International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

G.691

(03/2006)

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

Transmission media characteristics – Characteristics of optical components and subsystems

---

Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers

ITU-T Recommendation G.691

ITU-T G-SERIES RECOMMENDATIONS

TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

INTERNATIONAL TELEPHONE CONNECTIONS AND CIRCUITS	G.100–G.199
GENERAL CHARACTERISTICS COMMON TO ALL ANALOGUE CARRIER-TRANSMISSION SYSTEMS	G.200–G.299
INDIVIDUAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON METALLIC LINES	G.300–G.399
GENERAL CHARACTERISTICS OF INTERNATIONAL CARRIER TELEPHONE SYSTEMS ON RADIO-RELAY OR SATELLITE LINKS AND INTERCONNECTION WITH METALLIC LINES	G.400–G.449
COORDINATION OF RADIOTELEPHONY AND LINE TELEPHONY	G.450–G.499
TRANSMISSION MEDIA CHARACTERISTICS	G.600–G.699
General	G.600–G.609
Symmetric cable pairs	G.610–G.619
Land coaxial cable pairs	G.620–G.629
Submarine cables	G.630–G.649
Optical fibre cables	G.650–G.659
Characteristics of optical components and subsystems	**G.660–G.699**
DIGITAL TERMINAL EQUIPMENTS	G.700–G.799
DIGITAL NETWORKS	G.800–G.899
DIGITAL SECTIONS AND DIGITAL LINE SYSTEM	G.900–G.999
QUALITY OF SERVICE AND PERFORMANCE – GENERIC AND USER-RELATED ASPECTS	G.1000–G.1999
TRANSMISSION MEDIA CHARACTERISTICS	G.6000–G.6999
DATA OVER TRANSPORT – GENERIC ASPECTS	G.7000–G.7999
ETHERNET OVER TRANSPORT ASPECTS	G.8000–G.8999
ACCESS NETWORKS	G.9000–G.9999

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

ITU-T Recommendation G.691

Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers

Summary

This Recommendation provides parameters and values for optical interfaces of single-channel long-haul STM-4, STM-16 and STM-64 systems utilizing optical preamplifiers and/or optical booster amplifiers. Furthermore, it provides optical interface parameters for single-channel STM-64 intra-office and short-haul systems without optical amplification

Source

ITU-T Recommendation G.691 was approved on 29 March 2006 by ITU-T Study Group 15 (2005-2008) under the ITU-T Recommendation A.8 procedure.

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications. The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

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

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

NOTE

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

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

INTELLECTUAL PROPERTY RIGHTS

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

As of the date of approval of this Recommendation, ITU had received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementors are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database.

CONTENTS

ITU-T Recommendation G.691

Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers

1 Scope

The purpose of this Recommendation is to provide optical interface specifications to enable transverse (multi-vendor) compatibility of single-channel STM-4, STM-16, and STM-64 inter-office systems using optical preamplifiers and/or optical booster amplifiers. Specifications to enable transversely compatible single-channel STM-64 intra-office and short-haul systems not requiring optical amplification are also included.

The use of line amplifiers is not within the scope of this Recommendation.

This Recommendation is based on the use of one fibre per direction.

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.

[1] ITU-T Recommendation G.652 (2005), *Characteristics of a single-mode optical fibre and cable*.

[2] ITU-T Recommendation G.653 (2003), *Characteristics of a dispersion-shifted single-mode optical fibre and cable*.

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

[4] ITU-T Recommendation G.662 (2005), *Generic characteristics of optical amplifier devices and subsystems*.

[5] ITU-T Recommendation G.663 (2000), *Application related aspects of optical amplifier devices and subsystems*.

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

[7] ITU-T Recommendation G.671 (2005), *Transmission characteristics of optical components and subsystems*.

[8] ITU-T Recommendation G.693 (2005), *Optical interfaces for intra-office systems*.

[9] ITU-T Recommendation G.707/Y.1322 (2003), *Network node interface for the synchronous digital hierarchy (SDH)*.

[10] ITU-T Recommendation G.955 (1996), *Digital line systems based on the 1544 kbit/s and the 2048 kbit/s hierarchy on optical fibre cables*.

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

[12] ITU-T Recommendation G.959.1 (2006), *Optical transport network physical layer interfaces.*

3 Terms and definitions

3.1 Definitions

This Recommendation defines the following terms:

3.1.1 main (optical) path: The fibre plant between the S point of the transmitter equipment and the R point of the receiver equipment. The main path does not include any auxiliary paths.

3.1.2 main path interfaces: The interfaces to the fibre plant specified in this Recommendation.

3.1.3 auxiliary (optical) path: The optical interconnection between a non-amplified transmitter or receiver and an (stand-alone) optical pre- or booster-amplifier device. An auxiliary path is not included in the main path.

3.1.4 (optical) transponder: A transmitter-receiver combination with or without pulse shaping and retiming that converts an optical signal into another optical signal by a conversion into the electrical domain.

3.2 Terms defined in other Recommendations

This Recommendation uses the following terms defined in other ITU-T Recommendations:

Booster amplifier:	(ITU-T Rec. G.662)
Erbium doped fibre amplifier:	(ITU-T Rec. G.661)
Joint engineering:	(ITU-T Rec. G.957)
Longitudinal compatibility:	(ITU-T Rec. G.955)
Optical amplifier device:	(ITU-T Rec. G.662)
Optical amplifier subsystem:	(ITU-T Rec. G.662)
Optical amplifier:	(ITU-T Rec. G.662)
Optical fibre amplifier:	(ITU-T Rec. G.662)
Optical return loss:	(ITU-T Rec. G.957)
Optically amplified receiver:	(ITU-T Rec. G.662)
Optically amplified transmitter:	(ITU-T Rec. G.662)
Pre-amplifier:	(ITU-T Rec. G.662)
S/R reference points:	(ITU-T Rec. G.955)
Transverse compatibility:	(ITU-T Rec. G.957)

4 Abbreviations

This Recommendation uses the following abbreviations:

APD	Avalanche Photo Diode
ASE	Amplified Spontaneous Emission
ASK	Amplitude Shift Keying
BER	Bit Error Ratio
DA	Dispersion Accommodation
DGD	Differential Group Delay
DST	Dispersion Supported Transmission
EX	Extinction ratio
FEC	Forward Error Correction
ffs	For Further Study
FM	Frequency Modulation
FSK	Frequency Shift Keying
FSR	Free Spectral Range
FWHM	Full Width at Half Maximum
I	Intra-Office
IM	Intensity Modulation
L	Long-Haul
MLM	Multi-Longitudinal Mode
MPI	Main Path Interface
MPN	Mode Partition Noise
NA	Not Applicable
NRZ	Non-Return to Zero
ORL	Optical Return Loss
PCH	Prechirp
PDC	Passive Dispersion Compensator
PIN	"p-type" – intrinsic – "n-type"
PMD	Polarization Mode Dispersion
PRBS	Pseudo-Random Binary Sequence
PSP	Principal State of Polarization
RMS	Root Mean Square
S	Short-Haul
SDH	Synchronous Digital Hierarchy
SLM	Single-Longitudinal Mode
SMSR	Side Mode Suppression Ratio
SNR	Signal to Noise Ratio

SOP	State of Polarization
SPM	Self Phase Modulation
STM-N	Synchronous Transport Module of order N
U	Ultra Long-Haul
V	Very Long-Haul
WDM	Wavelength Division Multiplex

5 Classification of optical interfaces

5.1 Applications

This Recommendation defines optical interfaces for single-channel inter-office line systems for terrestrial long-distance applications from STM-4 to STM-64. It is an extension of ITU-T Rec. G.957 based on the addition of optical amplifiers and the STM-64 data rate. Systems with line amplifiers are not within the scope of this Recommendation.

The definitions of the application codes are extended from ITU-T Rec. G.957 as:

Application – STM level.suffix number,

where "application" corresponds to the target distance: I- (Intra-office), S- (Short-haul), L- (Long-haul), V- (Very long-haul), and U- (Ultra long-haul).

The suffix number denotes:

1 the use of nominally 1310 nm sources on G.652 (standard) fibre;

2 the use of nominally 1550 nm sources on G.652 fibre;

3 the use of nominally 1550 nm sources on G.653 (dispersion shifted) fibre;

5 the use of nominally 1550 nm sources on G.655 (non-zero dispersion shifted) fibre.

For some I-64 codes an "r" is added after the suffix number to indicate a reduced target distance. These application codes which belong to the intra-office family are dispersion limited. The same target distance can be achieved by means of other technological solutions, which are for further study (e.g., parallel interface approach).

The target distances are based on approximately 40 km intervals for 1550 nm and 20 km intervals for 1310 nm, except for the very short reach and intra-office applications. The target distances are to be used for classification only and not for specification. They are estimated using the assumption of 0.275 dB/km installed fibre loss including splices and cable margins for 1550 nm systems, and 0.55 dB/km for 1310 nm systems. From a practical point of view, attenuation spans of 11 dB/20 km at 1310 nm and 11 dB/40 km at 1550 nm are defined, except for very short reach and intra-office applications. In practice, these values may not apply to all fibre cables, in which case the realistic distances that can be reached may be shorter.

The primary specifications are the attenuation range and the maximum dispersion tolerance of the system. The main use of the target distance is to define the dispersion tolerance, which is calculated as the maximum fibre dispersion times the target distance. This gives added tolerance to the systems, as well as enabling the full utilization of low attenuation fibre plants. Tables 1a, 1b and 1c summarize the application codes described in this Recommendation.

Table 1a/G.691 – Classification of optical interfaces based on application and showing I application codes

Applications						
Source nominal wavelength [nm]	1310	1310	1550	1550	1550	1550
Fibre type	G.652	G.652	G.652	G.652	G.653	G.655
Targ dist. [km]	0.6	2	2	25	25	25
STM-64	I-64.1r	I-64.1	I-64.2r	I-64.2	I-64.3	I-64.5
Parameters given in	G.693	G.693	G.693	G.959.1	G.959.1	G.959.1
As code	VSR600-2R1	VSR2000-2R1	VSR2000-2L2	P1I1-2D2	P1I1-2D3	P1I1-2D5

NOTE 1 – The target distances are approximate and are to be used for classification only and not for specification.

NOTE 2 – I, S and L codes for STM-1, -4 and -16 are defined in ITU-T Rec. G.957.

Table 1b/G.691 – Classification of optical interfaces based on application and showing S and L application codes

Applications							
Source nominal wavelength [nm]	1310	1550	1550	1550	1310	1550	1550
Fibre type	G.652	G.652	G.653	G.655	G.652	G.652	G.653
Targ dist. [km]	20	40	40	40	40	80	80
STM-64	S-64.1	S-64.2	S-64.3	S-64.5	L-64.1	L-64.2	L-64.3
Parameters given in	G.959.1	G.959.1	G.959.1	G.959.1	G.959.1	Table 5c	Table 5c
As code	P1S1-2D1	P1S1-2D2	P1S1-2D3	P1S1-2D5	P1L1-2D1		

NOTE 1 – The target distances are approximate and are to be used for classification only and not for specification.

NOTE 2 – I, S and L codes for STM-1, -4 and -16 are defined in ITU-T Rec. G.957.

Table 1c/G.691 – Classification of optical interfaces based on application and showing V and U application codes

Applications					
Source nominal wavelength [nm]	1310	1550	1550	1550	1550
Fibre type	G.652	G.652	G.653	G.652	G.653
Targ dist. [km]	60	120	120	160	160
STM-1	–	–	–	–	–
STM-4	V-4.1	V-4.2	V-4.3	U-4.2	U-4.3
Parameters given in	Table 3	Table 3	Table 3	Table 3	Table 3
Targ dist. [km]	60	120	120	160	160
STM-16	–	V-16.2	V-16.3	U-16.2	U-16.3
Parameters given in		Table 4	Table 4	G.959.1	G.959.1
As code				P1U1-1A2	P1U1-1A3
Targ dist. [km]	60	120	120		
STM-64	–	V-64.2	V-64.3	–	–
Parameters given in		Table 5d	Table 5d		
NOTE – The target distances are approximate and are to be used for classification only and not for specification.					

