB points of the transmitter spectrum furthest from the nominal central frequency measured at point MPI-S_M. This is illustrated in Figure 7-1.

NOTE – The measurement of the -15 dB points of the transmitter spectrum should be performed with a nominal resolution bandwidth of 0.01 nm.

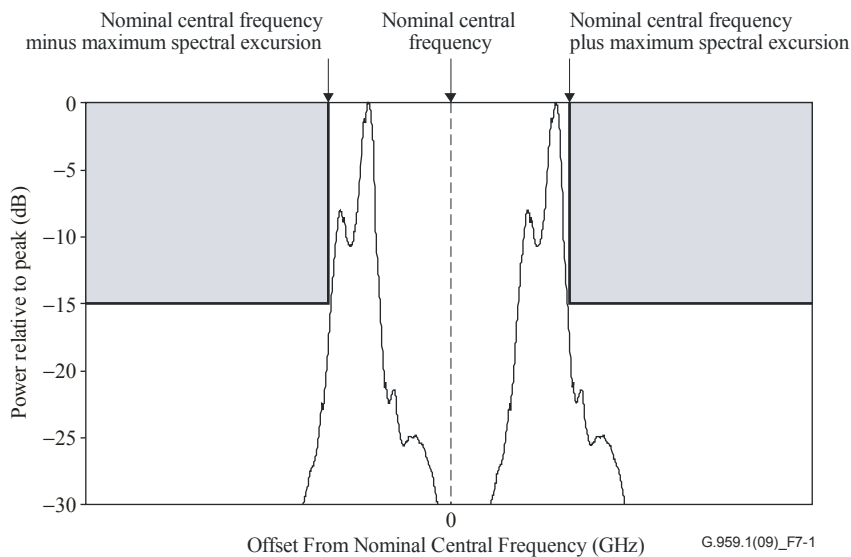


Figure 7-1 – Illustration of maximum spectral excursion

7.2.2.6 Operating wavelength range

The system operating wavelength range depends on the source characteristics, transmission fibre characteristics (attenuation, chromatic dispersion) and on the gain bandwidth of an optical amplifier (if used).

7.2.2.7 Source type

Depending on attenuation/dispersion characteristics and hierarchical level of each application code, feasible transmitter devices include multi-longitudinal mode (MLM) lasers and single-longitudinal mode (SLM) lasers. For each of the applications, this Recommendation indicates a nominal source type. It is understood that the indication of a nominal source type in this Recommendation is not a requirement and that SLM devices can be substituted for any application showing MLM as the nominal source type without any degradation in system performance.

7.2.2.8 Maximum and minimum duty cycle

For further study.

7.2.2.9 Maximum RMS width

The maximum root-mean-square (RMS) width or the standard deviation σ (in nm) of the spectral distribution of an MLM laser considers all laser modes which are not more than 20 dB down from the peak mode. Only a system with an MLM laser at 1310 nm requires this specification.

7.2.2.10 Maximum –20 dB width

The maximum –20 dB spectral width (in nm) of an SLM laser is specified by the maximum full width of the central wavelength peak, measured 20 dB down from the maximum amplitude of the central wavelength under standard operating conditions.

7.2.2.11 Maximum spectral power density

The maximum (optical) spectral power density is defined as the highest time-averaged power level per 10 MHz interval anywhere in the modulated signal spectrum. The measurement must, therefore, be made with a resolution of better (i.e., the optical filter bandwidth shall be less) than 10 MHz FWHM.

This parameter is used to avoid entering into the Brillouin scattering regime for high-power sources with potentially narrow inherent linewidths, such as laser-modulator-amplifier combinations. The specification, however, applies to all source types.

7.2.2.12 Minimum side mode suppression ratio

The minimum side mode suppression ratio is the minimum value of the ratio of the largest peak of the total transmitter spectrum to the second largest peak. The spectral resolution of the measurement shall be better than the maximum spectral width of the peak, as defined in clause 7.2.2.10. The second largest peak may be next to the main peak or far removed from it.

NOTE – Within this definition, spectral peaks that are separated from the largest peak by the clock frequency are not considered to be side modes.

7.2.2.13 Minimum (channel) extinction ratio

The extinction ratio (EX) is defined as:

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

where:

- A is the average optical power level at the centre of the logical "1"; and
- B is the average optical power level at the centre of the logical "0".

The convention adopted for optical logic levels is:

- emission of light for a logical "1";
- no emission for a logical "0".

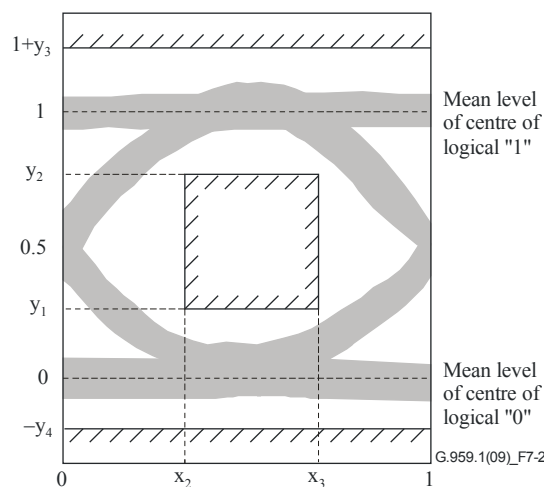
The minimum channel extinction ratio is not required to be met in the presence of a fourth-order Bessel-Thomson filter.

This definition can be directly applied to single-channel systems. In the case of the multichannel IrDI, two alternative methods can be used:

- Method A can be used when single-channel reference points are accessible at the transmit end of the link for verification. For this method, the procedures described in [ITU-T G.957] and [ITU-T G.691] are used. The configuration for this method is contained in Annex A.
- Method B employs a reference optical bandpass filter to isolate the individual transmitted signals. The characteristics of the reference optical bandpass filter are contained in Annex B.

7.2.2.14 Eye mask for NRZ optical transmit signals

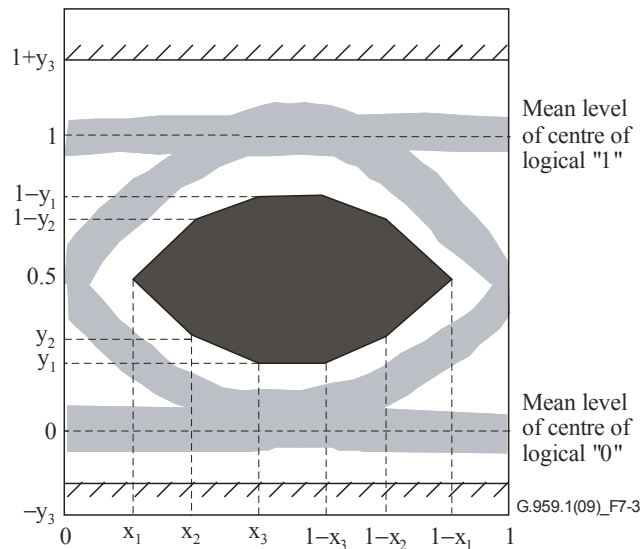
In this Recommendation, general transmitter pulse shape characteristics including rise time, fall time, pulse overshoot, pulse undershoot, and ringing, all of which should be controlled to prevent excessive degradation of the receiver sensitivity, are specified in the form of a mask of the transmitter eye diagram at point MPI-S. For the purpose of an assessment of the transmit signal, it is important to consider not only the eye opening, but also the overshoot and undershoot limitations. The parameters specifying the mask of the transmitter eye diagram are shown in Figure 7-2 for all NRZ optical transmit signals except the "ratio" eye masks which are shown in Figure 7-3. For the masks shown in Figure 7-2, acceptable transmitter eye diagrams must avoid crossing any of the hatched lines. For the "ratio" masks in Figure 7-3, the acceptable ratio of samples inside to outside the hatched area (the "hit ratio") must be met. The test arrangement is as specified for STM-64 in Annex A of [ITU-T G.691]. Filter tolerances for the NRZ 10G and NRZ 25G optical reference receivers are as specified for STM-64 in Annex A of [ITU-T G.691]. Filter tolerances for an NRZ 40G optical reference receiver are for further study.



	NRZ 2.5G	NRZ 10G 1310 nm region	NRZ 10G 1550 nm region	NRZ 10G amplified	NRZ 40G
$x_3 - x_2$ (Note 2)	0.2	0.2	0.2	0.2	0.2
y_1	0.25	0.25	0.25	$\Delta + 0.25$ (Note 1)	0.25
y_2	0.75	0.75	0.75	$\Delta + 0.75$ (Note 1)	0.75
y_3	0.25	0.4	0.25	0.25	0.25
y_4	0.25	0.25	0.25	0.25	0.25

NOTE 1 – Δ is a variable $-0.25 < \Delta < +0.25$.
NOTE 2 – 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.

Figure 7-2 – Mask of the eye diagram for NRZ optical transmit signals except ratio masks



	NRZ 10G Ratio small (Note)	NRZ 10G Ratio large (Note)	NRZ 25G Ratio
x_1	0.25	0.25	0.25
x_2	0.4	0.4	0.4
x_3	0.45	0.45	0.45
y_1	0.25	0.22	0.25
y_2	0.28	0.25	0.28
y_3	0.4	0.4	0.4
Max hit ratio	5×10^{-5}	5×10^{-5}	5×10^{-5}
NOTE – The NRZ 10G Ratio small and NRZ 10G Ratio large eye mask specifications are used in other ITU-T optical interface Recommendations.			

Figure 7-3 – Mask of the eye diagram for NRZ 10G ratio and NRZ 25G ratio

This definition can be directly applied to single-channel systems. In the case of the multichannel IrDI, two alternative methods can be used.

- Method A can be used when single-channel reference points are accessible at the transmit end of the link for verification. For this method, the procedures described in [ITU-T G.957] and [ITU-T G.691] are used. The configuration for this method is contained in Annex A.
- Method B employs a reference optical bandpass filter to isolate the individual transmitted signals, followed by a reference receiver. The characteristics of the reference optical bandpass filter and the reference receiver are contained in Annex B.

7.2.2.15 Eye mask for RZ optical transmit signals

Optical tributary signal class RZ 40G pulse characteristics, such as pulse height variation, are also specified in the form of a mask of the transmitter eye diagram.

The parameters specifying the mask of the transmitter eye diagram are shown in Figure 7-4. Acceptable transmitter eye diagrams must avoid crossing any of the hatched lines. The test arrangement is as specified for STM-64 in Annex A of [ITU-T G.691]. Filter tolerances for an RZ 40G optical reference receiver are for further study.

	RZ 40G
x_4-x_1	FFS
x_3-x_2	FFS
y_1	FFS
y_2	FFS
y_3	FFS
y_4	FFS

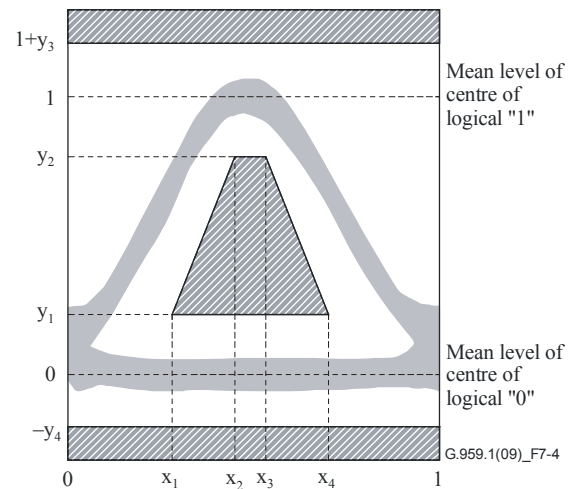


Figure 7-4 – Mask of the eye diagram for RZ 40G optical transmit signal

This definition can be directly applied to single-channel systems. In the case of the multichannel IrDI, two alternative methods can be used.

- Method A can be used when single-channel reference points are accessible at the transmit end of the link for verification. For this method, the procedures described in [ITU-T G.957] and [ITU-T G.691] are used. The configuration for this method is contained in Annex A.
- Method B employs a reference optical bandpass filter to isolate the individual transmitted signals, followed by a reference receiver. The characteristics of the reference optical bandpass filter and the reference receiver are contained in Annex B.

7.2.3 Optical path (single span) from point MPI-S_M to MPI-R_M or MPI-S to MPI-R

7.2.3.1 Maximum attenuation

The maximum path attenuation where the system in question operates under end-of-life conditions at a BER of 10^{-12} (or as given by the application code), under worst-case transmit-side signal and dispersion. The definition of effects included in the maximum attenuation is given in clause 6.3.1 of [ITU-T G.691]. The maximum attenuation values required for the IrDI target distances are based on the assumption of 0.275 dB/km installed fibre loss (including splices and cable margin) in the 1530-1565 nm range, and on an assumption of a 0.55 dB/km value for the 1310 nm single-channel IrDI. From a practical point of view, attenuation spans of 11 dB for 40 km and 22 dB for 80 km at 1550 nm, and 11 dB for 20 km and 22 dB for 40 km at 1310 nm are defined, except for very short reach and intra-office applications. It should be noted that this method, which is also used for the definition of other interfaces at the given wavelength, gives a theoretical value of span distance. Connector and splice losses, which are present in practical implementations, may lead to other distances.

7.2.3.2 Minimum attenuation

The minimum path attenuation that allows the system in question, operating under worst-case transmit-side conditions, to achieve a BER no worse than 10^{-12} (or as given by the application code).

7.2.3.3 Maximum chromatic dispersion at upper and lower wavelength limit

These two parameters define the maximum uncompensated value of the main path chromatic dispersion that the system shall be able to tolerate.

For wavelengths between the upper and lower wavelength limits, the maximum dispersion is linearly interpolated between the values given for the wavelength extremes. Where the maximum dispersion values are the same, this value is required to be met across the entire wavelength range.

For ITU-T G.652 fibre, the required maximum dispersion tolerance at the upper and lower wavelength limits is set to a value equal to 1.05 times the target distance (except for application codes 4I1-9D1F and 4L1-9C1F, where a factor of 1.0 is used) times the maximum dispersion coefficient for ITU-T G.652 fibre at those wavelengths. For ITU-T G.653 fibre, the required maximum dispersion tolerance is set to plus or minus a value equal to 1.05 times the target distance times the highest absolute value of the maximum dispersion coefficient for ITU-T G.653.B fibre at the upper or lower wavelength limits. For ITU-T G.655 fibre, the required maximum dispersion tolerance at the upper and lower wavelength limits is set to a value equal to 1.05 times the target distance times the maximum dispersion coefficient for ITU-T G.655.E fibre at those wavelengths.

These are considered worst-case dispersion values for the relevant fibre types. The worst-case approach on this parameter is intended to give some margins on a sensitive parameter, as well as making it possible to stretch the transmission distances for low-loss fibre plants.

The allowed optical path penalty considers all deterministic effects due to chromatic dispersion, as well as the penalty due to the maximum differential group delay.

7.2.3.4 Maximum chromatic dispersion deviation

This is the amount of the maximum allowable difference between the actual value of the chromatic dispersion of the optical path from MPI-S to MPI-R and the path dispersion value determined at the time of installation. The chromatic dispersion deviation is considered in applications using dispersion compensation (DC). An example is illustrated in Figure 7-5. There the receiver contains a DC module in front of the detector (Det). An optional optical amplifier (OA) may also be present.

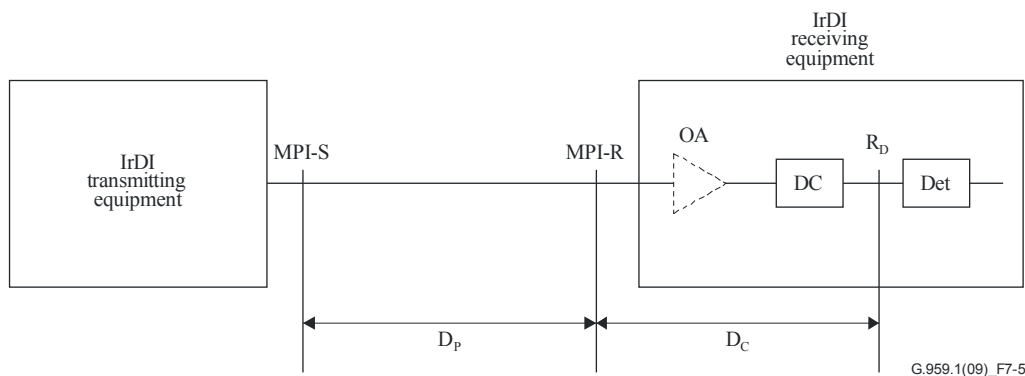


Figure 7-5 – Single channel IrDI with dispersion compensation (DC) in the receiver

At the time of installation of the receiver, the measured value of the dispersion of the optical path D_I is used to set the magnitude of the dispersion compensation within the receiver. Defining the actual value of the dispersion of the optical path to be D_P and the actual value of the dispersion compensation within the receiver to be D_C , there is a requirement that at any time after installation:

$$|D_P + D_C| < D_{r\max}$$

with $D_{r\max}$ being the maximum allowable residual dispersion. As an example, $D_{r\max} = 30$ ps/nm for NRZ 40G applications without adaptive dispersion compensation. Effects including measurement accuracy, temperature, repairs and aging cause D_P to differ from D_I by an amount δ_p . Likewise, effects including setting granularity, temperature and aging cause D_C to differ from D_I by an amount δ_c . The above constraint, therefore, means that to be sure that $D_{r\max}$ is not exceeded, it is required that:

$$|\delta_P| + |\delta_C| < D_{r\max}$$

While reasonable values for $D_{r\max}$ and δ_C were used in generating a specification for the chromatic dispersion deviation (δ_P), this Recommendation only specifies values for δ_P and these can be found in the tables in clause 8.

7.2.3.5 Minimum optical return loss at MPI-S_M or MPI-S

Reflections are caused by refractive index discontinuities along the optical path. If not controlled, they can degrade system performance through their disturbing effect on the operation of the optical source or amplifier, or through multiple reflections which lead to interferometric noise at the receiver. Reflections from the optical path are controlled by specifying:

- the minimum optical return loss of the cable plant at the source reference point (e.g., MPI-S_M, MPI-S), including any connectors; and
- the maximum discrete reflectance between source reference points (e.g., MPI-S_M, MPI-S) and receive reference points (e.g., MPI-R_M, MPI-R).

Reflectance denotes the reflection from any single discrete reflection point, whereas the optical return loss is the ratio of the incident optical power to the total returned optical power from the entire fibre, including both discrete reflections and distributed backscattering such as Rayleigh scattering.

Measurement methods for reflections are described in Appendix I of [ITU-T G.957]. For the purpose of reflectance and return loss measurements, points MPI-S and MPI-R are assumed to coincide with the endface of each connector plug. It is recognized that this does not include the actual reflection performance of the respective connectors in the operational system. These reflections are assumed to have the nominal value of reflection for the specific type of connectors used.

7.2.3.6 Maximum discrete reflectance between MPI-S_M and MPI-R_M, or MPI-S and MPI-R

Optical reflectance is defined to be the ratio of the reflected optical power present at a point, to the optical power incident to that point. Control of reflections is discussed extensively in [ITU-T G.957]. The maximum number of connectors or other discrete reflection points which may be included in the optical path (e.g., for distribution frames, or WDM components) must be such as to allow the specified overall optical return loss to be achieved. If this cannot be done using connectors meeting the maximum discrete reflections cited in the tables of clause 8, then connectors having better reflection performance must be employed. Alternatively, the number of connectors must be reduced. It also may be necessary to limit the number of connectors or to use connectors having improved reflectance performance in order to avoid unacceptable impairments due to multiple reflections.

In the tables of clause 8, the value –27 dB maximum discrete reflectance between source reference points and receive reference points is intended to minimize the effects of multiple reflections (e.g., interferometric noise). The value for maximum receiver reflectance is chosen to ensure acceptable penalties due to multiple reflections for all likely system configurations involving multiple connectors, etc. Systems employing fewer or higher performance connectors produce fewer multiple reflections and, consequently, are able to tolerate receivers exhibiting higher reflectance.

7.2.3.7 Maximum differential group delay

Differential group delay (DGD) is the time difference between the fractions of a pulse that are transmitted in the two principal states of polarization of an optical signal. For distances greater than several kilometres, and assuming random (strong) polarization mode coupling, DGD in a fibre can be statistically modelled as having a Maxwellian distribution.

In this Recommendation, the maximum differential group delay is defined to be the value of DGD that the system must tolerate with a maximum sensitivity degradation of approximately 1 dB, except in the case of application 4I1-9D1F where the maximum sensitivity degradation is approximately 0.5 dB.

Due to the statistical nature of polarization mode dispersion (PMD), the relationship between maximum DGD and mean DGD can only be defined probabilistically. The probability of the instantaneous DGD exceeding any given value can be inferred from its Maxwellian statistics. Therefore, if we know the maximum DGD that the system can tolerate, we can derive the equivalent mean DGD by dividing by the ratio of maximum to mean that corresponds to an acceptable probability. Some example ratios are given below in Table 7-2.

Table 7-2 – DGD means and probabilities

Ratio of maximum to mean	Probability of exceeding maximum
3.0	4.2×10^{-5}
3.5	7.7×10^{-7}
4.0	7.4×10^{-9}

7.2.4 Interface at point MPI-R_M or MPI-R

7.2.4.1 Maximum mean (channel) input power

The maximum acceptable value of the average received channel power at point MPI-R_M or MPI-R to achieve the specified maximum BER of the application code.

7.2.4.2 Minimum mean channel input power

The minimum value of the average received channel power at point MPI-R_M. This power is the minimum mean channel output power minus the maximum attenuation of the application.

NOTE – The minimum mean channel input power at MPI-R_M must be higher than the minimum equivalent sensitivity by the value of the maximum optical path penalty.

7.2.4.3 Maximum mean total input power

The maximum acceptable total input power at point MPI-R_M.

7.2.4.4 Maximum channel power difference

The difference between the largest value of the mean channel input power and the smallest value of the mean channel input power present at the same time within a given optical resolution bandwidth, independent of the number of channels, within the application.

7.2.4.5 Maximum optical path penalty

The path penalty is the apparent reduction of receiver sensitivity (or equivalent sensitivity in the case of multichannel applications) due to distortion of the signal waveform during its transmission over the path. It is manifested as a shift of the system's BER curves towards higher input power levels. This corresponds to a positive path penalty. Negative path penalties may exist under some circumstances, but should be small (a negative path penalty indicates that a less than perfect transmitter eye has been partially improved by the path-dependent distortions). Ideally, the BER curves should be translated only, but shape variations are not uncommon and may indicate the emergence of BER floors. Since the path penalty is a change in the receiver's sensitivity, it is measured at a BER level of 10^{-12} .

For application codes requiring FEC bytes to be transmitted (i.e., having a code with a suffix of F), both receiver sensitivities (with and without the degradation due to the optical path) are measured after the error correction (if used) has been applied.

For applications with channel bit rates corresponding to NRZ 2.5G and NRZ 10G, a maximum path penalty of 1 dB for low-dispersion systems, and 2 dB for high-dispersion systems, is allowed. The path penalties are not made proportional to the target distances to avoid operating systems with high penalties.

For applications with channel bit rates corresponding to NRZ 40G, the value of the optical path penalty is 1 dB higher than that for the lower rates. This is to allow for the penalty related to PMD (both first and second order).

In the future, systems employing dispersion accommodation techniques based on pre-distortion of the signal at the transmitter may be introduced. In this case, the path penalty in the above sense can only be defined between points with undistorted signals. These points, however, do not coincide with the main path interfaces, and may thus not even be accessible. The definition of path penalty for this case is for further study.