5.2 Reference and physical configurations

The focus of this Recommendation is to specify the main path interfaces (MPIs). The MPIs are the interfaces to the long-distance fibre plant. The properties of the main path set the requirements on the terminal equipment. The terminal equipment can, in principle, be organized in different ways in order to meet the required specifications of the MPIs. This concerns such aspects as integration level, dispersion accommodation method, or the use of stand-alone optical amplifiers.

Due to the multiplicity of active and passive equipment in the optical path (amplifiers, multiplexers, etc.) in the Recommendations for single- and multichannel systems with optical amplifiers, the S and R reference points must be interpreted in a generic sense, and have to be detailed for each system. To distinguish the MPI-S and -R points from other reference points (e.g., S in ITU-T Rec. G.957) the transmit and receive ends of the main path are denoted MPI-S and MPI-R respectively, when used in a general sense.

The optical interconnection paths (patchcords) between any optical devices within the terminal equipment, if present, are termed "auxiliary paths". For the purpose of this Recommendation, optical fibre line system interfaces can therefore be represented as shown in Figure 1.

In Figure 1, the transmitter side is illustrated using a transmitter, connected through an auxiliary path to a stand-alone optical amplifier device, whereas on the receiver side an optically amplified receiver directly interfaces with the main path.

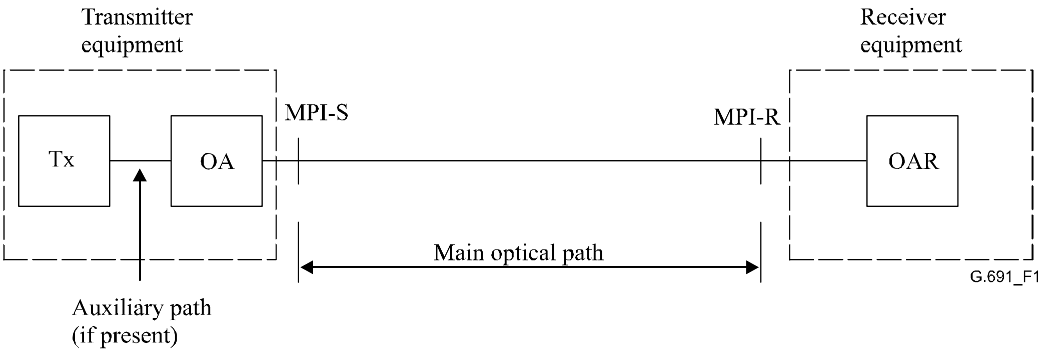


Figure 1/G.691 – An example of an optical link showing the interface points defined in this Recommendation

6 Parameter definitions

All parameter values are worst-case values, assumed to be met over the range of standard operating conditions (i.e., temperature and humidity ranges), and they include ageing effects. The parameters are specified relative to an optical section design objective of a bit error ratio (BER) not worse than 10^{-12} for any combination of parameters within the ranges given in the tables for each specified system.

The optical line coding used for system interfaces up to, and including, STM-64 is binary non-return to zero (NRZ) scrambled according to ITU-T Rec. G.707/Y.1322.

6.1 System operating wavelength range

The operating wavelength range is the maximum allowable range for source wavelength. Within this range, the source wavelength can be selected for different amplifier implementations and different fibre-related impairments. The receiver must have a minimum operating wavelength range that corresponds to the maximum allowable range for the source wavelength.

The operating wavelength range of fibre optic transmission systems is basically determined by the attenuation and dispersion characteristics of the various fibre and source types. A detailed discussion of these aspects can be found in ITU-T Rec. G.957. In the long-distance systems with optical amplifiers considered in this Recommendation, the operating wavelength range is further restricted by the optical amplifiers themselves.

NOTE – When a wavelength-fixed or tunable filter to eliminate amplified spontaneous emission (ASE) is used before the receiver, the operating wavelength band may be limited, and the transverse compatibility may not be guaranteed.

6.2 Transmitter

6.2.1 Spectral characteristics

It is not expected that spectral measurements alone will be able to guarantee transverse compatibility, and these parameters should be viewed as necessary, but not sufficient, for that purpose. Presently, few values for the spectral parameters are given. Until these values are available, transversal compatibility cannot be guaranteed for these systems.

6.2.1.1 Maximum spectral width for SLM sources

For single-longitudinal mode (SLM) sources, the spectral width is defined as the full width of the largest spectral peak, measured 20 dB down from the maximum amplitude of the peak.

The maximum time-averaged spectral width is mainly used to guard against excessive chirp in directly modulated lasers. Such sources would primarily be intended for the low-dispersion applications (e.g., STM-4, and systems on G.653 fibre), but may also be used in some high-dispersion systems.

High dispersion systems (mainly STM-16, or -64 on G.652 fibre) will usually employ modulator sources. Particularly STM-64 systems on G.652 fibre operate near to or at the typical dispersion limit. Their source power spectra must therefore, by definition, be practically ideal. The maximum spectral width definition, although still valid, then becomes less useful, and the most important parameter for modulator sources instead becomes the chirp parameter.

6.2.1.2 Maximum spectral width for MLM sources

The maximum root mean square (RMS) width or the standard deviation σ (in nm) of the spectral distribution of a multi-longitudinal mode (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.

6.2.1.3 Chirp parameter

The source frequency chirp parameter (also known as the α-parameter) is defined as:

$$\alpha = \frac{\frac{d\varphi}{dt}}{\frac{1}{2P}\cdot\frac{dP}{dt}}$$

where φ is the optical phase of the signal, and *P* its power. It should be noted that with this definition, the chirp parameter is not constant during a pulse. Therefore, a pulse may have zero average chirp parameter value, but still not be chirp free.

A positive chirp parameter corresponds to a positive frequency shift (blueshift) during the rising edge of a pulse, and to a negative frequency shift (redshift) during the falling edge of the pulse. A modulator typically has a chirp parameter of –1 to +1 rad, whereas the turn-on transient of a standard laser may have a chirp factor of 10-100 rad.

Since several systems in this Recommendation operate at or near to the typical dispersion limit, their source spectra must be close to ideal. The frequency chirp specification is needed to control and describe the phase behaviour of the signal, which is hardly visible in the power spectrum defined by the other parameters.

The phase behaviour of the signal can be used to "peak" the performance of a system, e.g., by employing chirp induced pulse compression. It can also be used to modify the behaviour of power-induced non-linearities. This interaction is complicated, and the allowed ranges of this parameter may therefore vary with the application code and other system parameters.

A test method for source chirp is discussed in Appendix IV.

6.2.1.4 Side mode suppression ratio

The side mode suppression ratio (SMSR) is defined as the ratio of the largest peak of the total source spectrum to the second largest peak. The spectral resolution of the measurement shall be better (i.e., the optical filter bandwidth shall be less) than the maximum spectral width of the peak, as defined above. 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.

The SMSR specification is intended to minimize the occurrence of BER degradations due to mode partition noise (MPN). Since MPN is a transient effect with low probability, SMSR measurements on PRBS or continuous signals may underestimate the MPN. The SMSR specification is relevant only to SLM laser sources.

6.2.1.5 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.

6.2.2 Mean launched power

The mean launched power at point MPI-S is the average power of a pseudo-random data sequence coupled into the fibre by the transmitter. It is given as a range to allow for some cost optimization and to cover allowances for operation under the standard operating conditions, transmitter connector degradations, measurement tolerances, and ageing effects. These values allow the calculation of values for the sensitivity and overload point for the receiver at reference point MPI-R.

In the case of fault conditions in the transmit equipment, the launched power and maximum possible exposure time of personnel should be limited for optical fibre/laser safety considerations.

6.2.3 Extinction ratio

The minimum admitted value of the extinction ratio (EX) is defined as:

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

where A is the average optical power level at the centre of a logical "1", and B is the average optical power level at the centre of a logical "0". The convention adopted for optical logic levels is:

– emission of light for a logical "1";

– no emission for a logical "0".

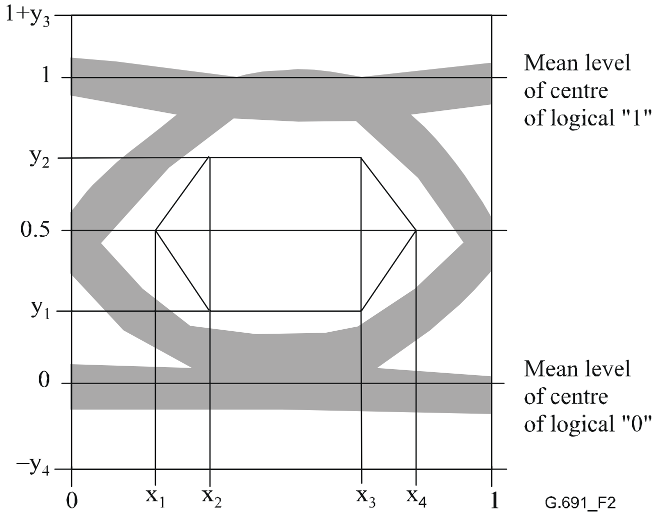
6.2.4 Eye pattern mask

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 2. Annex A considers further aspects of the eye mask definitions.

For systems employing dispersion accommodation techniques based on predistortion of the signal, the eye mask in the above sense can only be defined at points with undistorted signals. These points, however, do not coincide with the main path interfaces, and may thus not even be accessible. This definition is for further study.

For systems employing non-linear effects for dispersion accommodation (presently L-64.2b and V-64.2b), the eye mask may be different from the eye mask employed for linear systems.

Additionally, for systems that are subject to self phase modulation (SPM) due to high power output, a specification of the minimum rise time to avoid the SPM breakdown is required. The minimum rise time (10% to 90% value of the single pulse) for systems with transmitter power levels of +12 to +15 dBm has to be 30 ps. For lower power levels such as +10 to +13 dB this value and the interaction with the signal chirp is for further study.



	STM-4	**STM-16**	**STM-64 (a, c) (Notes 2, 3)**	**STM-64 (b) (Notes 2, 4)**
x_1/x_4	0.25/0.75	–	ffs	–
x_2/x_3	0.40/0.60	–	ffs	–
$x_3–x_2$	–	0.2	ffs	0.2
y_1/y_2	0.20/0.80	0.25/0.75	ffs	Δ + 0.25/Δ + 0.75 with Δ variable –0.25 < Δ < +0.25
y_3/y_4	0.20/0.20	0.25/0.25	ffs	0.25/0.25

NOTE 1 – In the case of STM-16 and STM-64, 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. The extent of this deviation is for further study. In view of the frequencies involved in STM-16 and STM-64 systems, and the consequent difficulties in making this filter (see Annex A), the parameter values for STM-16 and STM-64 may need slight revision in light of experience.

NOTE 2 – a, b and c refer to the dispersion accommodation techniques used for the applications in Tables 5c and 5d.

NOTE 3 – Includes L-64.2a, L-64.2c, and V-64.2a.

NOTE 4 – Includes L-64.2b, L-64.3, V-64.2b, and V-64.3.

Figure 2/G.691 – Mask of the eye diagram for the optical transmit signal

6.3 Optical path

To ensure system performance for each of the applications considered in Table 1, it is necessary to specify attenuation and dispersion characteristics of the optical path between points MPI-S and MPI-R.