The average value of the random dispersion penalties due to PMD is included in the allowed path penalty. In this respect, for most of the application codes the transmitter/receiver combination is required to tolerate an actual DGD of 0.3 bit period with a maximum sensitivity degradation of approximately 1 dB (with 50% of optical power in each principal state of polarization). For a well-designed receiver, this corresponds to a penalty of 0.1-0.2 dB for an instantaneous DGD of 0.1 bit period (which is equal to the average DGD corresponding to a maximum DGD of 0.3 bit period and a ratio between the maximum and mean of 3.0). The actual DGD that may be encountered in operation is a randomly varying fibre/cable property and cannot be specified in this Recommendation. This subject is further discussed in Appendix I of [ITU-T G.691].

Note that a signal-to-noise ratio reduction due to optical amplification is not considered a path penalty.

This definition can be directly applied to single-channel systems. In the case of the multichannel IrDI, two alternative methods can be used.

- Method A can be used when single-channel reference points are accessible at the receive end of the link for verification. For this method, the procedures described in [ITU-T G.957] and [ITU-T G.691] are used. The configuration for this method is contained in Annex A.
- Method B employs a reference optical bandpass filter to isolate the individual transmitted signals, followed by a reference receiver. The characteristics of the reference optical bandpass filter and the reference receiver are contained in Annex B.

NOTE – The optical path penalty observed in the reference receiver may not be exactly the same as actually experienced in the receiving equipment depending on the design implementation.

7.2.4.6 Minimum equivalent sensitivity

This is the minimum sensitivity that would be required of a receiver placed at MPI-R_M in multichannel applications to achieve the specified maximum BER of the application code if all except one of the channels were to be removed (with an ideal lossless filter) at point MPI-R_M. This must be met with a transmitter with worst-case values of transmitter eye mask, extinction ratio, optical return loss at point MPI-S_M, connector degradations, transmit-side crosstalk, optical amplifier noise and measurement tolerances. This does not have to be met in the presence of dispersion, non-linearity, or reflections from the optical path; these effects are specified separately in the allocation of maximum optical path penalty.

NOTE 1 – The minimum mean channel input power at MPI-R_M must be higher than the minimum equivalent sensitivity by the value of the maximum optical path penalty.

NOTE 2 – The receiver sensitivity does not have to be met in the presence of transmitter jitter in excess of the appropriate jitter generation limit (e.g., [ITU-T G.8251] for OTN optical tributary signals).

Aging effects are not specified separately. Worst-case, end-of-life values are specified.

7.2.4.7 Maximum reflectance of optical network element

Reflections from the ONE back into the cable plant are specified by the maximum permissible reflectance of the ONE measured at reference point MPI-R_M or MPI-R. Optical reflectance is defined in clause 7.2.3.6.

7.2.4.8 Minimum sensitivity

The minimum value of average received power at point MPI-R to achieve the specified maximum BER of the application code. This must be met with a transmitter with worst-case values of transmitter eye mask, extinction ratio, optical return loss at points MPI-S, connector degradations, optical amplifier noise and measurement tolerances. This does not have to be met in the presence of dispersion or reflections from the optical path; these effects are specified separately in the allocation of maximum optical path penalty.

NOTE 1 – The minimum average optical power at the receiver must be higher than the minimum sensitivity by the value of the maximum optical path penalty.

NOTE 2 – The receiver sensitivity does not have to be met in the presence of transmitter jitter in excess of the appropriate jitter generation limit (e.g., [ITU-T G.8251] for OTN optical tributary signals).

Aging effects are not specified separately. Worst-case, end-of-life values are specified.

8 Parameter values

8.1 Multichannel IrDI

The physical layer parameters and values for multichannel inter-domain interfaces are given in Tables 8-1 to 8-5.

Table 8-1 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 2.5G short-haul applications

Parameter (Note)	Units	P16S1-1D2 P16S1-1D5	P32S1-1D2 P32S1-1D5
General information			
Maximum number of channels	–	16	32
Bit rate/line coding of optical tributary signals	–	NRZ 2.5G	NRZ 2.5G
Maximum bit error ratio	–	10 ⁻¹²	10 ⁻¹²
Fibre type	–	G.652, G.655	G.652, G.655

Table 8-1 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 2.5G short-haul applications

Parameter (Note)	Units	P16S1-1D2 P16S1-1D5	P32S1-1D2 P32S1-1D5
Interface at point MPI-S_M			
Maximum mean channel output power	dBm	-4	-4
Minimum mean channel output power	dBm	-10	-10
Maximum mean total output power	dBm	+8	+11
Central frequency	THz	192.1 + 0.2 m, m = 0 to 15	192.1 + 0.1 m, m = 0 to 31
Channel spacing	GHz	200	100
Maximum spectral excursion	GHz	40	20
Minimum channel extinction ratio	dB	8.2	8.2
Eye mask	-	NRZ 2.5G	NRZ 2.5G
Optical path (single span) from point MPI-S_M to MPI-R_M			
Maximum attenuation	dB	11	11
Minimum attenuation	dB	2	2
Maximum chromatic dispersion at upper wavelength limit	ps/nm	800 for G.652, 420 for G.655	800 for G.652, 420 for G.655
Maximum chromatic dispersion at lower wavelength limit	ps/nm	800 for G.652, 420 for G.655	800 for G.652, 420 for G.655
Minimum optical return loss at MPI-S _M	dB	24	24
Maximum discrete reflectance between MPI-S _M and MPI-R _M	dB	-27	-27
Maximum differential group delay	ps	120	120
Interface at point MPI-R_M			
Maximum mean channel input power	dBm	-6	-6
Minimum mean channel input power	dBm	-21	-21
Maximum mean total input power	dBm	+6	+9
Maximum channel power difference	dB	NA	NA
Maximum optical path penalty	dB	1	1
Minimum equivalent sensitivity	dBm	-22	-22
Maximum reflectance of optical network element	dB	-27	-27
NOTE – The parameter values in this table may not be applicable to future systems that use line amplifiers or to intra-domain interfaces (IaDIs).			

Table 8-2 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 10G intra-office applications

Parameter (Note 1)	Units	P16I1-2D2 P16I1-2D3 (Note 2) P16I1-2D5	P32I1-2D2 P32I1-2D5
General information			
Maximum number of channels	–	16	32
Bit rate/line coding of optical tributary signals	–	NRZ 10G	NRZ 10G
Maximum bit error ratio	–	10^{-12}	10^{-12}
Fibre type	–	G.652, G.653, G.655	G.652, G.655
Interface at point MPI-S_M			
Maximum mean channel output power	dBm	–3	–3
Minimum mean channel output power	dBm	–6	–6
Maximum mean total output power	dBm	+9	+12
Central frequency	THz	192.1 + 0.2 m, m = 0 to 15	192.1 + 0.1 m, m = 0 to 31
Channel spacing	GHz	200	100
Maximum spectral excursion	GHz	40	20
Minimum channel extinction ratio	dB	8.2	8.2
Eye mask	–	NRZ 10G amplified	NRZ 10G amplified
Optical path (single span) from point MPI-S_M to MPI-R_M			
Maximum attenuation	dB	6 (Note 2)	6
Minimum attenuation	dB	0	0
Maximum chromatic dispersion at upper wavelength limit	ps/nm	400 for G.652, ±70 for G.653, 210 for G.655	400 for G.652, 210 for G.655
Maximum chromatic dispersion at lower wavelength limit	ps/nm	400 for G.652, ±70 for G.653, 210 for G.655	400 for G.652, 210 for G.655
Minimum optical return loss at MPI-S _M	dB	24	24
Maximum discrete reflectance between MPI-S _M and MPI-R _M	dB	–27	–27
Maximum differential group delay	ps	30	30

Table 8-2 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 10G intra-office applications

Parameter (Note 1)	Units	P16I1-2D2 P16I1-2D3 (Note 2) P16I1-2D5	P32I1-2D2 P32I1-2D5
Interface at point MPI-R_M			
Maximum mean channel input power	dBm	–3	–3
Minimum mean channel input power	dBm	–12	–12
Maximum mean total input power	dBm	+9	+12
Maximum channel power difference	dB	NA	NA
Maximum optical path penalty	dB	2 for G.652, 1 for G.653 (Note 2), 1 for G.655	2 for G.652, 1 for G.655
Minimum equivalent sensitivity	dBm	–14 for G.652, –13 for G.653, –13 for G.655	–14 for G.652, –13 for G.655
Maximum reflectance of optical network element	dB	–27	–27
NOTE 1 – The parameter values in this table may not be applicable to future systems that use line amplifiers or to intra-domain interfaces (IaDIs).			
NOTE 2 – For an optical path penalty of 1 dB, the transmission distance of multichannel intra-office interfaces on G.653 fibres is recommended to be within 2 km due to fibre non-linearity. If this distance is longer than 2 km, a further penalty (in addition to the 1 dB optical path penalty) may be observed. Alternatively, unequally spaced channel central frequencies may be used via joint engineering.			

Table 8-3 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 10G short-haul applications

Parameter (Note)	Units	P16S1-2B2 P16S1-2B5	P16S1-2C2 P16S1-2C3 P16S1-2C5	P32S1-2B2 P32S1-2B5	P32S1-2C2 P32S1-2C5
General information					
Maximum number of channels	–	16	16	32	32
Bit rate/line coding of optical tributary signals	–	NRZ 10G	NRZ 10G	NRZ 10G	NRZ 10G
Maximum bit error ratio	–	10 ⁻¹²	10 ⁻¹²	10 ⁻¹²	10 ⁻¹²
Fibre type	–	G.652, G.655	G.652, G.653, G.655	G.652, G.655	G.652, G.655

Table 8-3 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 10G short-haul applications

Parameter (Note)	Units	P16S1-2B2 P16S1-2B5	P16S1-2C2 P16S1-2C3 P16S1-2C5	P32S1-2B2 P32S1-2B5	P32S1-2C2 P32S1-2C5
Interface at point MPI-S_M					
Maximum mean channel output power	dBm	+3	-7	+3	-7
Minimum mean channel output power	dBm	0	-11	0	-11
Maximum mean total output power	dBm	+15	+5	+18	+8
Central frequency	THz	192.1 + 0.2 m, m = 0 to 15	192.1 + 0.2 m, m = 0 to 15	192.1 + 0.1 m, m = 0 to 31	192.1 + 0.1 m, m = 0 to 31
Channel spacing	GHz	200	200	100	100
Maximum spectral excursion	GHz	40	40	20	20
Minimum channel extinction ratio	dB	8.2	8.2	8.2	8.2
Eye mask	–	NRZ 10G amplified	NRZ 10G amplified	NRZ 10G amplified	NRZ 10G amplified
Optical path (single span) from point MPI-S_M to MPI-R_M					
Maximum attenuation	dB	11	11	11	11
Minimum attenuation	dB	0	0	0	0
Maximum chromatic dispersion at upper wavelength limit	ps/nm	800 for G.652, 420 for G.655	800 for G.652, ±130 for G.653, 420 for G.655	800 for G.652, 420 for G.655	800 for G.652, 420 for G.655
Maximum chromatic dispersion at lower wavelength limit	ps/nm	800 for G.652, 420 for G.655	800 for G.652, ±130 for G.653, 420 for G.655	800 for G.652, 420 for G.655	800 for G.652, 420 for G.655
Minimum optical return loss at MPI-S _M	dB	24	24	24	24
Maximum discrete reflectance between MPI-S _M and MPI-R _M	dB	-27	-27	-27	-27
Maximum differential group delay	ps	30	30	30	30

Table 8-3 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 10G short-haul applications

Parameter (Note)	Units	P16S1-2B2 P16S1-2B5	P16S1-2C2 P16S1-2C3 P16S1-2C5	P32S1-2B2 P32S1-2B5	P32S1-2C2 P32S1-2C5
Interface at point MPI-R_M					
Maximum mean channel input power	dBm	+3	-7	+3	-7
Minimum mean channel input power	dBm	-11	-22	-11	-22
Maximum mean total input power	dBm	+15	+5	+18	+8
Maximum channel power difference	dB	NA	2	NA	2
Maximum optical path penalty	dB	2 for G.652, 1 for G.655	2 for G.652, 1 for G.653, 1 for G.655	2 for G.652, 1 for G.655	2 for G.652, 1 for G.655
Minimum equivalent sensitivity	dBm	-13 for G.652, -12 for G.655	-24 for G.652, -23 for G.653, -23 for G.655	-13 for G.652, -12 for G.655	-24 for G.652, -23 for G.655
Maximum reflectance of optical network element	dB	-27	-27	-27	-27

NOTE – The parameter values in this table may not be applicable to future systems that use line amplifiers or to intra-domain interfaces (IaDIs).

Table 8-4 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 2.5G and NRZ 10G long-haul applications

Parameter (Note)	Units	P16L1-1A2 P16L1-1A5	P16L1-2A2 P16L1-2A5
General information			
Maximum number of channels	–	16	16
Bit rate/line coding of optical tributary signals	–	NRZ 2.5G	NRZ 10G
Maximum bit error ratio	–	10 ⁻¹²	10 ⁻¹²
Fibre type	–	G.652, G.655	G.652, G.655
Interface at point MPI-S_M			
Maximum mean channel output power	dBm	+5	+5
Minimum mean channel output power	dBm	+2	0
Maximum mean total output power	dBm	+17	+17
Central frequency	THz	192.1 + 0.2 m, m = 0 to 15	192.1 + 0.2 m, m = 0 to 15
Channel spacing	GHz	200	200
Maximum spectral excursion	GHz	40	40
Minimum channel extinction ratio	dB	8.2	8.2

Table 8-4 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 2.5G and NRZ 10G long-haul applications

Parameter (Note)	Units	P16L1-1A2 P16L1-1A5	P16L1-2A2 P16L1-2A5
Eye mask	–	NRZ 2.5G	NRZ 10G amplified
Optical path (single span) from point MPI-S_M to MPI-R_M			
Maximum attenuation	dB	22	22
Minimum attenuation	dB	11	11
Maximum chromatic dispersion at upper wavelength limit	ps/nm	1600 for G.652, 840 for G.655	1600 for G.652, 840 for G.655
Maximum chromatic dispersion at lower wavelength limit	ps/nm	1600 for G.652, 840 for G.655	1600 for G.652, 840 for G.655
Minimum optical return loss at MPI-S _M	dB	24	24
Maximum discrete reflectance between MPI-S _M and MPI-R _M	dB	–27	–27
Maximum differential group delay	ps	120	30
Interface at point MPI-R_M			
Maximum mean channel input power	dBm	–6	–6
Minimum mean channel input power	dBm	–20	–22
Maximum mean total input power	dBm	+6	+6
Maximum channel power difference	dB	3	3
Maximum optical path penalty	dB	2 for G.652, 1 for G.655	2 for G.652, 1 for G.655
Minimum equivalent sensitivity	dBm	–22 for G.652, –21 for G.655	–24 for G.652, –23 for G.655
Maximum reflectance of optical network element	dB	–27	–27
NOTE – The parameter values in this table may not be applicable to future systems that use line amplifiers or to intra-domain interfaces (IaDIs).			

Table 8-5 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 25G applications

Parameter	Units	4I1-9D1F	4L1-9C1F
General information			
Maximum number of channels	–	4	4
Bit rate/line coding of optical tributary signals	–	OTL4.4	OTL4.4
Maximum bit error ratio	–	10 ⁻¹² (Note)	10 ⁻¹² (Note)
Fibre type	–	G.652	G.652

Table 8-5 – Multichannel IrDI parameters and values for optical tributary signal class NRZ 25G applications

Parameter	Units	4I1-9D1F	4L1-9C1F
Interface at point MPI-S_M			
Maximum mean channel output power	dBm	4.5	2.9
Minimum channel extinction ratio	dB	4 8	8
Minimum mean channel output power	dBm	-0.6 -2.9	-2.7
Maximum mean total output power	dBm	10.5	8.9
Maximum channel power difference	dB	5	3.6
Central frequency	THz	229.0 + 0.8 m, m=0 to 3	229.0 + 0.8 m, m=0 to 3
Channel spacing	GHz	800	800
Maximum spectral excursion	GHz	±184	±184
Eye mask	–	NRZ 25G Ratio	NRZ 25G Ratio
Optical path (single span) from point MPI-S_M to MPI-R_M			
Maximum attenuation	dB	6.3	18
Minimum attenuation	dB	0	0
Maximum chromatic dispersion at upper wavelength limit	ps/nm	-28.5 to +9.5	-114 to +38
Maximum chromatic dispersion at lower wavelength limit	ps/nm	-28.5 to +9.5	-114 to +38
Minimum optical return loss at MPI-S _M	dB	20	20
Maximum discrete reflectance between MPI-S _M and MPI-R _M	dB	-26	-26
Maximum differential group delay	ps	8	10.3
Interface at point MPI-R_M			
Maximum mean channel input power	dBm	4.5	4.5
Minimum mean channel input power	dBm	-6.9 -9.2	-20.7
Maximum mean total input power	dBm	10.5	10.5
Maximum channel power difference	dB	5.5	4.5
Maximum optical path penalty	dB	1.5	2.5
Minimum equivalent sensitivity	dBm	-8.4 -10.7	-23.2
Maximum reflectance of optical network element	dB	-26	-26
NOTE – The BER for these application codes is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10 ⁻¹² .			

8.2 Single channel IrDI

The physical layer parameters and values for single channel inter-domain interfaces are given in Tables 8-6 to 8-17.

Table 8-6 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 2.5G intra-office and short-haul applications

Parameter	Units	P1I1-1D1	P1S1-1D1	P1S1-1D2
General information		(Note)	(Note)	(Note)
Maximum number of channels	–	1	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 2.5G	NRZ 2.5G	NRZ 2.5G
Maximum bit error ratio	–	10 ⁻¹²	10 ⁻¹²	10 ⁻¹²
Fibre type	–	G.652	G.652	G.652
Interface at point MPI-S				
Operating wavelength range	nm	1266-1360	1260-1360	1530-1565
Source type		MLM	SLM	SLM
Maximum RMS width (σ)	nm	3.4	NA	NA
Maximum –20 dB width	nm	NA	1	< 1
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	NA	30	30
Maximum mean output power	dBm	–3	0	0
Minimum mean output power	dBm	–10	–5	–5
Minimum extinction ratio	dB	8.2	8.2	8.2
Eye mask	–	NRZ 2.5G	NRZ 2.5G	NRZ 2.5G
Optical path from point MPI-S to MPI-R				
Maximum attenuation	dB	6	11	11
Minimum attenuation	dB	0	0	0
Maximum chromatic dispersion at upper wavelength limit	ps/nm	±12	±140	800
Maximum chromatic dispersion at lower wavelength limit	ps/nm	±12	±140	715
Minimum optical return loss at MPI-S	dB	14	14	14
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27	–27
Maximum differential group delay	ps	120	120	120
Interface at point MPI-R				
Maximum mean input power	dBm	–3	0	0
Minimum sensitivity	dBm	–17	–17	–17
Maximum optical path penalty	dB	1	1	1
Maximum reflectance of optical network element	dB	–14	–14	–14
NOTE – Parameter values for these application codes are largely based on [ITU-T G.957].				

Table 8-7 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 2.5G long-haul applications

Parameter	Units	P1L1-1D1	P1L1-1D2	1L1-1D2F
General information				
Maximum number of channels	–	(Note 1) 1	(Note 1) 1	1
Bit rate/line coding of optical tributary signals	–	NRZ 2.5G	NRZ 2.5G	NRZ OTU1 FEC enabled
Maximum bit error ratio	–	10^{-12}	10^{-12}	10^{-12} (Note 2)
Fibre type	–	G.652	G.652	G.652
Interface at point MPI-S				
Operating wavelength range	nm	1280-1335	1530-1565	1530-1565
Source type		SLM	SLM	SLM
Maximum RMS width (σ)	nm	NA	NA	NA
Maximum –20 dB width	nm	1	1	1
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	30	30	30
Maximum mean output power	dBm	+3	+3	+3
Minimum mean output power	dBm	–2	–2	–2
Minimum extinction ratio	dB	8.2	8.2	8.2
Eye mask	–	NRZ 2.5G	NRZ 2.5G	NRZ 2.5G
Optical path from point MPI-S to MPI-R				
Maximum attenuation	dB	22	22	24
Minimum attenuation	dB	12	12	12
Maximum chromatic dispersion at upper wavelength limit	ps/nm	± 180	1600	1600
Maximum chromatic dispersion at lower wavelength limit	ps/nm	± 180	1430	1430
Minimum optical return loss at MPI-S	dB	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27	–27
Maximum differential group delay	ps	120	120	120
Interface at point MPI-R				
Maximum mean input power	dBm	–9	–9	–9
Minimum sensitivity	dBm	–25	–26	–28
Maximum optical path penalty	dB	1	2	2
Maximum reflectance of optical network element	dB	–27	–27	–27
NOTE 1 – Parameter values for these application codes are largely based on [ITU-T G.957].				
NOTE 2 – The BER for these application codes is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10^{-12} .				

Table 8-8 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 2.5G ultra long-haul applications

Parameter	Units	P1U1-1A2	P1U1-1A3	P1U1-1A5	1U1-1B2F 1U1-1B5F	1U1-1B3F
G.691 application code		U-16.2	U-16.3	–	–	–
General information		(Note 1)	(Note 1)			
Maximum number of channels	–	1	1	1	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 2.5G	NRZ 2.5G	NRZ 2.5G	NRZ OTU1 FEC enabled	NRZ OTU1 FEC enabled
Maximum bit error ratio	–	10^{-12}	10^{-12}	10^{-12}	10^{-12} (Note 2)	10^{-12} (Note 2)
Fibre type	–	G.652	G.653	G.655	G.652, G.655	G.653
Interface at point MPI-S						
Operating wavelength range	nm	1530-1565	1530-1565	1530-1565	1530-1565	1530-1565
Source type		SLM	SLM	SLM	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	30	30	30	30	30
Maximum mean output power	dBm	+15	+15	+15	+18	+18
Minimum mean output power	dBm	+12	+12	+12	+15	+15
Minimum extinction ratio	dB	8.2	8.2	8.2	8.2	8.2
Eye mask	–	NRZ 2.5G	NRZ 2.5G	NRZ 2.5G	NRZ 2.5G	NRZ 2.5G

Table 8-8 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 2.5G ultra long-haul applications

Parameter	Units	P1U1-1A2	P1U1-1A3	P1U1-1A5	1U1-1B2F 1U1-1B5F	1U1-1B3F
Optical path from point MPI-S to MPI-R						
Maximum attenuation	dB	44	44	44	44	44
Minimum attenuation	dB	33	33	33	27	27
Maximum chromatic dispersion at upper wavelength limit	ps/nm	3200	±550	1700	3200 G.652, 1700 G.655	±550 (Note 3)
Maximum chromatic dispersion at lower wavelength limit	ps/nm	2860	±550	1390	2860 G.652, 1390 G.655	±550 (Note 3)
Minimum optical return loss at MPI-S	dB	24	24	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	-27	-27	-27	-27	-27
Maximum differential group delay	ps	120	120	120	120	120
Interface at point MPI-R						
Maximum mean input power	dBm	-18	-18	-18	-9	-9
Minimum sensitivity	dBm	-34	-33	-34	-31	-30
Maximum optical path penalty	dB	2	1	2	2	1
Maximum reflectance of optical network element	dB	-27	-27	-27	-27	-27
<p>NOTE 1 – Parameter values for these application codes are largely based on [ITU-T G.691].</p> <p>NOTE 2 – The BER for this application code is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10^{-12}.</p> <p>NOTE 3 – For G.653 fibre, some combinations of transmitter wavelength and fibre zero dispersion wavelength can result in negative link dispersion. Adequate operation in this regime has not been verified at the power levels required for this application. In this situation, joint engineering may be necessary between the link provider and the system vendor to avoid this condition.</p>						

Table 8-9 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 10G intra-office applications