6.3.1 Attenuation

In this Recommendation, the attenuation for each application is specified as a range, characteristic of the broad application distances indicated in Table 1. Attenuation specifications are assumed to be worst-case values including losses due to splices, connectors, optical attenuators (if used) or other passive optical devices, and any additional cable margin to cover allowances for:

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

6.3.2 Dispersion

6.3.2.1 Maximum chromatic dispersion

All systems considered in this Recommendation are dispersion sensitive. Some of the systems even operate beyond the "classic" limit for chromatic dispersion by means of certain compensation methods known as dispersion accommodation techniques, see 8.3. This parameter defines the maximum uncompensated value of the main path chromatic dispersion that the system shall be able to tolerate.

The required maximum dispersion tolerance of the systems is set to a value equal to the target distance times 20 ps/km × nm for G.652 fibre, and 3.3 ps/nm × km for G.653 fibre in the 1550 nm region, as well as for G.652 fibre in the 1310 nm region. This is considered a worst-case dispersion value 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 penalty for the optical path considers all deterministic effects due to chromatic dispersion as well as the penalty due to the average polarization mode dispersion (PMD). The statistical variations of the first and second order PMD are, however, not included in this path penalty, see 6.4.3 and Appendix I.

6.3.2.2 Minimum chromatic dispersion

Systems that employ any form of dispersion compensation through passive or active means may require a certain minimum dispersion to be present in the path.

The minimum chromatic dispersion value is the lowest dispersion value that the system is required to operate with. This does not preclude systems that can operate at even lower or zero dispersion. Since the exact operating wavelength of the system is unknown, the value is determined as the minimum value for G.652 fibre over the system operating wavelength region.

6.3.2.3 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 km, 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 1 dB.

Due to the statistical nature of 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 2.

Table 2/G.691 – 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}

6.3.3 Dispersion compensation

The typical dispersion limit for STM-64 systems operating on G.652 fibre is about 60 km when using an ideal (transform limited) source spectrum. Several systems in this Recommendation operate beyond that limit by means of certain techniques known as dispersion accommodation (DA) techniques. A DA technique is any method used to span longer distances on a certain fibre type than what is possible using an ideal intensity modulated signal. These methods are only used in STM-64 systems. More detailed descriptions of the DA techniques are contained in 8.3 and in the tutorial Appendices III to V.

6.3.4 Reflections

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. In this Recommendation, reflections from the optical path are controlled by specifying the:

- minimum optical return loss (ORL) of the cable plant at point MPI-S, including any connectors; and
- maximum discrete reflectance between points MPI-S and MPI-R.

Reflectance denotes the reflection from any single discrete reflection point, whereas the return loss is the total returned 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/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.

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 Tables 3 to 5, then connectors having better reflection performance must be employed. Alternatively, the number of connectors must be reduced. It may also 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 Tables 3 to 5 the value of –27 dB maximum discrete reflectance between points MPI-S and MPI-R 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.

6.4 Receiver

6.4.1 Sensitivity

Receiver sensitivity is defined as the minimum value of mean received power at point MPI-R to achieve a 1 × 10^{-12} BER. This must be met with a transmitter with worst-case values of transmitter eye mask, extinction ratio, optical return loss at point MPI-S, receiver connector degradations and measurement tolerances. The definition of receiver sensitivity under worst-case conditions is further discussed in Annex A.

The receiver sensitivity 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 – 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., G.783 for SDH optical tributary signals).

Ageing effects are not specified separately since they are typically negotiated between a network provider and an equipment manufacturer.

Typical margins between a beginning-of-life, nominal temperature receiver and its end-of-life, worst-case counterpart are desired to be in the 2 to 4 dB range. The receiver sensitivities specified in Tables 3 to 5 are worst-case, end-of-life values.

6.4.2 Overload

Receiver overload is the maximum acceptable value of the received average power at point MPI-R for a 1 × 10^{-12} BER.

6.4.3 Path penalty

The path penalty is the apparent reduction of receiver sensitivity 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}.

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 systems employing dispersion accommodation techniques based on predistortion of the signal at the transmitter, 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, the transmitter/receiver combination is required to tolerate an actual DGD of 0.3 bit period with a maximum sensitivity degradation of 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 a DGD of 0.1 bit period. 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.

Note that an SNR reduction due to optical amplification is not considered a path penalty.

6.4.4 Reflectance

Reflections from the receiver back to the cable plant are specified by the maximum permissible reflectance of the receiver measured at reference point MPI-R.

7 Optical parameter values

Optical parameter values for the applications of Table 1 are given in Tables 3 to 5. Definitions are given in clause 6. Some measurement methods are discussed in annexes and appendices. These tables do not preclude the use of systems that meet the requirements of more than one application code.

The terminal equipment can in principle be organized in different ways to meet the requirements of the main path. There are also different options that increase the flexibility of the basic application code, and which are indicated by notes.

Higher or lower power level ranges may be used to meet specific requirements such as upgradability, accommodation of higher losses, or countering optical non-linearities. Currently, these power levels are not specified in this Recommendation.

Currently the optical parameter values in this Recommendation are obtained without the application of in-band FEC according to ITU-T Rec. G.707/Y.1322.

Table 3/G.691 – Parameters specified for STM-4 optical interfaces

Application code (Table 1)	Unit	V-4.1	V-4.2	V-4.3	U-4.2	U-4.3
		(Note 1)	(Note 2)	(Note 2)	(Note 3)	(Note 3)
Transmitter at reference point MPI-S						
Operating wavelength range	nm	1290-1330	1530-1565	1530-1565	1530-1565	1530-1565
Mean launched power						
– maximum	dBm	4	4	4	15	15
– minimum	dBm	0	0	0	12	12
Spectral characteristics						
– maximum –20 dB width	nm	ffs	ffs	ffs	ffs	ffs
– chirp parameter, α	rad	NA	NA	NA	NA	NA
– maximum spectral power density	mW/ 10 MHz	ffs	ffs	ffs	ffs	ffs
– minimum SMSR	dB	ffs	ffs	ffs	ffs	ffs
Minimum EX	dB	10	10	10	10	10
Main optical path, MPI-S to MPI-R						
Attenuation range						
– maximum	dB	33	33	33	44	44
– minimum	dB	22	22	22	33	33
Chromatic dispersion						
– maximum	ps/nm	200	2400	400	3200	530
– minimum	ps/nm	NA	NA	NA	NA	NA
Maximum DGD	ps	480	480	480	480	480
Min ORL of cable plant at MPI-S, including any connectors	dB	24	24	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27	–27	–27	–27
Receiver at reference point MPI-R						
Minimum sensitivity (BER of 1×10^{-12})	dBm	–34	–34	–34	–34	–33
Minimum overload	dBm	–18	–18	–18	–18	–18
Maximum optical path penalty	dB	1	1	1	2	1
Maximum reflectance of receiver, measured at MPI-R	dB	–27	–27	–27	–27	–27

NOTE 1 – The target distance is only achieved with installed fibre loss including splices and cable margins less than or equal to 0.55 dB/km.

NOTE 2 – Under the assumptions given in 8.4, a G.957 transmitter and receiver together with a booster amplifier give similar system performance.

NOTE 3 – The optical preamplifier specified for, e.g., U-16.x or V-64.x systems may be used instead of an optical booster amplifier. That system may get a somewhat lower attenuation range.

Table 4/G.691 – Parameters specified for STM-16 optical interfaces

Application code (Table 1)	Unit	V-16.2	V-16.3	U-16.2	U-16.3
		(Notes 1, 2)	(Notes 1, 2)	Parameters given in G.959.1 as code P1U1-1A2	Parameters given in G.959.1 as code P1U1-1A3
Transmitter at reference point MPI-S					
Operating wavelength range	nm	1530-1565	1530-1565		
Mean launched power					
– maximum	dBm	13	13		
– minimum	dBm	10	10		
Spectral characteristics					
– maximum –20 dB width	nm	ffs	ffs		
– chirp parameter, α	rad	ffs	ffs		
– maximum spectral power density	mW/ 10 MHz	ffs	ffs		
– minimum SMSR	dB	ffs	ffs		
Minimum EX	dB	8.2	8.2		
Main optical path, MPI-S to MPI-R					
Attenuation range					
– maximum	dB	33	33		
– minimum	dB	22	22		
Chromatic dispersion					
– maximum	ps/nm	2400	400		
– minimum	ps/nm	NA	NA		
Maximum DGD	ps	120	120		
Min ORL of cable plant at MPI-S, including any connectors	dB	24	24		
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27		
Receiver at reference point MPI-R					
Minimum sensitivity (BER of 1×10^{-12})	dBm	–25	–24		
Minimum overload	dBm	–9	–9		
Maximum optical path penalty	dB	2	1		
Maximum reflectance of receiver, measured at MPI-R	dB	–27	–27		

NOTE 1 – The optical preamplifier specified for, e.g., U-16.x or V-64.x systems may be used instead of an optical booster amplifier. That system may get a somewhat lower attenuation range.

NOTE 2 – Under the assumptions given in 8.4, a G.957 transmitter and receiver together with a booster amplifier give similar system performance.

Table 5a/G.691 – Parameters specified for STM-64 optical interfaces

Application code (Table 1)	Unit	I-64.1r	I-64.1	I-64.2r	I-64.2	I-64.3	I-64.5
Transmitter at reference point MPI-S		Parameters given in G.693 as code VSR600-2R1	Parameters given in G.693 as code VSR2000-2R1	Parameters given in G.693 as code VSR2000-2L2	Parameters given in G.959.1 as code P1I1-2D2	Parameters given in G.959.1 as code P1I1-2D3	Parameters given in G.959.1 as code P1I1-2D5
Source type							
Operating wavelength range	nm						
Mean launched power							
– maximum	dBm						
– minimum	dBm						
Spectral characteristics							
– maximum RMS width (σ)	nm						
– maximum –20 dB width	nm						
– chirp parameter, α	rad						
– maximum spectral power density	mW/ 10 MHz						
– minimum SMSR	dB						
Minimum EX	dB						
Main optical path, MPI-S to MPI-R							
Attenuation range							
– maximum	dB						
– minimum	dB						
Chromatic dispersion							
– maximum	ps/nm						
– minimum	ps/nm						
Passive dispersion compensation							
– maximum	ps/nm						
– minimum	ps/nm						
Maximum DGD	ps						
Min ORL of cable plant at MPI-S, including any connectors	dB						
Maximum discrete reflectance between MPI-S and MPI-R	dB						
Receiver at reference point MPI-R							
Minimum sensitivity (BER of 1 × 10^{-12})	dBm						
Minimum overload	dBm						
Maximum optical path penalty	dB						
Maximum reflectance of receiver, measured at MPI-R	dB						

NOTE – All applications in this Recommendation use single-longitudinal mode (SLM) lasers as sources except the I-64.1r application that uses multi-longitudinal mode (MLM) lasers.

Table 5b/G.691 – Parameters specified for STM-64 optical interfaces

Application code (Table 1)	Unit	S-64.1	S-64.2a	S-64.2b	S-64.3a	S-64.3b	S-64.5a	S-64.5b
Transmitter at reference point MPI-S		Parameters given in G.959.1 as code P1S1-2D1	Parameters given in G.959.1 as code P1S1-2D2a	Parameters given in G.959.1 as code P1S1-2D2b	Parameters given in G.959.1 as code P1S1-2D3a	Parameters given in G.959.1 as code P1S1-2D3b	Parameters given in G.959.1 as code P1S1-2D5a	Parameters given in G.959.1 as code P1S1-2D5b
Operating wavelength range	nm							
Mean launched power								
– maximum	dBm							
– minimum	dBm							
Spectral characteristics								
– maximum –20 dB width	nm							
– chirp parameter, α	rad							
– maximum spectral power density	mW/ 10 MHz							
– minimum SMSR	dB							
Minimum EX	dB							
Main optical path, MPI-S to MPI-R								
Attenuation range								
– maximum	dB							
– minimum	dB							
Chromatic dispersion								
– maximum	ps/nm							
– minimum	ps/nm							
Passive dispersion compensation								
– maximum	ps/nm							
– minimum	ps/nm							
Maximum DGD	ps							
Min ORL of cable plant at MPI-S, including any connectors	dB							
Maximum discrete reflectance between MPI-S and MPI-R	dB							
Receiver at reference point MPI-R								
Minimum sensitivity (BER of 1×10^{-12})	dBm							
Minimum overload	dBm							
Maximum optical path penalty	dB							
Maximum reflectance of receiver, measured at MPI-R	dB							
NOTE – S-64.2a, 3a, and 5a have transmitter power levels appropriate for APD receivers; S-64.2b, 3b, and 5b have transmitter power levels appropriate for PIN receivers.								

Table 5c/G.691 – Parameters specified for STM-64 optical interfaces

Application code (Table 1)	Unit	L-64.1	L-64.2a	L-64.2b	L-64.2c	L-64.3
		Parameters given in G.959.1 as code P1L1-2D1	(Notes 1, 2)	(Note 1)	(Note 1)	
Transmitter at reference point MPI-S						
Operating wavelength range	nm		1530-1565	1530-1565	1530-1565	1530-1565
Mean launched power						
– maximum	dBm		+2	13	+2	13
– minimum	dBm		–2	10	–2	10
Spectral characteristics						
– maximum –20 dB width	nm		ffs	ffs	ffs	ffs
– chirp parameter, α	rad		ffs	ffs	ffs	ffs
– maximum spectral power density	mW/ 10MHz		ffs	ffs	ffs	ffs
– minimum SMSR	dB		ffs	ffs	ffs	ffs
Minimum EX	dB		10	8.2	10	8.2
Main optical path, MPI-S to MPI-R						
Attenuation range						
– maximum	dB		22	22	22	22
– minimum	dB		11	16	11	16
Chromatic dispersion						
– maximum	ps/nm		1600	1600	1600	260
– minimum	ps/nm		ffs	ffs	ffs	NA
Passive dispersion compensation						
– maximum	ps/nm		ffs	NA	NA	NA
– minimum	ps/nm		ffs	NA	NA	NA
Maximum DGD	ps		30	30	30	30
Min ORL of cable plant at MPI-S, including any connectors	dB		24	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB		–27	–27	–27	–27
Receiver at reference point MPI-R						
Minimum sensitivity (BER of 1 × 10^{-12})	dBm		–26	–14	–26	–13
Minimum overload	dBm		–9	–3	–9	–3
Maximum optical path penalty	dB		2	2	2	1
Maximum reflectance of receiver, measured at MPI-R	dB		–27	–27	–27	–27

NOTE 1 – L-64.2a uses PDC as DA, L-64.2b uses SPM as DA, and L-64.2c uses prechirp as DA.

NOTE 2 – See 8.3.2 on the values and placement of the PDC.

Table 5d/G.691 – Parameters specified for STM-64 optical interfaces

Application code (Table 1)	Unit	V-64.2a	V-64.2b	V-64.3
		(Notes 1, 2)	(Note 2)	
Transmitter at reference point MPI-S				
Operating wavelength range	nm	1530-1565	1530-1565	1530-1565
Mean launched power				
– maximum	dBm	13	15	13
– minimum	dBm	10	12	10
Spectral characteristics				
– maximum –20 dB width	nm	ffs	ffs	ffs
– chirp parameter, α	rad	ffs	ffs	ffs
– maximum spectral power density	mW/ 10 MHz	ffs	ffs	ffs
– minimum SMSR	dB	ffs	ffs	ffs
Minimum EX	dB	10	8.2	8.2
Main optical path, MPI-S to MPI-R				
Attenuation range				
– maximum	dB	33	33	33
– minimum	dB	22	22	22
Chromatic dispersion				
– maximum	ps/nm	2400	2400	400
– minimum	ps/nm	ffs	ffs	NA
Passive dispersion compensation				
– maximum	ps/nm	ffs	ffs	NA
– minimum	ps/nm	ffs	ffs	NA
Maximum DGD	ps	30	30	30
Min ORL of cable plant at MPI-S, including any connectors	dB	24	24	24
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27	–27
Receiver at reference point MPI-R				
Minimum sensitivity (BER of 1×10^{-12})	dBm	–25	–23	–24
Minimum overload	dBm	–9	–7	–9
Maximum optical path penalty	dBm	2	2	1
Maximum reflectance of receiver, measured at MPI-R	dB	–27	–27	–27

NOTE 1 – See 8.3.2 on the values and placement of the PDC.

NOTE 2 – V-64.2a uses PDC as DA and V-64.2b uses a combination of SPM and PDC as DA.

8 Optical engineering approach

8.1 Design assumptions

This clause discusses the design aspects introduced in this Recommendation due to, e.g., optical amplifiers and dispersion accommodation. A general discussion on worst-case and statistical design approaches can be found in ITU-T Rec. G.957.

8.2 Non-linearities

Due to the introduction of optical amplifiers, sufficiently high optical powers may be used that significant effects due to optical non-linearities may be encountered. A detailed discussion of these non-linearities can be found in ITU-T Rec. G.663.

8.3 Dispersion accommodation

The typical dispersion limit for STM-64 systems operating on G.652 fibre is about 60 km when using an ideal (transform limited) source spectrum. Several systems in this Recommendation operate beyond that limit by means of certain techniques known as dispersion accommodation (DA) techniques. A DA technique is any method used to span longer distances on a certain fibre type than is possible using an ideal intensity modulated signal. These methods are only used in STM-64 systems.

Presently, this Recommendation includes DA by passive dispersion compensation (PDC), self phase modulation (SPM), prechirp (PCH), and dispersion supported transmission (DST). The preferred choice of method is for further study.

8.3.1 Design principle

Dispersion accommodation is required above 50-60 km of G.652 fibre at STM-64 data rates. The S-64.2 systems are below this limit and do not employ any DA. For the L-64.2 systems, some form of DA is applied to compensate the additional dispersion incurred in the 40-80 km range. This DA may be of different forms.

Both active and passive DA methods are employed for the L-64.2 systems. The passive method uses a PDC to compensate the inherent dispersion of the fibre. The active methods (SPM, PCH, and DST) instead tailor the interface parameters in such a way that the dispersion is balanced out. For the V-64.2 systems, additional passive DA is added to compensate for the extra 40 km of fibre.

In practice, all presently proposed DA schemes compensate the dispersion over a more restricted range than from zero to full link length. These systems may depend on some minimum dispersion to be present in the link. The parameter "minimum chromatic dispersion" has therefore been introduced. When testing DA systems back to back, it may, for some systems, be necessary to introduce a minimum dispersion in the test set-up. This is analogous to the use of attenuators in order not to overload a receiver during back-to-back testing.

All methods are required to be transverse compatible within their application code. However, until the spectral characteristics and measurement methods have been defined, transversal compatibility cannot be guaranteed. The transverse compatibility between different DA methods is for further study.

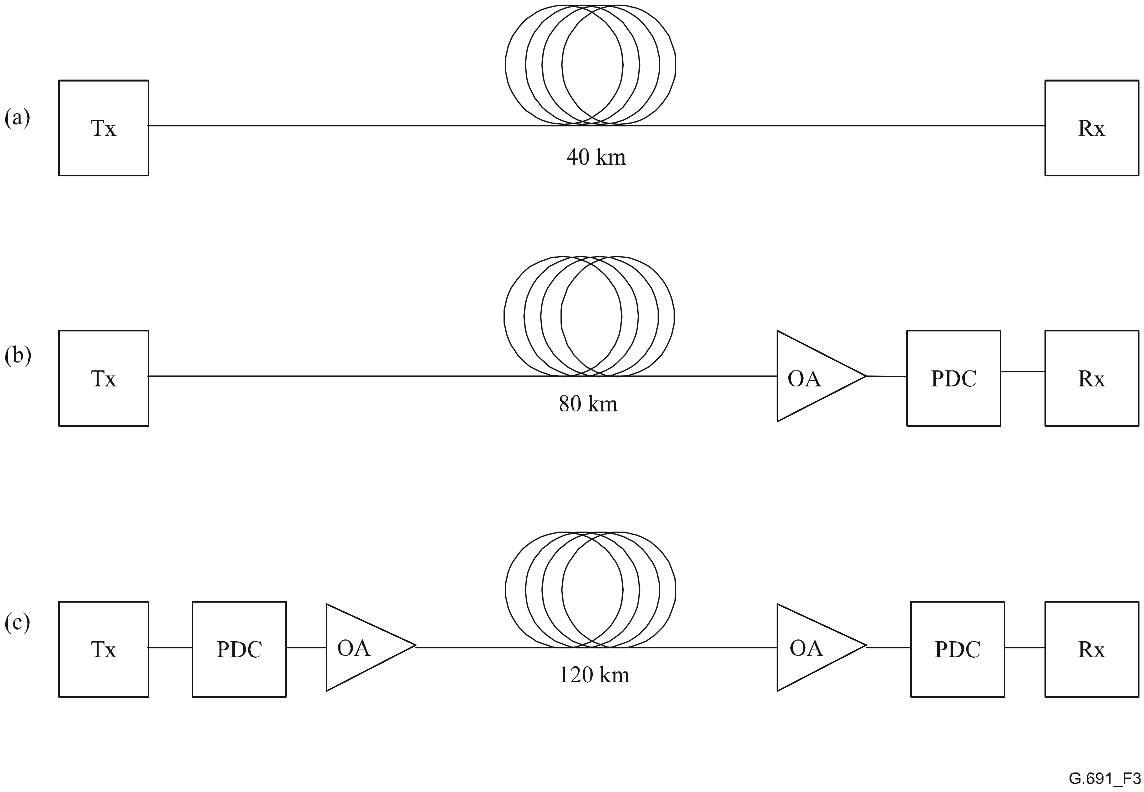
8.3.2 Passive dispersion compensation

One method to overcome the dispersion limit is to add a passive dispersion compensator (PDC) to the transmitter, the receiver, or both. This Recommendation is intended to cover all types of passive dispersion compensators.

It is assumed that the PDC is not inserted into the main path since the insertion loss of the device (presently several dBs) would decrease the system attenuation range. Instead, the PDC is normally added before an optical power amplifier or after an optical preamplifier. The gain of the amplifiers is used to compensate for the insertion loss of the PDC without detracting from the system power budget.

This description does not imply any particular integration level of the transmitter or receiver, i.e., they can be realized as either stand-alone devices or as integrated, optically amplified, transmitters or receivers.

The guiding principle for the use of PDCs in STM-64 systems is that the S-systems at 40 km are designed without DA. For each longer application code, i.e., L-64.2 and V-64.2, a PDC for each additional 40 km is added, see Figure 3. The nominal dispersion value for each PDC then becomes –680 ps/nm at 1550 nm. The exact value, and whether the PDC should create an over- or under-compensation, is for further study. In theory, the PDC for an L-64.2 system would only need to compensate for the difference between the target distance and the typical dispersion limit. However, that would lead to small operating margins, and the present approach also facilitates the use of identical equipment building blocks that are used in all systems. PDCs are specified in ITU-T Rec. G.671.



NOTE – The values and placement of the PDC are for further study.

Figure 3/G.691 – Scheme for passive dispersion compensation for systems without line amplifiers

If a PDC is used at the transmitter side, the PDC creates a predistortion of the signal before it is sent out on the optical path. The transmitter eye diagrams specified in 6.2.4 are then not available at point MPI-S. If the non-distorted signal is available, the eye diagrams specifications are valid at that point. The MPI-S eye diagram specification for predistorted systems is for further study.