Parameter	Units	P1I1-2D2	P1I1-2D3	P1I1-2D5
G.691 application code		I-64.2	I-64.3	I-64.5
General information				
Maximum number of channels	–	1	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 10G	NRZ 10G	NRZ 10G
Maximum bit error ratio	–	10 ⁻¹²	10 ⁻¹²	10 ⁻¹²
Fibre type	–	G.652	G.653	G.655
Interface at point MPI-S				
Operating wavelength range	nm	1500-1565	1500-1565	1500-1565
Source type		SLM	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	30	30	30
Maximum mean output power	dBm	–1	–1	–1
Minimum mean output power	dBm	–5	–5	–5
Minimum extinction ratio	dB	8.2	8.2	8.2
Eye mask	–	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region
Optical path from point MPI-S to MPI-R				
Maximum attenuation	dB	7	7	7
Minimum attenuation	dB	0	0	0
Maximum chromatic dispersion at upper wavelength limit	ps/nm	500	±150	270
Maximum chromatic dispersion at lower wavelength limit	ps/nm	400	±150	180
Minimum optical return loss at MPI-S	dB	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27	–27
Maximum differential group delay	ps	30	30	30
Interface at point MPI-R				
Maximum mean input power	dBm	–1	–1	–1
Minimum sensitivity	dBm	–14	–13	–13
Maximum optical path penalty	dB	2	1	1
Maximum reflectance of optical network element	dB	–27	–27	–27

Table 8-10 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 10G short-haul applications for G.652 fibre

Parameter	Units	P1S1-2D1	P1S1-2D2a	P1S1-2D2b	1S1-2D2bF
G.691 application code		S-64.1	S-64.2a	S-64.2b	
General information					
Maximum number of channels	–	1	1	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 10G	NRZ 10G	NRZ 10G	NRZ OTU2 FEC enabled
Maximum bit error ratio	–	10 ⁻¹²	10 ⁻¹²	10 ⁻¹²	10 ⁻¹² (Note 2)
Fibre type	–	G.652	G.652	G.652	G.652
Interface at point MPI-S					
Operating wavelength range	nm	1290-1330	1530-1565	1530-1565	1530-1565
Source type	–		SLM	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	30	30	30	30
Maximum mean output power	dBm	+5	–1	+2	+2
Minimum mean output power	dBm	+1	–5	–1	–2
Minimum extinction ratio	dB	6	8.2	8.2	8.2
Eye mask	–	NRZ 10G 1310 nm region	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region
Optical path from point MPI-S to MPI-R					
Maximum attenuation	dB	11	11	11	12
Minimum attenuation	dB	6	7	3	3
Maximum chromatic dispersion at upper wavelength limit	ps/nm	±70	800	800	800
Maximum chromatic dispersion at lower wavelength limit	ps/nm	±70	720	720	720
Minimum optical return loss at MPI-S	dB	14	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27	–27	–27
Maximum differential group delay	ps	30	30	30	30

Table 8-10 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 10G short-haul applications for G.652 fibre

Parameter	Units	P1S1-2D1	P1S1-2D2a	P1S1-2D2b	1S1-2D2bF
Interface at point MPI-R					
Maximum mean input power	dBm	-1	-8	-1	-1
Minimum sensitivity	dBm	-11	-18	-14	-16
Maximum optical path penalty	dB	1	2	2	2
Maximum reflectance of optical network element	dB	-14	-27	-27	-27
NOTE 1 – Application codes with a suffix "a" have transmitter power levels appropriate to APD receivers; application codes with the suffix "b" have transmitter power levels appropriate to PIN receivers.					
NOTE 2 – The BER for this application code is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10^{-12} .					

Table 8-11 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 10G short-haul applications for G.653 and G.655 fibres

Parameter	Units	P1S1-2D3a P1S1-2D5a	P1S1-2D3b P1S1-2D5b	1S1-2D3bF 1S1-2D5bF
G.691 application code		S-64.3a S-64.5a	S-64.3b S-64.5b	
General information				
Maximum number of channels	–	1	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 10G	NRZ 10G	NRZ OTU2 FEC enabled
Maximum bit error ratio	–	10^{-12}	10^{-12}	10^{-12} (Note 2)
Fibre type	–	G.653, G.655	G.653, G.655	G.653, G.655
Interface at point MPI-S				
Operating wavelength range	nm	1530-1565	1530-1565	1530-1565
Source type	–	SLM	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	30	30	30
Maximum mean output power	dBm	-1	+2	+2
Minimum mean output power	dBm	-5	-1	-2
Minimum extinction ratio	dB	8.2	8.2	8.2
Eye mask	–	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region

Table 8-11 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 10G short-haul applications for G.653 and G.655 fibres

Parameter	Units	P1S1-2D3a P1S1-2D5a	P1S1-2D3b P1S1-2D5b	1S1-2D3bF 1S1-2D5bF
Optical path from point MPI-S to MPI-R				
Maximum attenuation	dB	11	11	12
Minimum attenuation	dB	7	3	3
Maximum chromatic dispersion at upper wavelength limit	ps/nm	±140 G.653, 430 G.655	±140 G.653, 430 G.655	±140 G.653, 430 G.655
Maximum chromatic dispersion at lower wavelength limit	ps/nm	±140 G.653, 350 G.655	±140 G.653, 350 G.655	±140 G.653, 350 G.655
Minimum optical return loss at MPI-S	dB	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	-27	-27	-27
Maximum differential group delay	ps	30	30	30
Interface at point MPI-R				
Maximum mean input power	dBm	-8	-1	-1
Minimum sensitivity	dBm	-17	-13	-15
Maximum optical path penalty	dB	1	1	1
Maximum reflectance of optical network element	dB	-27	-27	-27
NOTE 1 – Application codes with a suffix "a" have transmitter power levels appropriate to APD receivers; application codes with the suffix "b" have transmitter power levels appropriate to PIN receivers.				
NOTE 2 – The BER for these application codes is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10^{-12} .				

Table 8-12 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 10G long-haul applications

Parameter	Units	P1L1-2D1	P1L1-2D2	1L1-2D2F
G.691 application code		L-64.1	–	–
General information				
Maximum number of channels	–	1	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 10G	NRZ 10G	NRZ OTU2 FEC enabled
Maximum bit error ratio	–	10^{-12}	10^{-12}	10^{-12} (Note)
Fibre type	–	G.652	G.652	G.652

Table 8-12 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 10G long-haul applications

Parameter	Units	P1L1-2D1	P1L1-2D2	1L1-2D2F
Interface at point MPI-S				
Operating wavelength range	nm	1290-1320	1530-1565	1530-1565
Source type	–	SLM	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	30	30	30
Maximum mean output power	dBm	+7	+4	+4
Minimum mean output power	dBm	+3	0	–1
Minimum extinction ratio	dB	6	9	8.2
Eye mask	–	NRZ 10G 1310 nm region	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region
Optical path from point MPI-S to MPI-R				
Maximum attenuation	dB	22	22	22
Minimum attenuation	dB	16	11	11
Maximum chromatic dispersion at upper wavelength limit	ps/nm	±140	1600	1600
Maximum chromatic dispersion at lower wavelength limit	ps/nm	±140	1430	1430
Minimum optical return loss at MPI-S	dB	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27	–27
Maximum differential group delay	ps	30	30	30
Interface at point MPI-R				
Maximum mean input power	dBm	–9	–7	–7
Minimum sensitivity	dBm	–20	–24	–25
Maximum optical path penalty	dB	1	2	2
Maximum reflectance of optical network element	dB	–27	–27	–27
NOTE – The BER for these application codes is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10^{-12} .				

Table 8-13 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 10G very long-haul applications

Parameter	Units	P1V1-2C2	1V1-2C2F	P1V1-2B5	1V1-2B5F
General information					
Maximum number of channels	–	1	1	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 10G	NRZ OTU2 FEC enabled	NRZ 10G	NRZ OTU2 FEC enabled
Maximum bit error ratio	–	10 ⁻¹²	10 ⁻¹² (Note 1)	10 ⁻¹²	10 ⁻¹² (Note 1)
Fibre type	–	G.652	G.652	G.655	G.655
Interface at point MPI-S					
Operating wavelength range	nm	–	–	1530-1565	1530-1565
Central frequency	THz	192.1	192.1	–	–
Maximum spectral excursion	GHz	40	40	–	–
Source type	–	SLM	SLM	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	30	30	30	30
Maximum mean output power	dBm	+7	+7	+13	+13
Minimum mean output power	dBm	+4	+3	+10	+10
Minimum extinction ratio	dB	9 (Note 2)	9 (Note 2)	9	8.2
Eye mask	–	NRZ 10G amplified	NRZ 10G amplified	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region
Optical path from point MPI-S to MPI-R					
Maximum attenuation	dB	33	33	33	33
Minimum attenuation	dB	21	21	20	20
Maximum chromatic dispersion at upper wavelength limit	ps/nm	2400	2400	1280	1280
Maximum chromatic dispersion at lower wavelength limit	ps/nm	2400	2400	1050	1050
Minimum optical return loss at MPI-S	dB	24	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27	–27	–27
Maximum differential group delay	ps	30	30	30	30

Table 8-13 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 10G very long-haul applications

Parameter	Units	P1V1-2C2	1V1-2C2F	P1V1-2B5	1V1-2B5F
Interface at point MPI-R					
Maximum mean input power	dBm	-14	-14	-7	-7
Minimum sensitivity	dBm	-30	-31	-24	-24
Maximum optical path penalty	dB	1	1	1	1
Maximum reflectance of optical network element	dB	-27	-27	-27	-27
NOTE 1 – The BER for these application codes is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10^{-12} .					
NOTE 2 – The extinction ratio of these application codes is not required to be met in the presence of a fourth-order Bessel-Thompson filter.					

Table 8-14 – Single-channel IrDI parameters for optical tributary signal class NRZ 10G long- and very long-haul applications using electronic dispersion compensation

Parameter	Units	P1L1-2D2E	1L1-2D2FE	P1V1-2B2E	1V1-2B2FE
General information					
Maximum number of channels	–	(Note 1) 1	(Note 1) 1	(Note 1) 1	(Note 1) 1
Bit rate/line coding of optical tributary signals	–	NRZ 10G	NRZ OTU2 FEC enabled	NRZ 10G	NRZ OTU2 FEC enabled
Maximum bit error ratio	–	10^{-12}	10^{-12} (Note 2)	10^{-12}	10^{-12} (Note 2)
Fibre type	–	G.652	G.652	G.652	G.652
Interface at point MPI-S					
Operating wavelength range	nm	FFS	FFS	FFS	FFS
Source type	–	SLM	SLM	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	FFS	FFS	FFS	FFS
Maximum mean output power	dBm	FFS	FFS	FFS	FFS
Minimum mean output power	dBm	FFS	FFS	FFS	FFS
Minimum extinction ratio	dB	FFS	FFS	FFS	FFS
Eye mask	–	FFS	FFS	FFS	FFS

**Table 8-14 – Single-channel IrDI parameters for optical tributary signal class
NRZ 10G long- and very long-haul applications using electronic dispersion compensation**

Parameter	Units	P1L1-2D2E	1L1-2D2FE	P1V1-2B2E	1V1-2B2FE
Optical path from point MPI-S to MPI-R					
Maximum attenuation	dB	22	22	33	33
Minimum attenuation	dB	FFS	FFS	FFS	FFS
Maximum chromatic dispersion at upper wavelength limit	ps/nm	FFS	FFS	FFS	FFS
Maximum chromatic dispersion at lower wavelength limit	ps/nm	FFS	FFS	FFS	FFS
Minimum optical return loss at MPI-S	dB	FFS	FFS	FFS	FFS
Maximum discrete reflectance between MPI-S and MPI-R	dB	FFS	FFS	FFS	FFS
Maximum differential group delay	ps	30	30	30	30
Interface at point MPI-R					
Maximum mean input power	dBm	FFS	FFS	FFS	FFS
Minimum sensitivity	dBm	FFS	FFS	FFS	FFS
Maximum optical path penalty	dB	FFS	FFS	FFS	FFS
Maximum reflectance of optical network element	dB	FFS	FFS	FFS	FFS
NOTE 1 – These application codes require an additional parameter to ensure that the transmitter spectral characteristics are adequate. This parameter is under study. An initial set of values for the parameters above can be found in Appendix VII.					
NOTE 2 – The BER for these application codes is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10^{-12} .					