Since the use of a PDC at the transmitter side implies the use of an optical booster amplifier to compensate for the loss of the PDC, the power levels will be high enough to generate SPM and possibly other non-linear effects in the signal. The PDC is, however, a linear dispersion compensator, and the non-linear distortion of the transmitted signal may degrade the linear dispersion compensation if applied at the transmitter.

For the L-64.2 system, the specified placement of the PDC is therefore at the receiver. This will lead to the use of an optical preamplifier and a non-amplified transmitter, and give a system that does not operate in the non-linear regime.

For the V-64.2 system, where the use of a booster amplifier is necessary, further actions may have to be taken to ascertain that the non-linear effects do not excessively degrade the linear dispersion compensation if it is placed at the transmitter side. This is for further study.

If a PDC is located in the fibre plant, it is considered to belong to the path, and it will typically then "convert" a G.652 path to a G.653-like path if the transmit power level is lower than approximately +10 dBm, and the behaviour of the optical path is linear. The system itself is then considered to be a X-xx.3 system, and the system requirements with regard to path attenuation and dispersion are given by the X-xx.3 application codes. Partial compensation of a path is considered as joint engineering and is not treated in this Recommendation.

8.3.3 Self phase modulation

Self phase modulation (SPM) uses the non-linear Kerr effect in the G.652 fibre to obtain a pulse compression that increases the transmission distance. A tutorial description of the technique is given in Appendix II.

Since this technique requires the power level of the signal to be in the non-linear regime of the fibre, the SPM dispersion compensation effect is caused by the transmitted power and occurs in the transmission fibre close to the transmitter, as long as the signal power is above the non-linearity threshold. When the signal has propagated on the order of 15-40 km (with the power levels used in the L- and V-64.2 systems), it has been attenuated so that it is no longer in the non-linear regime. The rest of the propagation is therefore linear. This gives the possibility to combine SPM on the transmitter side with a PDC on the receiver side.

The pulse propagation is also influenced by the frequency chirping of the pulse, which can also be used for pulse compression. It is therefore necessary to specify the chirp parameter. In order not to overcompensate for the dispersion, the chirping parameter should be close to zero when using SPM.

The non-linear phase modulation depends also on the pulse shape. This may lead to different eye masks for systems employing SPM as compared to the linear systems. This is for further study.

8.3.4 Prechirp

Another method uses prechirp in the transmitter to obtain a pulse compression effect, and thereby increase the transmission distance. However, the use of a high-power transmitter in this case would give rise to both prechirp and SPM at the same time. This combination would lead to an overcompensation of the system for the L-64 application code.

The prechirp scheme is therefore used with a low power transmitter and an optically preamplified receiver. This will, however, lead to required transmitter power levels of –1 dBm, which may presently not be easy to achieve with all transmitter types. The transmitter and receiver interface parameters for this application code are for further study.

8.3.5 Combinations of techniques

The only combination of DA techniques presently specified is to use SPM together with a PDC in a V-64.2 system. The SPM is used to accommodate the dispersion for the first 80 km, as in the basic L-64.2b SPM based system, and the added 40 km are fully compensated by a PDC. This latter compensation occurs in the linear regime, and should therefore not be influenced by the non-linear technique employed for the initial part of the link.

In a similar way a DST system designed for an 80 km target distance (DST L-64.2) can be combined with a PDC in a V-64.2 system if the added 40 km are fully compensated by a PDC.

8.3.6 Dispersion supported transmission

A further method, dispersion supported transmission (DST), uses a combination of intensity and frequency modulation instead of intensity modulation to counter the dispersion. A tutorial description and a specification for the DST method, as applied to L-64.2 and V-64.2 systems, are given in Appendix III.

8.4 Stand-alone amplifiers

A stand-alone amplifier (optical amplifier device) can be used for new installations or as an upgrade path. In either case, a stand-alone booster- or pre-amplifier interfaces the main path, as specified in this Recommendation, on one side, and a non-amplified (selected G.957, S-64.x, etc.) system on the other side. Since the purpose of the stand-alone amplifier is to increase the transmission distance, the system integrator must ascertain that the properties of the interfaced, non-amplified, system are such that it can indeed operate over the extended distance. This may require wavelength ranges and spectral characteristics as suggested in 6.1/G.957 and 6.2.2/G.957, and additional parameter values in accordance with this Recommendation.

If the original system does not possess the properties necessary for operation over longer distances, the stand-alone amplifier functionality can be extended to adapt these parameters to become compatible with this Recommendation. It may, for example, implement some dispersion accommodation technique as described in 8.3, or it may use a transponder for spectral conversion.

The supervision of stand-alone booster- and/or pre-amplifiers can be accomplished through an electrical interface to the SDH equipment or through direct access to the management system.

8.5 Upgradability considerations

Transmission-capacity requirements of the systems covered by this Recommendation are expected to increase in the near future. Upgradability would be a key to cope with this evolution.

The term "upgrade" means any equipment change intended to achieve increased performance that does not require new fibres or buildings. Most upgrades require equipment replacement in which case the upgrade is, by definition, out of service. Protection switching may, however, be used to keep the system operating while specific parts of the systems are out of service. System performance is generally not sacrificed for upgradability.

Forward error correction (FEC) can provide both improvement of the BER and additional system margin. For SDH systems treated in this Recommendation only in-band FEC is applicable according to ITU-T Rec. G.707/Y.1322. However, the optical parameter values specified for the application codes are applicable when the FEC is disabled. Possible modification to the optical parameter values when FEC is enabled is for further study.

Various types of upgrades are categorized in 8.5.1 followed by upgrade guidelines in 8.5.2.

8.5.1 Types of upgrades

8.5.1.1 Upgrades to longer distances

In general, upgrades to longer distances are equal to "equipment reuse or replacement" since longer distances require larger attenuation spans and tighter tolerances on, e.g., spectral properties.

8.5.1.2 Upgrades to higher bit rates

Capacity expansion by going to a higher bit rate also means equipment replacement and would lead to service interruption if no additional measures are taken (e.g., protection switching). Within a wavelength band the target distances for inter-office systems are in equal steps in each wavelength band (40 km for the 1550 nm band and 20 km for the 1310 nm band).

Appendix V provides additional information on upgrades to higher bit rate systems.

8.5.1.3 Upgrades from single- to multichannel systems

An upgrade from a single-channel to a multichannel system is an out-of-service, equipment-reuse type of upgrade. If an in-service capacity expansion is required, a multichannel system should be employed from the beginning.

8.5.1.4 Upgrades using stand-alone optical amplifiers

When using a stand-alone amplifier for upgrade purposes, the same considerations as in 8.4 apply.

8.5.2 Guidelines of upgrades

Reserving upgradabilities of single-channel systems and of multichannel systems with no line amplifiers may not be advantageous because the optically amplified transmitter and optically amplified receiver have to be significantly modified or even renewed for a bit rate upgrade, while just the fibres are reused.

Reserving upgradabilities from single-channel systems to multichannel systems may not be advantageous. This is because their design philosophies are very different from many viewpoints including fibre-amplifier design and control, power budget and, from the considerations of dispersion, fibre non-linearity and signal-to-noise ratios.

8.6 Optical safety considerations

See ITU-T Rec. G.664 for optical safety considerations.

Annex A

Extinction ratio and eye mask penalties

A.1 Measurement parameters

The eye mask measurement specification is grouped in two parts; one for STM-4 and STM-16 interfaces, and one for the STM-64 interfaces.

i) For STM-4/STM-16, an eye mask measurement procedure and reference receiver such as is outlined in Annex B/G.957 is assumed, i.e., a fourth order Bessel-Thomson filter with the appropriate cut-off frequencies for the bit rate in question. The tolerance values of this reference receiver are given in Table A.1.

ii) For STM-64, an eye mask measurement procedure and optical reference receiver such as is outlined in Annex B/G.957 is assumed also, i.e., a fourth order Bessel-Thomson filter with the appropriate cut-off frequencies for the STM-64. For this rate, however, the optical reference receiver function is defined as the total frequency response of any combination of photodetector, low-pass filter and oscilloscope functional elements, together with any interconnection of those elements. The tolerance values of this transfer function are given in the last column (STM-64) of Table A.1.

Table A.1/G.691 – Tolerance values of the attenuation of the optical reference receiver

f/f_r	Δa [dB]		
	STM-4	STM-16	STM-64
0.001 to 1	±0.3	±0.5	±0.85
1 to 2 (Note)	±0.3 to ±2.0	±0.5 to ±3.0	±0.85 to ±4.0
NOTE – Intermediate values of Δa should be interpolated linearly on a logarithmic frequency scale.			

Figure A.1 illustrates the penalties that may be incurred from eye mask and extinction ratio (EX) imperfections. In the figure, the EX is the ratio a/b, and the relative eye opening is the ratio d/c. Ideally, the EX is infinite, and the eye is completely open and symmetric. The entire optical power is then available for modulation, and the EX and eye mask penalties are 0 dB.

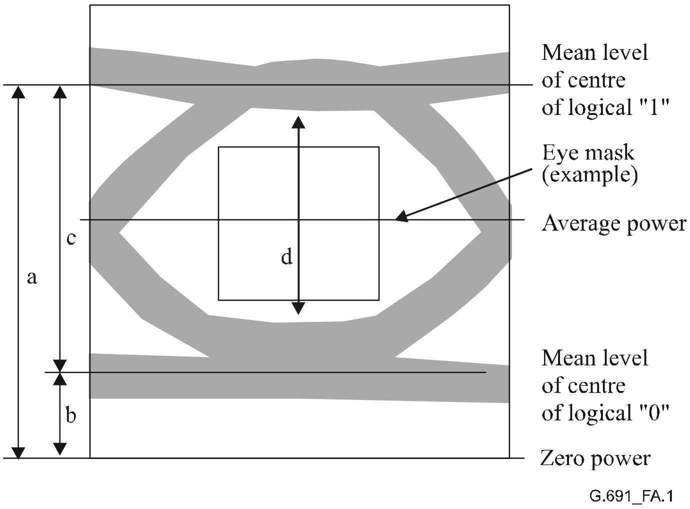


Figure A.1/G.691 – Eye mask and extinction ratio penalties

A.2 Extinction ratio penalty

The extinction ratio leads to some fraction of the optical power not being available for modulation, it corresponds to a receiver sensitivity penalty. The exact penalty depends on the application and the chosen receiver implementation.

A.3 Eye mask penalty

In addition to the limited EX, the eye may be closed from its average "0" and "1" levels due to transient signal imperfections such as rise and fall times, overshoot, etc. If the relative eye opening d/c is less than one, a penalty is incurred. The eye mask penalty, P_{EM} can be written as:

$$P_{EM} = 10\log_{10}\left(\frac{d}{c}\right) \quad [dB]$$

which corresponds to the loss in receiver sensitivity compared to a signal with completely open eye.

Since the BER is an extremely steep function of the signal, a single imperfection can determine the entire BER. It is therefore the innermost lines in the eye (the open eye) that determine the BER. Even lines that are so rare that they are not easily visualized in an eye mask measurement (due to a limited measurement time) can have profound effects on the BER.

The present eye mask allows for an eye closure of up to 50% of the eye opening. The actual system penalty associated with this eye closure depends upon the implementation of the system. In a given situation, the eye mask penalty can be reasonably well estimated as the relative (vertical) eye opening at the decision point of the receiver.

To evaluate the eye mask penalty, the eye mask measurement filter and measurement procedure should correspond to the used receiver behaviour. Since this is not specified in detail, the eye mask penalty is not a precise receiver penalty. However, the correspondence is usually quite good since most receiver designs are reasonably similar to the filter used in the eye mask measurement procedure.

A.4 Receiver sensitivity

Extinction ratio penalty and eye mask penalty are additive in dB. For example, if the EX penalty is 1.3 dB, and the eye mask penalty is 3 dB, the worst-case signal will show a sensitivity of 4.3 dB less than when using an ideal transmitter.

According to the definition of the receiver sensitivity, it should be measured under worst-case conditions. If this is not done, a correction for the receiver sensitivity due to a measurement under too benign conditions can be estimated from the EX and relative eye opening of the test transmitter. This estimation may be preferred to testing with a strict worst-case signal, which may be difficult to generate.

Appendix I

Polarization mode dispersion

I.1 The statistical distribution of PMD

As described in 6.3.2.3, the differential group delay (DGD) between the polarization states in a non-polarization preserving fibre is a random variable. It is often assumed to have a Maxwellian distribution with the following probability density function:

$$f(\Delta\tau) = 32 \frac{\Delta\tau^2}{\pi^2 < \Delta\tau >^3} \exp\left(\frac{4\Delta\tau^2}{\pi < \Delta\tau >^2} \right)$$

where $\Delta\tau$ is the DGD, $< \Delta\tau >$ is the mean DGD. Figure I.1 shows the probability density function $f(\Delta\tau)$. At a given instant, however, the system will experience a specific DGD, τ, that is some realization of the random distribution of DGD values, with the average given by the PMD of the link. A pulse train may thus suffer from a delay difference that is smaller or larger than the average PMD of the link.

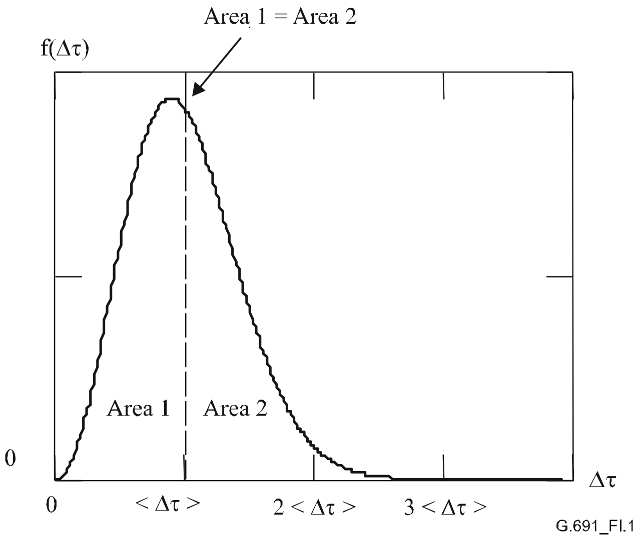


Figure I.1/G.691 – The Maxwellian distribution function (illustration) – Probability density function *f*(Δτ) vs differential group delay, Δτ

Integrating this probability density function from $\Delta\tau_1$ to + ∞ gives the probability $P(\Delta\tau \geq \Delta\tau_1)$:

$$P(\Delta\tau \geq \Delta\tau_1) = \int_{\Delta\tau_1}^{\infty} f(\Delta\tau)d(\Delta\tau)$$

This probability $P(\Delta\tau \geq \Delta\tau_1)$ is depicted in Figure I.2.

For example, if DGD is greater than 3 times the mean of DGD, $\Delta\tau_1 = 3 <\Delta\tau>$, then it can be read from Figure I.2 that $P(\Delta\tau \geq 3 < \Delta\tau >) \approx 4 \times 10^{-5}$.

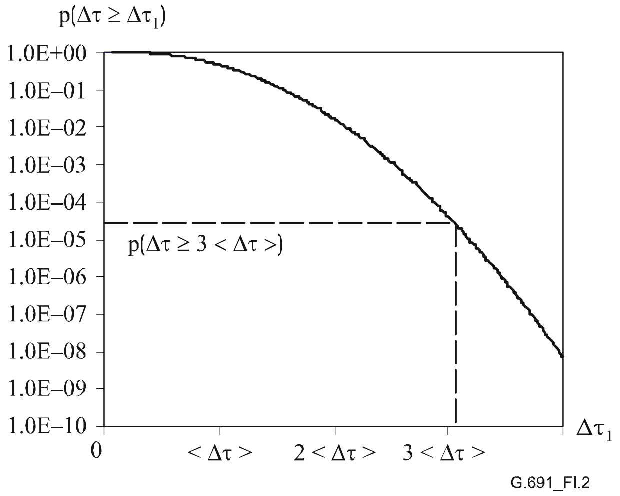


Figure I.2/G.691 – Probability $P(\Delta\tau \geq \Delta\tau_1)$

The DGD variations depend on the polarization states excited in the fibre, the strain in different parts of the fibre, temperature variations, etc., and are thus rather slowly varying. Assuming that it takes about a day for the DGD to change significantly, the above probability corresponds to a period of about 70 years between instances when the PMD rises to three times its average value.

The characteristic time of the PMD variations are, however, strongly influenced by the fibre environment, and, e.g., aerial cables may have shorter variation times. If the characteristic time is instead assumed to be one minute, the PMD will rise to three times its average about once every 17 days.

The "outage time", during which the path penalty due to PMD is high, will also be on the order of the characteristic time, i.e., one day, and one minute, respectively, in the above two examples.

I.2 The path penalty due to PMD

Since PMD is a fibre property, it cannot be specified in this Recommendation. Instead, the amount of total PMD in the link corresponding to a worst-case path penalty of 1 dB is considered. The worst case is based on a DGD of 0.3 bit period in conjunction with the assumption that both principal states of polarization (PSP) carry the same optical power.

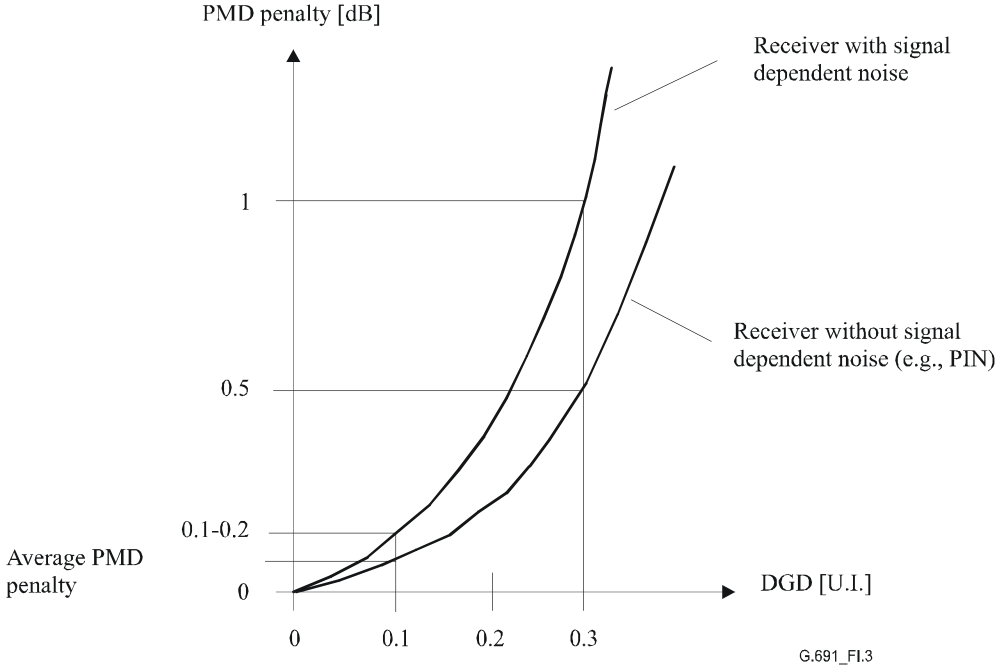


Figure I.3/G.691 – The dependence of the receiver penalty on the actual DGD (illustration)

A Maxwellian distribution function is assumed for the DGD (see Figure I.1). The connection between the DGD (being in direct coincidence with the PMD-induced signal pulse width broadening if the same optical power in both PSPs is assumed) and the corresponding path penalty, is a receiver characteristic, and is illustrated in Figure I.3. With realistic assumptions and a well-designed receiver, it can be deduced that an actual DGD of 0.3 bit period (and 50% of optical power in both PSPs) will give a penalty of about 0.5 dB for a receiver with signal independent noise (PIN-receiver), and up to 1 dB for a receiver with signal dependent noise (APD or preamplifier).

The corresponding allowable maximum PMD of the fibre depends on several items including:

- the statistical distribution of the DGD;
- the tolerable probability that the penalty may exceed 0.5 dB (PIN) or 1 dB (e.g., APD);
- the correlation between the spatial fluctuations of the PSPs and the fluctuations of the DGD;
- the orientation of the input state of polarization (SOP) of the light emitted by the laser transmitter, relative to the orientation of the PSPs.

A realistic correlation between the allowable maximum PMD and the maximum signal pulse width broadening is for further study. A first estimation can be deduced by the following illustrative example: A maximum PMD of 0.1 bit period indicates a probability of 4×10^{-5} for a path penalty of larger than 1 dB (see Figures I.2 and I.3). However, it is expected to have a much smaller probability than 4×10^{-5} for >1 dB path penalty in this example because of the following reason: when the DGD is changed (e.g., by strain or temperature variation) then, in general, the spatial orientation of the PSPs is changed as well. Consequently, the orientation of the input SOP of laser transmitter light relative to the orientation of the PSPs will alter. Therefore, the spatially fluctuating PSPs will usually not carry the same optical power resulting in a smaller penalty at the receiver (because the probability of 4×10^{-5} only holds for the assumption of equal power in both PSPs). Inversely, it is likely that a tolerable probability of 4×10^{-5} for >1 dB path penalty will allow a maximum PMD which is larger than 0.1 bit period.

Appendix II

Description of SPM as dispersion accommodation

II.1 SPM basics

When using high power transmitters, as in unrepeated long-haul transmission systems, non-linear effects such as self phase modulation (SPM) play an important role in the transmission quality. In intensity modulated systems, a modulation of the refractive index of the optical fibre is introduced at high transmitter powers, giving rise to different refractive indices in a "1", as compared to a "0" in the bits. The modulation of the refractive index by the changing power levels is referred to as the Kerr effect.

The optical intensity variation of a given pulse modulates the refractive index of the fibre which in turn leads to a modulation of the phase of the optical wave. This is the process known as SPM. The time derivative of phase is frequency, and the optical signal will experience an asymmetrical frequency deviation from its midpoint so that the spectral components at the rising edge of the pulse experience a downward frequency shift, a red shift, whilst the spectral components at the falling edge of the pulse experience an upward frequency shift, a blue shift.

In G.652 fibre at 1550 nm, red shifted components travel slower whilst blue shifted components travel faster relative to one another. The propagation speed of the spectral components towards the back of the pulse is therefore faster than that of the spectral components at the front. This will lead to a reduced net chromatic dispersion effect, or pulse compression, and will delay the onset of the chromatic dispersion induced transmission span limitation.

The maximum phase shift introduced by SPM is proportional to the optical power launched by the transmitter, and inversely proportional to the attenuation coefficient and the effective core area of the transmission fibre.

II.2 Using self phase modulation as a dispersion accommodation technique

The pulse compression obtained by SPM counteract the pulse broadening caused by the fibre dispersion. Therefore SPM can be used as a dispersion accommodation (DA) technique. The SPM used as a dispersion accommodation technique depends on the following parameters: transmitter output power, fibre attenuation coefficient, fibre core area, fibre non-linear index, transmitter wavelength, transmitter prechirp, and fibre chromatic dispersion.

In 10 Gbit/s systems with a target distance of 80 km and with non-dispersion shifted fibres, SPM can be used as a dispersion accommodation technique with transmitter output powers up to +17 dBm, and with dispersion shifted fibres up to +13 dBm with a penalty of less than 1.5 dB.