Table 8-15 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 40G intra-office applications

Parameter	Units	P1I1-3D1	1I1-3D1F
General information			
Maximum number of channels	–	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 40G	NRZ OTU3 FEC enabled
Maximum bit error ratio	–	10^{-12}	10^{-12} (Note)
Fibre type	–	G.652	G.652
Interface at point MPI-S			
Operating wavelength range	nm	1307-1317	1307-1317
Source type	–	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS
Minimum side mode suppression ratio	dB	35	35
Maximum mean output power	dBm	+4	+4
Minimum mean output power	dBm	0	0
Minimum extinction ratio	dB	8.2	8.2
Eye mask	–	NRZ 40G	NRZ 40G
Optical path from point MPI-S to MPI-R			
Maximum attenuation	dB	6	6
Minimum attenuation	dB	0	0
Maximum chromatic dispersion at upper wavelength limit	ps/nm	± 16	± 16
Maximum chromatic dispersion at lower wavelength limit	ps/nm	± 16	± 16
Minimum optical return loss at MPI-S	dB	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27
Maximum differential group delay	ps	7.5	7.5
Interface at point MPI-R			
Maximum mean input power	dBm	+4	+4
Minimum sensitivity	dBm	–7	–7
Maximum optical path penalty	dB	1	1
Maximum reflectance of optical network element	dB	–27	–27
NOTE – The BER for these application codes is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10^{-12} .			

Table 8-16 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 40G short- and long-haul applications in the 1300 nm region

Parameter	Units	P1S1-3D1	1S1-3D1F	P1L1-3C1	1L1-3C1F
General information					
Maximum number of channels	–	1	1	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 40G	NRZ OTU3 FEC enabled	NRZ 40G	NRZ OTU3 FEC enabled
Maximum bit error ratio	–	10 ⁻¹²	10 ⁻¹² (Note)	10 ⁻¹²	10 ⁻¹² (Note)
Fibre type	–	G.652	G.652	G.652	G.652
Interface at point MPI-S					
Operating wavelength range	nm	1310-1314	1310-1314	1310-1314	1310-1314
Source type	–	SLM	SLM	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	35	35	35	35
Maximum mean output power	dBm	+7	+4	+7	+4
Minimum mean output power	dBm	+4	+1	+4	+1
Minimum extinction ratio	dB	8.2	8.2	8.2	8.2
Eye mask	–	NRZ 40G	NRZ 40G	NRZ 40G	NRZ 40G
Optical path from point MPI-S to MPI-R					
Maximum attenuation	dB	10.5	10.5	20	20
Minimum attenuation	dB	3	0	9	6
Maximum chromatic dispersion at upper wavelength limit	ps/nm	±27	±27	±53	±53
Maximum chromatic dispersion at lower wavelength limit	ps/nm	±27	±27	±53	±53
Minimum optical return loss at MPI-S	dB	24	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27	–27	–27
Maximum differential group delay	ps	7.5	7.5	7.5	7.5
Interface at point MPI-R					
Maximum mean input power	dBm	+4	+4	–2	–2
Minimum sensitivity	dBm	–7.5	–10.5	–18	–21
Maximum optical path penalty	dB	1	1	2	2
Maximum reflectance of optical network element	dB	–27	–27	–27	–27
NOTE – The BER for these application codes is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10 ⁻¹² .					

Table 8-17 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 40G short- and long-haul applications in the 1550 nm region

Parameter	Units	P1S1-3C2 P1S1-3C3 P1S1-3C5	P1L1-3A2 P1L1-3A3 P1L1-3A5	1L1-3C2FD 1L1-3C3FD 1L1-3C5FD	1L1-3C2F 1L1-3C3F 1L1-3C5F
General information					
Maximum number of channels	–	1	1	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 40G	NRZ 40G	NRZ OTU3 FEC enabled	NRZ OTU3 FEC enabled
Maximum bit error ratio	–	10 ⁻¹²	10 ⁻¹²	10 ⁻¹² (Note 3)	10 ⁻¹² (Note 3)
Fibre type	–	G.652, G.653, G.655	G.652, G.653, G.655	G.652, G.653, G.655	G.652, G.653, G.655
Interface at point MPI-S					
Central frequency	THz	192.1	192.1	192.1	192.1
Maximum spectral excursion	GHz	40	40	40	40
Source type	–	SLM	SLM	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	35	35	35	35
Maximum mean output power	dBm	+3	+8	+5	+5
Minimum mean output power	dBm	–3	+5	+2	+2
Minimum extinction ratio	dB	8.2	10	10	10
Eye mask	–	NRZ 40G	NRZ 40G	NRZ 40G	NRZ 40G

Table 8-17 – Single-channel IrDI parameters and values for optical tributary signal class NRZ 40G short- and long-haul applications in the 1550 nm region

Parameter	Units	P1S1-3C2 P1S1-3C3 P1S1-3C5	P1L1-3A2 P1L1-3A3 P1L1-3A5	1L1-3C2FD 1L1-3C3FD 1L1-3C5FD	1L1-3C2F 1L1-3C3F 1L1-3C5F
Optical path from point MPI-S to MPI-R					
Maximum attenuation	dB	11	22	22	22
Minimum attenuation	dB	0	11	11	11
Maximum chromatic dispersion at upper wavelength limit	ps/nm	800 for G.652, ±120 for G.653, 420 for G.655	1600 for G.652, ±240 for G.653, 840 for G.655	1600 for G.652, ±240 for G.653, 840 for G.655	1600 for G.652, ±240 for G.653, 840 for G.655
Maximum chromatic dispersion at lower wavelength limit	ps/nm	800 for G.652, ±120 for G.653, 420 for G.655	1600 for G.652, ±240 for G.653, 840 for G.655	1600 for G.652, ±240 for G.653, 840 for G.655	1600 for G.652, ±240 for G.653, 840 for G.655
Maximum chromatic dispersion deviation	ps/nm	(Note 2)	(Note 2)	±80	(Note 2)
Minimum optical return loss at MPI-S	dB	24	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	-27	-27	-27	-27
Maximum differential group delay	ps	7.5 (Note 1)	7.5 (Note 1)	7.5 (Note 1)	7.5 (Note 1)
Interface at point MPI-R					
Maximum mean input power	dBm	+3	-3	-6	-6
Minimum sensitivity	dBm	-17	-20	-22	-23
Maximum optical path penalty	dB	3	3	2	3
Maximum reflectance of optical network element	dB	-27	-27	-27	-27
NOTE 1 – Some categories of G.652, G.653 and G.655 fibre have too high a PMD coefficient to guarantee this value of DGD.					
NOTE 2 – This value must be agreed by joint engineering between the link provider and the system vendor.					
NOTE 3 – The BER for these application codes is required to be met only after the error correction (if used) has been applied. The BER at the input of the FEC decoder can therefore be significantly higher than 10^{-12} .					

9 Optical safety considerations

See [ITU-T G.664] for optical safety considerations.

NOTE – For the optical power levels specified in this version of this Recommendation, automatic power reduction (APR) is not necessary according to [ITU-T G.664], [IEC 60825-1] and [IEC 60825-2]. Future versions of this Recommendation may, however, contain power levels exceeding the safe levels. In this case, for non-OTN applications, the ALS procedure defined in [ITU-T G.664] shall be applied on individual SDH client signal interfaces only.

10 Power level management

For further study.

Annex A

Configuration for method A for assessment of single-channel characteristics in a multichannel IrDI

(This annex forms an integral part of this Recommendation)

A.1 Reference configuration

In the case of the multichannel IrDI, single-channel reference points can be used to access the individual transmitted signals for assessing single-channel characteristics (extinction ratio, eye mask and optical path penalty).

The eye mask measurements are performed by submitting the single-channel signal at the S_x reference point to the "measurement set-up for transmitter eye diagram" illustrated in Figure B.1 of [ITU-T G.957].

For the optical path penalty, two measurements are performed as illustrated in Figure A.1. The first (measurement 1) involves measuring the power required to achieve the reference BER using the signal at S_x , this is then repeated (measurement 2) using the signal at R_x reference point.

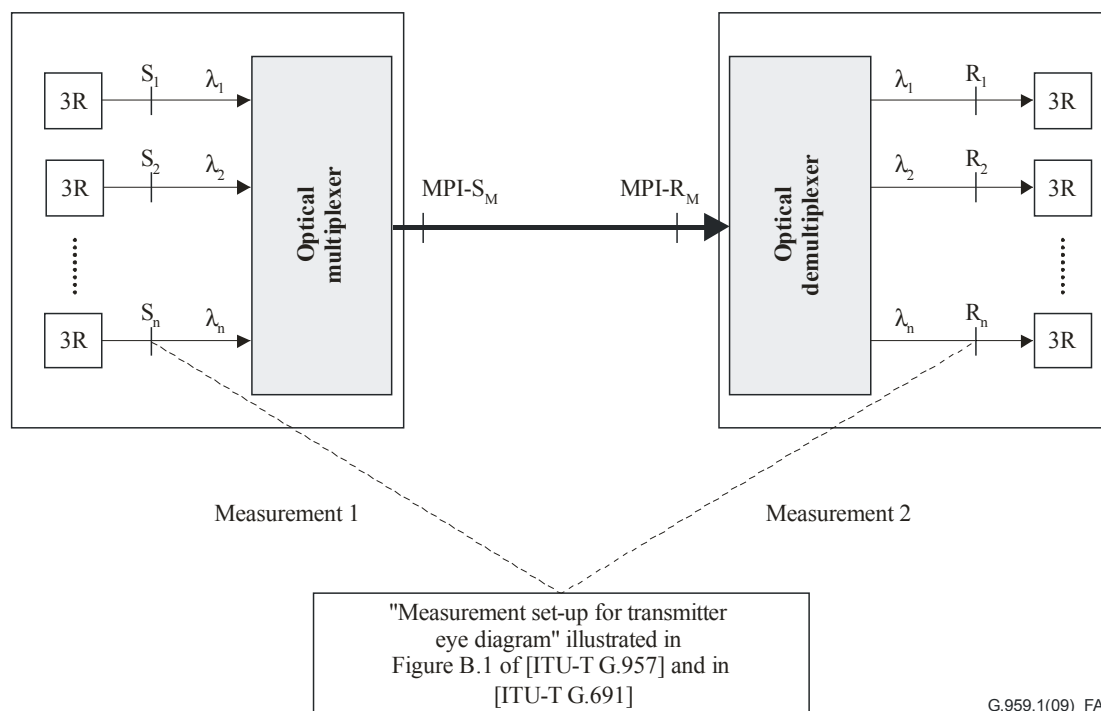


Figure A.1 – Method A configuration

Annex B

Reference optical bandpass filter and reference receiver characteristics for method B, for assessment of single-channel characteristics in a multichannel IrDI

(This annex forms an integral part of this Recommendation)

B.1 Reference configuration

In the case of the multichannel IrDI, a reference optical bandpass filter can be used to isolate the individual transmitted signals for assessing single-channel characteristics (extinction ratio, eye mask and optical path penalty).

The eye mask measurements are performed by submitting the signal at MPI-S_M to the reference optical bandpass filter and taking the output to a reference receiver in accordance with the configuration given in Annex B of [ITU-T G.957].

In the case of the optical path penalty, two measurements are performed as illustrated in Figure B.1. The first (measurement 1) involves measuring the power required to achieve the reference BER using the signal at MPI-S_M, this is then repeated (measurement 2) using the signal at MPI-R_M.

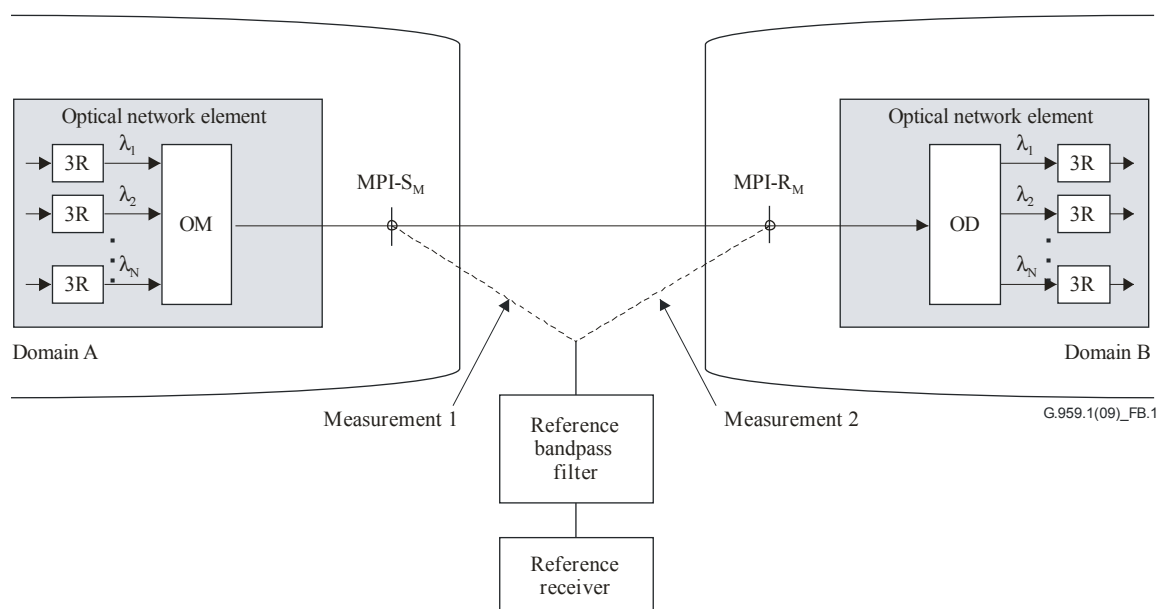


Figure B.1 – Method B configuration

B.2 Reference optical bandpass filter

The purpose of the reference optical bandpass filter is to isolate the individual optical channels from the composite multichannel signal. It should have adequate characteristics to ensure minimal interference from adjacent channels whilst introducing negligible distortion to the signal under test. A minimum set of requirements is given in clause B.2.1.

There are several technologies available to perform this function, e.g., tuneable filter or a demultiplexer.

B.2.1 Optical filter parameters

The requirements on the reference optical bandpass filter frequency response are illustrated in Figure B.2. The value of Y is chosen such that the ratio of the power in the channel being measured to the sum of the powers of all of the other channels is greater than 20 dB.

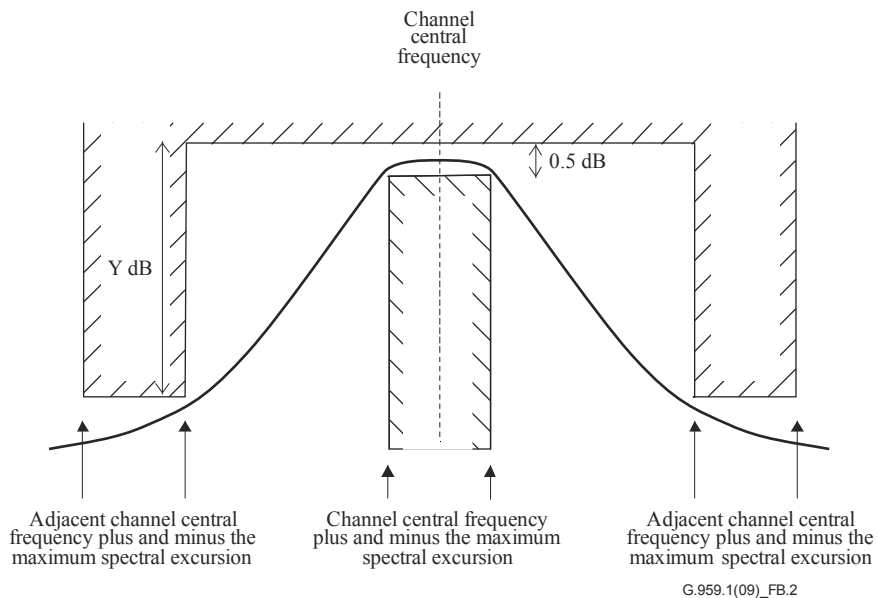


Figure B.2 – Optical bandpass filter frequency response

The design of the filter should be chosen so that a maximum rate signal should undergo no significant distortion due to amplitude and phase ripple.

B.3 Reference receiver

This is a receiver with a frequency response such as is outlined in Annex A of [ITU-T G.691], i.e., a fourth-order Bessel-Thomson filter with a cutoff frequency at 0.75 times the bit rate in question. The tolerance values of this filter are given in Table A.1 of [ITU-T G.691].

In the case where the reference receiver is used to measure the bit error ratio (BER) for optical path penalty assessment, the decision threshold should be adjusted for the lowest BER for measurement 1 and then reoptimized for measurement 2 in order to accommodate the requirements of different application codes and cover various design implementations meeting those application codes.

In order to perform single-channel tests on some application codes, it may be necessary to include a pre-amplifier inside the reference receiver.

Different reference receiver characteristics are required for the various per-channel signal bit rates as defined in Annex A of [ITU-T G.691].

Appendix I

Single-channel client interfaces with 3R regeneration

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

I.1 Introduction

This appendix describes the use of 3R regeneration at client signal interfaces to OTN optical networks. The use of 3R regeneration will facilitate the interconnection of such optical networks with existing transport networks, e.g., SDH networks, and is expected to accelerate OTN deployment as optical networking technology is maturing.

I.2 Description of client signal interfaces with 3R regeneration

Client signals with optical characteristics that meet the physical layer specifications, e.g., wavelengths and frequency tolerances, of OTN optical networks may appear to be attractive because such networks avoid the cost of optical-to-electrical-to-optical (OEO) processing at network interfaces. However, in order to transport client signals from legacy SONET/SDH equipment, an OEO conversion may be necessary. Additionally, in order to achieve interoperability, the use of physically compliant client signals will require joint engineering until such time as the required physical layer optical interface specifications can be agreed.

If the OEO processing described above includes 3R regeneration plus any other required adaptation, e.g., wavelength conversion, then the specification of physical-layer optical parameters at the client interface can be taken from short-reach applications specified in [ITU-T G.957]. This short-reach client signal interface based on the use of 3R regeneration on the network side of the interface can be used for legacy client signals, as well as for newer client signal transmitters and receivers. This interface is an example of the non-OTN inter-domain interface (non-OTN_IrDI) described in [ITU-T G.872]. The interface is shown in Figure I.1, where λ_s denotes wavelength used for the short-reach interconnect.

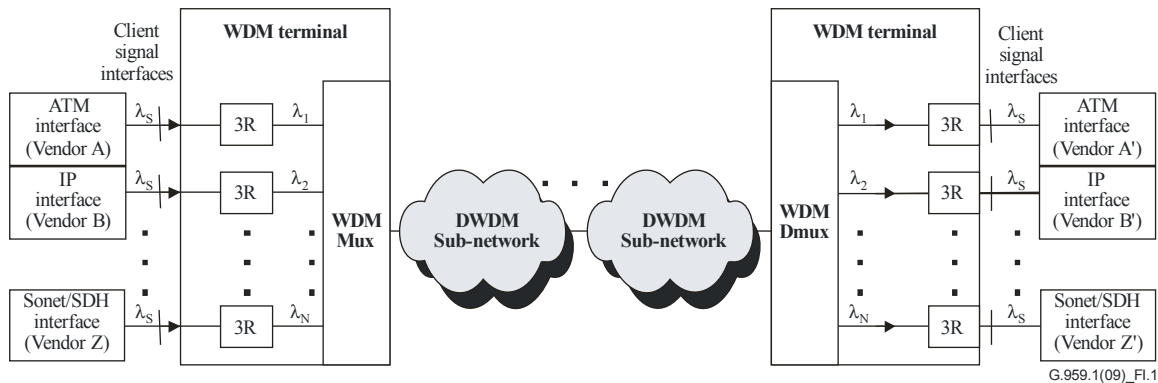


Figure I.1 – Example of client signal interface with 3R regeneration

Appendix II

Generic reference points within the OTN

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

Figure II.1 shows a set of "generic" reference points for optical network elements (ONEs) in the future OTN.

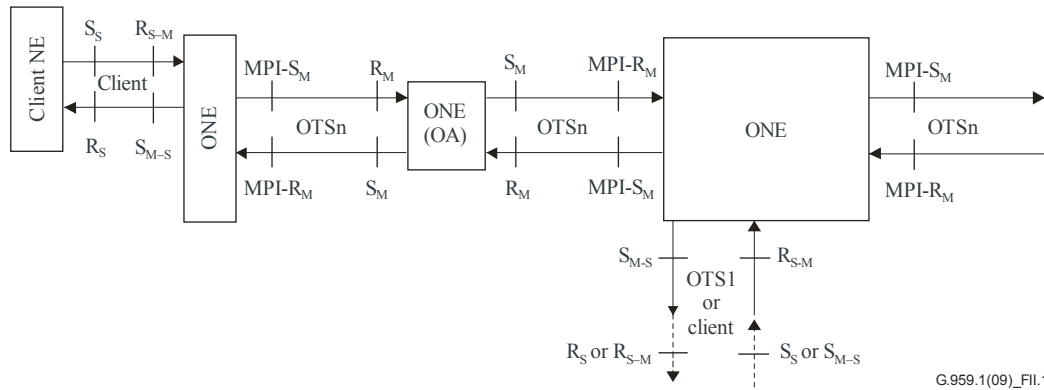


Figure II.1 – Generic reference points for optical network elements

The reference points in Figure II.1 are defined as follows:

- S_S is a (single-channel) reference point on the optical fibre just after a single channel client NE transmitter optical connector.
- R_S is a (single-channel) reference point just before a single channel client NE receiver optical connector.
- S_{M-S} is a (single-channel) reference point just after each of the optical network element tributary interface output optical connectors (the "M-S" subscript indicating a single-channel output from a system that may be multichannel).
- R_{S-M} is a (single-channel) reference point on the optical fibre just before each of the optical network element tributary interface input optical connectors (the "S-M" subscript indicating a single-channel input to a system that may be multichannel).
- $MPI-S_M$ is a (multichannel) reference point on the optical fibre just after the optical network element transport interface output optical connector.
- $MPI-R_M$ is a (multichannel) reference point on the optical fibre just before the optical network element transport interface input optical connector.
- S_M is a reference point just after the line multichannel OA output optical connector.
- R_M is a reference point on the optical fibre just before the line multichannel OA input optical connector.

Client interfaces at reference points S_S , R_S , and line amplifiers with reference points S_M and R_M are not within the scope of this Recommendation.

The term "optical network element" (ONE) serves to illustrate the general case of a generic network element within the optical transport network. In general, an ONE may have:

- 1) only multichannel interfaces;
- 2) only single-channel interfaces; or
- 3) any combination of single- and multichannel interfaces (i.e., the ONEs found in Figure II.1 are not meant to imply any particular configuration).