II.3 SPM-breakdown

There is an upper limit for the transmitter output power. This limit is given by the SPM-breakdown. The SPM-breakdown power level is defined as the transmitter power for which the leading edge and the trailing edge of the pulse coincide. If the transmitter power is increased above the SPM-breakdown level, it will lead to a dramatic penalty increase.

The dominating parameters in determining the SPM-breakdown power level are the rise and fall times, and the extinction ratio. Both parameters are used to control the time derivative of the optical power and thus the SPM. The other parameters (e.g., fibre attenuation coefficient, fibre effective core area, etc.) have a minor influence on the SPM-breakdown power level compared to these parameters.

II.4 Optical parameter values for applications

Following the principle of SPM for STM-64 systems, a more precise description of the spectral behaviour than the pure spectral width value of the transmitted optical signal is in principle required. The most important additional parameter is the source chirp, mostly described as the α-parameter in case of directly modulated sources. It has to be noted, that if this value is specified, it has to be done not only for small signal operation, but for large signal operation in the non-linear optical regime of the fibres as well.

There are measurement methods for this parameter. However, the simplest method is to measure the transmission behaviour in conjunction with the related optical path. That means, in principle it is not really necessary to specify this parameter, but to specify a table where the receiver and transmitter values have to be considered together with the path. That means the transmitter spectral behaviour is defined indirectly in conjunction with receiver sensitivity and path characteristics, in this case namely dispersion and attenuation.

II.5 Source type

The optical source type for 10 Gbit/s L- and V-type, intensity modulated, signals can normally be an indirectly modulated laser, where both Mach-Zehnder or electro-absorption modulator implementations can be used. Integrated with the optical transmitter, a booster amplifier is normally used to achieve the necessary transmitter power levels. However, the implementations are not subject to be standardized, and the only relevant values are those specified in Tables 4 and 5. In addition to these values, the definition of the eye mask is necessary in order to achieve transverse compatibility.

II.6 Eye pattern mask

The general transmitter pulse shape characteristic including rise- and fall-times, and pulse over- and under-shoot, which should be controlled in order to prevent degradation, should be specified in form of an eye mask. This eye mask is valid at the reference point MPI-S.

II.7 Receiver

For these systems implementing an intensity modulation scheme, direct detection receiver implementations can be used. However, the implementation is not subject to standardization. The required sensitivity and reflectance values are given in Tables 4 and 5.

Appendix III

Dispersion accommodation by means of DST

III.1 Introduction

Dispersion supported transmission (DST) is an active dispersion accommodation (DA) technique. The transmitter generates an optical signal that includes a suitable optical frequency modulation. The chromatic dispersion of transmission fibre is used to convert the optical frequency modulation into an intensity modulation at the receiver. Using this effect, transmission beyond the typical dispersion limit (for conventional ASK modulation with ideal transform limited source spectrum) is possible. This appendix considers a tutorial description of the DST technique and DST system parameters and values.

III.2 Principle of the DST technique

The optical transmitter generates an optical FSK/ASK (or a pure optical FSK) output signal in the new transmission scheme. The dispersive fibre is used to convert the FSK signal part at transmitter side into an ASK signal part at the receiver side. The full ASK signal is then detected by the optical receiver.

By the incoming binary signal the optical frequency ν is switched between two values with the frequency shift $\Delta\nu$, corresponding to the wavelength shift: $\Delta\lambda = \Delta\nu\lambda^2/c$. Owing to the fibre dispersion, the different signal components with different wavelengths arrive at different times at the output of the fibre of length L. The time difference $\Delta\tau$ is given by $\Delta\tau = \Delta\lambda D\ L$. On the receiver side a 4- (or 3-) level signal is generated. The original signal can be recovered by:

a) a low-pass filter and a decision circuit with single threshold; or

b) a dual-threshold detection with threshold P_1 and P_0 and memory.

In Figure III.1, the principle of "dispersion supported transmission" is shown for transmitter signals a) and receiver signals b), where I indicates the transmitter driving signal, ν the optical frequency, P_{opt} the optical input power, V_{LP} the voltage at low-pass filter (LP) output and V_{dec} the voltage at the decision circuit output.

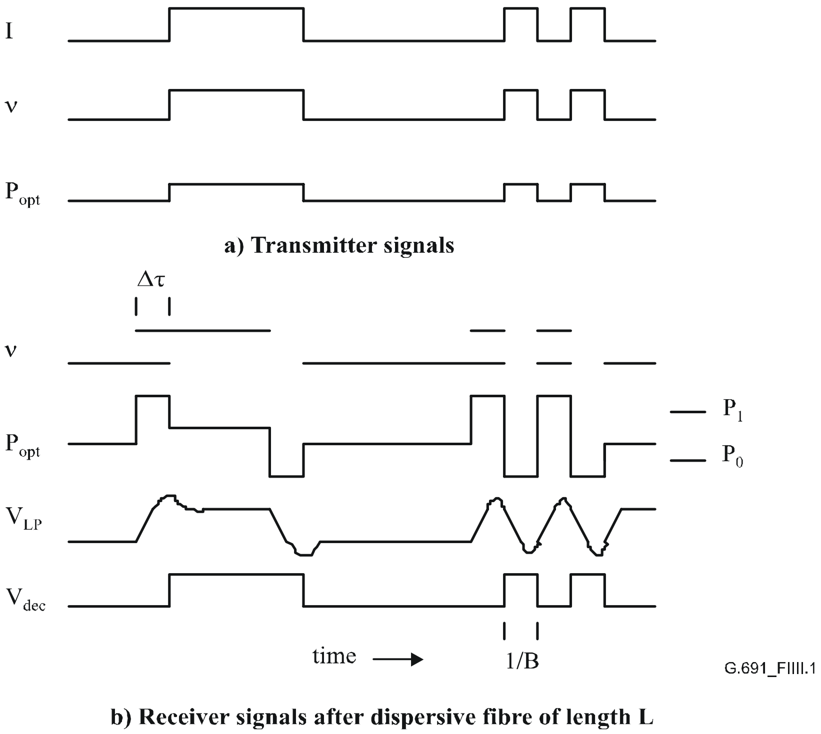
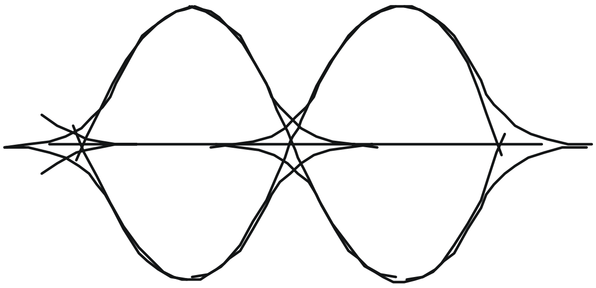


Figure III.1/G.691 – Principle of dispersion supported transmission; optical FSK/ASK transmission

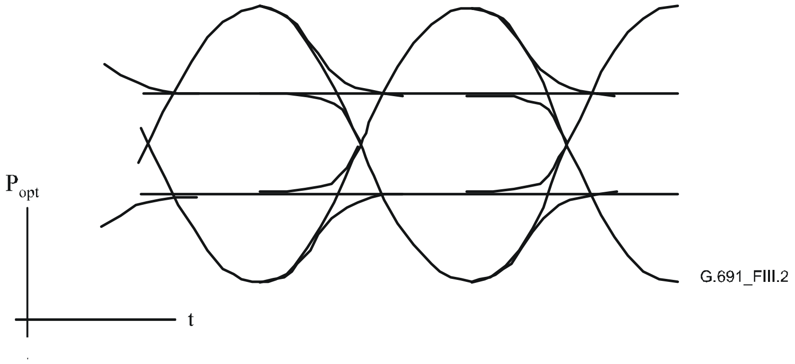
The principle of DST can also be described using a small signal analysis in the frequency domain: the adiabatic chirping (optical frequency modulation) of the transmitted optical signal in combination with the effect of the chromatic dispersion of the fibre leads to a high-pass-like transfer characteristic for low frequencies. This response can be equalized in the electrical domain by, e.g., using a low-pass filter ("DST-filter") in the receiver.

III.3 Optical receiver eye pattern mask after dispersive fibre transmission

In contrast to a 2-level receiver eye diagram of a pure optical ASK signal, a pure optical FSK signal shows a 3-level receiver eye diagram and a joint FSK/ASK signal shows a 4-level receiver eye diagram after dispersive fibre transmission as indicated in Figure III.2 a) and b), respectively.



a) Pure optical FSK signal of transmitter



b) For joint optical FSK/ASK signal of transmitter

Figure III.2/G.691 – Receiver eye diagrams after dispersive fibre

III.4 Parameter definitions

Only parameters with definitions unique to DST, or otherwise requiring comments, are defined here. Other parameters are defined in clause 6, and are fully applicable to the DST method if no other definition is given in this subclause.

III.4.1 Transmitter at reference point MPI-S

III.4.1.1 Frequency deviation

The frequency deviation is used to ensure that the transmit signal has the appropriate amount of optical frequency modulation for the transmission range in question.

The frequency deviation $\Delta\nu$ of the transmitted optical signal at reference point MPI-S is defined by $\Delta\nu = \nu_1 - \nu_{\tilde{0}}$, where ν_1 is the optical frequency ν during transmission of a signal representing a logical "1" symbol (also corresponding to a high optical power level), and $\nu_{\tilde{0}}$ is the optical frequency during transmission of a signal representing a logical "0" symbol (also corresponding to a low optical power level).

III.4.1.1.1 Measurement method

The measurement set-up described in Appendix IV can be applied. The variables $V^+(t)$ and $V^-(t)$ are evaluated as described in Appendix IV. The time resolved frequency chirping ν_c (t) = ν (t) – ν_r is given by:

$$\nu_c(t) = (2\pi)^{-1} FSR \arcsin\left(\frac{V^-(t)}{V^+(t)}\right)$$

ν_c (t) is calculated and plotted together with P(t), compare with Figure IV.4.

$\nu_1 - \nu_r$ is evaluated from ν_c (t) in the middle of the third bit of the A1 byte (11110110).

$\nu_{\tilde{0}} - \nu_r$ is evaluated from ν_c (t) in the middle of the last bit of the A2 byte (00101000).

The frequency deviation is evaluated from $\Delta\nu = \nu_1 - \nu_{\tilde{0}} = (\nu_1 - \nu_r) - (\nu_{\tilde{0}} - \nu_r)$.

(An alternative evaluation of the frequency deviation using the test pattern shown in Figure II.1/G.957 is for further study.)

III.4.1.2 Transmitter eye pattern mask

As for pure IM systems, the transmitter eye mask is used to specify transmitter pulse shape characteristics and degradations. Since DST systems employ both intensity modulation as well as frequency modulation to convey the information, two eye mask measurement techniques are used to characterize the optical transmitter signal at reference point MPI-S.

III.4.1.2.1 IM eye mask

The IM eye mask definition specifies the intensity modulated part of the signal, and is identical to the IM eye mask definition and use in 6.2.4. Values for the IM eye mask as defined in 6.2.4, Figure 2, are given in Table III.1 below:

Table III.1/G.691 – Values for the IM eye mask for DST systems

STM-64 IM eye mask (DST)	
x_1/x_4	–
x_2/x_3	–
$x_3 - x_2$	0.2
y_1/y_2	0.3/0.6

III.4.1.2.2 FM/IM eye mask

The FM/IM eye mask has the corresponding function for the frequency modulation used to counter the link dispersion. To visualize also the FM-part of the signal, the FM/IM-mask test includes a specified FM to IM conversion and a specified frequency response of the reference receiver in the eye mask measurement set-up. The FM/IM eye mask measurement set-up is described in the following.