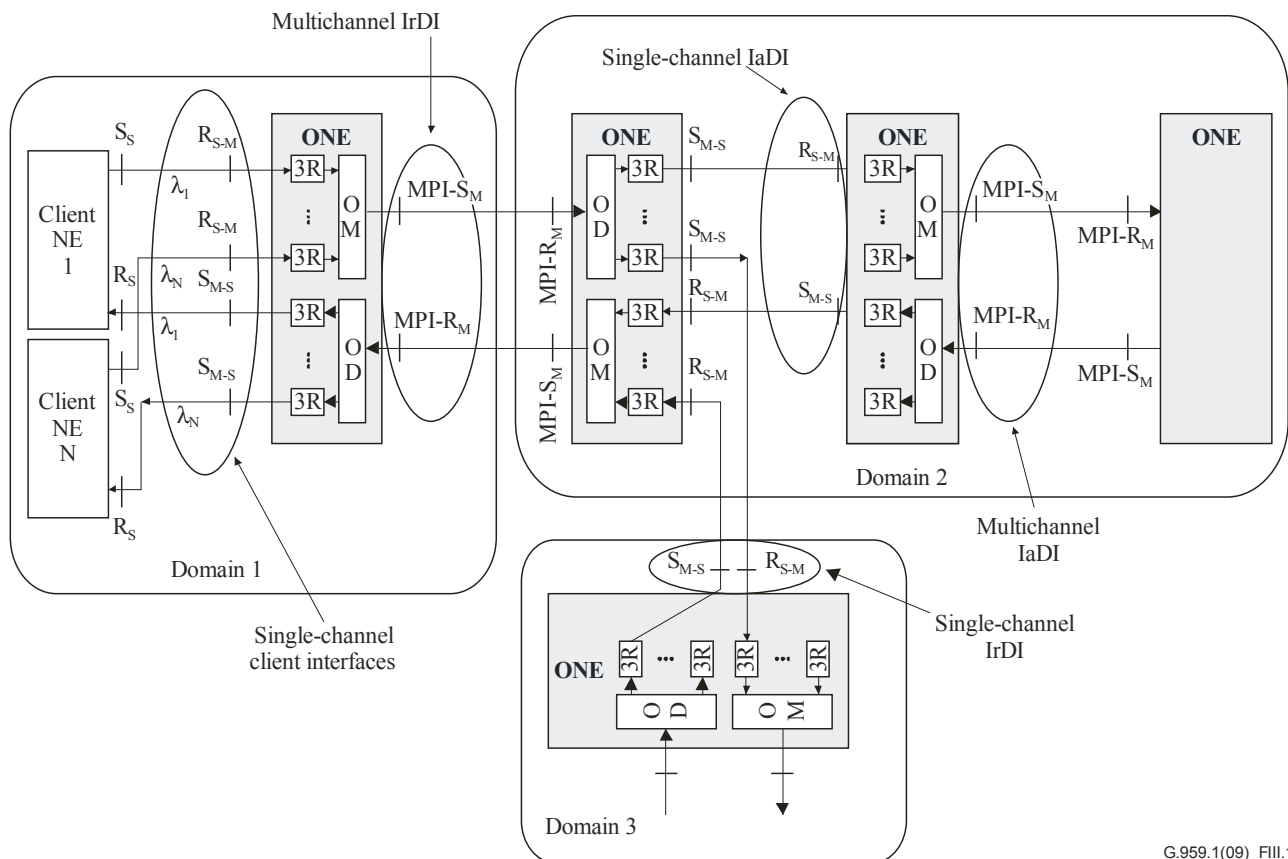
Appendix III

Clarification of use of reference points within IrDI and IaDI

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

In Figure III.1, a further clarification is given on the application of the generic OTN reference points as specified in Appendix II.

Simple optical networks can be configured using back-to-back connected WDM demultiplexers and multiplexers forming a simple optical add-drop multiplexer (OADM). They are interconnected via single-channel interfaces. Figure III.1 shows such an arrangement.



G.959.1(09)_FIII.1

Figure III.1 – Examples of multichannel and single-channel inter-domain and intra-domain interfaces

Appendix IV

Considerations for management signal implementations

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

The presence of signals to manage the optical channel, optical multiplex section and optical transmission section layers is defined for OTN IaDIs and is foreseen for some future OTN IrDIs. Considerations for physical implementations of such signals are presented below.

IV.1 Optical channel management signal implementation

Both channel-associated and channel-non-associated OCh management signal implementations may be needed.

For channel-associated management signals, a "digital wrapper" approach is defined in [ITU-T G.709]. This method employs a digital frame structure, comprising overhead bytes, payload bytes and bytes for forward error correction.

OCh-associated overhead transport by non-digital (optical) mechanisms, e.g., sub-carrier-modulation, may also be appropriate for certain applications, and are for further study. Further system penalties may be introduced by these techniques.

An optical supervisory channel (OSC) is the approach specified in [ITU-T G.709] for implementing channel non-associated signals. This is discussed below in connection with optical multiplex section and optical transmission section management signal implementation.

The OCh overhead information for each optical channel originates and terminates in the OCh layer of optical network elements.

IV.2 Optical multiplex section and optical transmission section management signal implementation

The OSC is a separate channel which carries overhead information for network management purposes. Management messages for the OMS and OTS layers, together with management messages for the OCh layer which are transported via a channel-non-associated implementation, share an OSC. For monitoring the multichannel signal in the OTS and OMS layers of optical network elements, an OSC may be provided for each transmission direction. An OSC originates and terminates in each optical network element.

Currently, the preferred wavelength for the OSC is given in [ITU-T G.692]. Full transverse compatibility and redundancy of application codes should be taken into consideration when specifying the OSC wavelength in the future.

Appendix V

Nomenclature for the highest class of optical tributary signal supported

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

In clause 5.3, the application code notation is constructed as follows:

PnW_x-y_{tz}

Within this structure, **y** indicates the highest class of optical tributary signal supported:

- **1** indicating NRZ 2.5G;
- **2** indicating NRZ 10G;
- **9** indicating NRZ 25G;
- **3** indicating NRZ 40G;
- **7** indicating RZ 40G.

The reasoning behind the choice of 7 for RZ 40G is that 4 is reserved for optical tributary signal class NRZ 100G (however, it is recognized that when they are introduced, the modulation format of 100G signals may well not be NRZ) and that the RZ signal classes would therefore start with **y** = 5. Optical tributary signal class NRZ 25G was added after this allocation was made, and it is therefore indicated with 9. The allocation of numbers is shown in Table V.1.

Table V.1 – Allocated values for **y within the application code nomenclature**

Rate of optical tributary signal	NRZ	RZ
1.25G	0	
2.5G	1	
10G	2	5
25G	9	6
40G	3	7
100G	4	8

Appendix VI

Optical tributary signal class RZ 40G applications

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

A future revision of this Recommendation is expected to contain specifications for single-channel IrDIs with a bit rate/line coding of RZ 40G. These applications are expected to show a higher tolerance to PMD than shown by applications with a bit rate/line coding of NRZ 40G.

The characteristics of these applications are under study for three different RZ duty cycles: 33%, 50% and 67%.

- Tolerance to first-order PMD is expected to be highest for 33% and lowest for 67%.
- Tolerance to second-order PMD, however, is expected to be ordered in the reverse direction, with the highest tolerance for 67% and lowest for 33% due to its wider optical spectrum.
- The amount of second-order PMD that each duty cycle can tolerate for a given penalty depends on the residual chromatic dispersion at the detector (point R_D in Figure 7-5) and this, in turn, depends on the maximum chromatic dispersion deviation of the link and the design of the receiver black-box. Since the maximum chromatic dispersion deviation is a critical factor in the design of links at these rates, applications that do not contain adaptive dispersion compensation have this parameter set by joint engineering between the link provider and the system vendor.

The list of parameters and values found in Table VI.1 are expected to form the basis for this future application.

**Table VI.1 – Single-channel IrDI parameters and values
for optical tributary signal class RZ 40G**

Parameter	Units	P1L1-7A2 P1L1-7A3 P1L1-7A5
General information		
Maximum number of channels	–	1
Bit rate/line coding of optical tributary signals	–	RZ 40G
Maximum bit error ratio	–	10^{-12}
Fibre type	–	G.652, G.653, G.655
Interface at point MPI-S		
Central frequency	THz	192.1
Maximum spectral excursion	GHz	40
Source type	–	SLM
Maximum duty cycle	%	FFS
Minimum duty cycle	%	FFS
Maximum spectral power density	mW/10 MHz	FFS
Minimum side mode suppression ratio	dB	35
Maximum mean output power	dBm	+12

**Table VI.1 – Single-channel IrDI parameters and values
for optical tributary signal class RZ 40G**

Parameter	Units	P1L1-7A2 P1L1-7A3 P1L1-7A5
Minimum mean output power	dBm	+9
Minimum extinction ratio	dB	10
Eye mask	–	RZ 40G
Optical path from point MPI-S to MPI-R		
Maximum attenuation	dB	22
Minimum attenuation	dB	11
Maximum chromatic dispersion at upper wavelength limit	ps/nm	1600 for G.652, ±240 for G.653 (Note 1), 840 for G.655 (Note 1)
Maximum chromatic dispersion at lower wavelength limit	ps/nm	1600 for G.652, ±240 for G.653 (Note 1), 840 for G.655 (Note 1)
Maximum chromatic dispersion deviation	ps/nm	(Note 2)
Minimum optical return loss at MPI-S	dB	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27
Maximum differential group delay	ps	FFS
Interface at point MPI-R		
Maximum mean input power	dBm	+1
Minimum sensitivity	dBm	–16
Maximum optical path penalty	dB	3 (Note 1)
Maximum reflectance of optical network element	dB	–27
NOTE 1 – Links using G.653 or G.655 fibres may show excessive path penalty due to non-linear effects depending on the exact dispersion distribution through the link.		
NOTE 2 – This value must be agreed by joint engineering between the link provider and the system vendor.		

Appendix VII

Applications using electronic dispersion compensation

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

A future revision of this Recommendation is expected to contain parameter values for the applications P1L1-2D2E, 1L1-2D2FE, P1V1-2B2E and 1V1-2B2FE in Table 8-14. These application codes require an additional parameter to be developed to ensure that the transmitter spectral characteristics are adequate. This parameter is under study. An initial set of the other parameter values for these applications can be found in Table VII.1.

Table VII.1 – Single-channel IrDI parameters for optical tributary signal class NRZ 10G long- and very long-haul applications using electronic dispersion compensation

Parameter	Units	P1L1-2D2E	1L1-2D2FE	P1V1-2B2E	1V1-2B2FE
General information					
Maximum number of channels	–	1	1	1	1
Bit rate/line coding of optical tributary signals	–	NRZ 10G	NRZ OTU2 FEC enabled	NRZ 10G	NRZ OTU2 FEC enabled
Maximum bit error ratio	–	10 ⁻¹²	10 ⁻¹²	10 ⁻¹²	10 ⁻¹²
Fibre type	–	G.652	G.652	G.652	G.652
Interface at point MPI-S					
Operating wavelength range	nm	1530-1565	1530-1565	1530-1565	1530-1565
Source type	–	SLM	SLM	SLM	SLM
Maximum spectral power density	mW/ 10 MHz	FFS	FFS	FFS	FFS
Minimum side mode suppression ratio	dB	30	30	30	30
Maximum mean output power	dBm	+4	+4	+14	+14
Minimum mean output power	dBm	0	-1	+11	+11
Minimum extinction ratio	dB	9	8.2	8.2	8.2
Eye mask	–	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region	NRZ 10G 1550 nm region
Optical path from point MPI-S to MPI-R					
Maximum attenuation	dB	22	22	33	33
Minimum attenuation	dB	11	11	21	21
Maximum chromatic dispersion at upper wavelength limit	ps/nm	1600	1600	2400	2400
Maximum chromatic dispersion at lower wavelength limit	ps/nm	1430	1430	2150	2150
Minimum optical return loss at MPI-S	dB	24	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	-27	-27	-27	-27

Table VII.1 – Single-channel IrDI parameters for optical tributary signal class NRZ 10G long- and very long-haul applications using electronic dispersion compensation

Parameter	Units	P1L1-2D2E	1L1-2D2FE	P1V1-2B2E	1V1-2B2FE
Maximum differential group delay	ps	30	30	30	30
Interface at point MPI-R					
Maximum mean input power	dBm	-7	-7	-7	-7
Minimum sensitivity	dBm	-24	-25	-24	-24
Maximum optical path penalty	dB	2	2	2	2
Maximum reflectance of optical network element	dB	-27	-27	-27	-27

Bibliography

- [b-ITU-T G.871] Recommendation ITU-T G.871/Y.1301 (2000), *Framework for Optical Transport Network Recommendations*.
- [b-ITU-T G-Sup.39] ITU-T G-series Recommendations – Supplement 39 (2006), *Optical system design and engineering considerations*.

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