The measurement set-up is similar to the set-up described in Figure B.1/G.957. In addition, the new measurement set-up includes:

i) a dispersive element that has a chromatic dispersion equivalent to a defined length of fibre according to ITU-T Rec. G.652; and

ii) an optical pre-amplifier for compensation of the attenuation of the dispersive element.

The additional equipment i) and ii) is located between the transmitter under test and the optical input of the reference receiver. The transfer function *H*(*p*) of the optical reference receiver is defined by (see Figure B.2/G.957):

$$H(p) = \frac{U_0}{2U_2}$$

For the FM/IM eye mask measurement, the following transfer function of the reference receiver is used:

$$H = H_B \cdot H_D$$

where H_B represents a fourth-order Bessel-Thomson response according to Annex B/G.957, and H_D first order low-pass filter given by:

$$H_D = \left(1 + j\frac{f}{f_g}\right)^{-1} = \left(1 + \frac{f_r}{f_g}p\right)^{-1} = \left(1 + 0.75\frac{f_0}{f_g}p\right)^{-1} = \left(1 + \frac{0.75}{2.114}\frac{f_0}{f_g}y\right)^{-1}$$

where:

$$p = j\frac{\omega}{\omega_r},\ y = 2.114p,\ \omega_r = 1.5\pi f_0,\ f_0 = \text{bit rate},\ f_r = 0.75 f_0$$

with cut-off frequency f_g.

The filter can be realized in hardware. As an alternative, it is proposed to realize the filter in software using, e.g., a PC or an eye diagram analyser; this is for further study.

The characteristic values of the dispersive element that has a chromatic dispersion equivalent to a defined length of fibre according to ITU-T Rec. G.652 and the receiver filter cut-off frequency f_g used in the measurement set-up are given in Table III.2 below:

Table III.2/G.691 – DST filter values

	Unit	DST L-64.2/1	DST L-64.2/2	DST V-64.2
Filter cut-off frequency	MHz	2500	2500	1400
Equivalent length of fibre (ITU-T Rec. G.652)	km	80	80	120

After this signal conversion in the dispersive element and including the modified frequency response of the reference receiver for the eye mask measurement, the definition and procedure is identical to the IM eye mask definition and use in 6.2.4.

Values for the FM/IM eye mask are given in Table III.3:

Table III.3/G.691 – Values for the FM/IM eye mask for DST systems

STM-64 FM/IM eye mask (DST)	
x_1/x_4	–
x_2/x_3	–
$x_3 - x_2$	0.2
y_1/y_2	0.3/0.6

III.4.2 Receiver at reference point MPI-R

III.4.2.1 Minimum sensitivity

Receiver sensitivity is defined as the minimum acceptable value of average received power at point MPI-R to achieve a 1×10^{-12} BER. In DST systems, the receiver sensitivity definition includes a dispersive element between MPI-S and MPI-R. The chromatic dispersion of this dispersive element is equal to the minimum chromatic dispersion defined for the considered target distance, and the values are given in Table III.4. All other requirements on the receiver sensitivity as in 6.4.1 also apply to the DST receiver.

In the main body of this Recommendation, details on the realization of the receiver, e.g., a specification of specific filter transfer function, are not given. Only the filter transfer function in the measurement set-up for the transmitter eye mask is standardized in Annex B/G.957. This does not imply that the optical receiver in the transmission system has the same filter transfer function.

The same strategy applies for DST systems: only the filter transfer functions of the reference receivers for the transmitter eye-mask measurements are standardized. The filter transfer function in the optical receiver of the transmission system is not subject to standardization. A low-pass filter may be applied in the receiver; however, also a different approach using a specialized decision circuit capable of detecting multi-level eye diagrams may be employed.

III.4.2.2 Maximum optical path penalty

The definition of path penalty is given in 6.4.3. This definition is also applied for DST systems, taking into account the definition of receiver sensitivity for DST systems given above.

III.5 Optical parameter values

Optical parameter values are given in Table III.4.

Table III.4/G.691 – Parameters values for STM-64 optical interfaces using DST

Application code	Unit	DST L-64.2/1	DST L-64.2/2	DST V-64.2
Transmitter at reference point MPI-S				
Operating wavelength range	nm	1530-1565	1530-1565	1530-1565
Mean launched power				
– maximum	dBm	3	13	17
– minimum	dBm	0	10	14
Spectral characteristics				
– maximum chirp parameter α	rad	3.5	3.5	3.5
– maximum frequency deviation	GHz	8	8	6
– minimum frequency deviation	GHz	7	7	5
– maximum spectral power density	mW/MHz	0.02	0.02	0.02
– minimum SMSR	dB	35	35	35
Minimum EX	dB	3	3	2
Main optical path, MPI-S to MPI-R				
Attenuation range				
– maximum	dB	22	22	33
– minimum	dB	11	16	22
Chromatic dispersion				
– maximum	ps/nm	1600	1600	2400
– minimum	ps/nm	800	800	1600
Passive dispersion compensation				
– maximum	ps/nm	NA	NA	NA
– minimum	ps/nm	NA	NA	NA
Maximum DGD	ps	30	30	30
Min ORL of cable plant at MPI-S, including any connectors	dB	24	24	24

Table III.4/G.691 – Parameters values for STM-64 optical interfaces using DST

Application code	Unit	DST L-64.2/1	DST L-64.2/2	DST V-64.2
Maximum discrete reflectance between MPI-S and MPI-R	dB	–27	–27	–27
Receiver at reference point MPI-R				
Minimum sensitivity	dBm	–24	–14	–21
Minimum overload	dBm	–8	–3	–5
Maximum optical path penalty	dB	2	2	2
Maximum reflectance of receiver, measured at MPI-R	dB	–27	–27	–27

Appendix IV

Measurement of the chirp parameter α of the optical transmit signal

This method for measuring the chirp parameter α is based on a direct time domain measurement of the power and the frequency deviation of the optical transmit signal.

IV.1 Measurement set-up

The recommended set-up for measuring the chirp parameter is based on an optical two-beam interferometer (e.g., a Michelson interferometer or a Mach-Zehnder interferometer) a broadband optical converter and a broadband digital oscilloscope, see Figure IV.1.

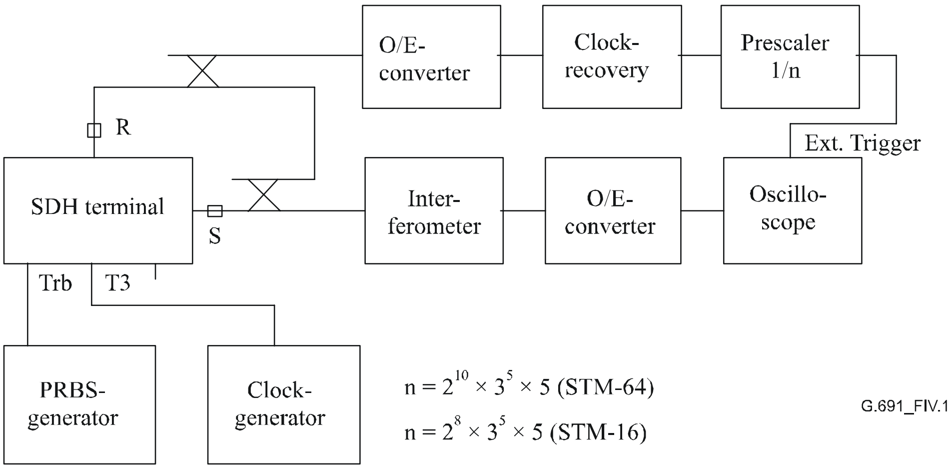


Figure IV.1/G.691 – Measurement set-up

The optical output of the transmitter under test is connected at the reference point S to the two-beam interferometer. The output of the interferometer is connected to the optical converter and the electrical signal out of the converter is recorded by the broadband digital oscilloscope. The oscilloscope is triggered by a frame sync signal generated by pre-scaling a clock recovered from the optically received signal.

In order to keep the transmitter turned on during the measurement, a fraction of the light to the interferometer is coupled to the optical receiver port of the transmitter equipment. A $2^{23}-1$ PRBS data generator is connected to the tributary ports, which are configured in the loop-back mode.

IV.2 Technical requirements for the measuring equipment

Two-beam interferometer

Free spectral range (FSR): At least four times larger than the chirp of the transmitter.

Transmitter

Off-set wavelength: Adjustable. The range must be equal to or larger than the free spectral range of the interferometer.

The two-beam interferometer must have a control circuit which locks the interferometer to the input signal. This control circuit should allow to lock the interferometer to the input signal at quadrature point A as well as quadrature point B, see Figure IV.2.

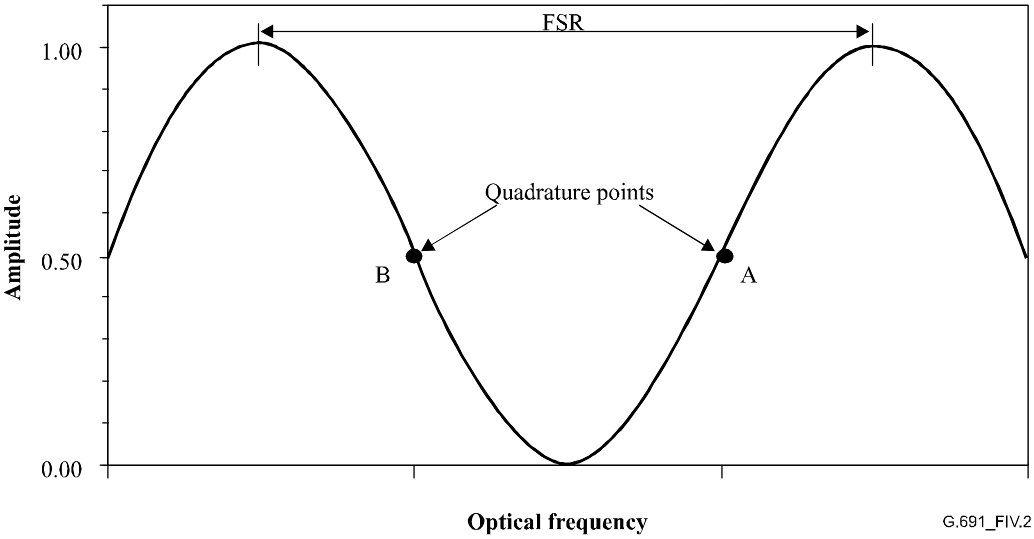


Figure IV.2/G.691 – Sketch of the transfer function of the two-beam interferometer showing the quadrature points A and B and defining the free spectral range

Combined frequency response for the optical converter and the oscilloscope

Low –3 dB cut-off frequency:	<100 kHz
High –3 dB cut-off frequency:	>20 GHz

The oscilloscope shall have a storage capacity of at least four traces and be able to perform advanced mathematical functions on the traces or have the capability to transfer the measured data trace to a computer for further processing.

IV.3 Calibration

The free spectral range of the interferometer is determined by the delay t_d related to the two optical paths inside the interferometer:

$$FSR = \frac{1}{t_d}$$

t_d can either be measured directly by detecting the time difference in the arrival of data from each of the beams by using the oscilloscope or it can be measured indirectly by using a ruler and calculating the delay. The FSR can also be found by measuring the transfer function of the interferometer using a lightwave component analyser. The first zero in the transfer function occurs at a frequency equal to FSR/2.

The quadrature point of the interferometer is adjusted to match the transmitter wavelength by fine tuning the FSR. The correct position is identified by monitoring the average power of the SDH transmitter signal through the interferometer as a function of the fine tuning of the FSR. The quadrature point is the position where the average power through the interferometer is halfway between the maximum and the minimum power on a linear scale. The interferometer shall be locked to the transmitter signal in this position.

IV.4 Measurement procedure

1) Arrange the equipment as shown in Figure IV.1. Apply sufficient attenuation to the signal to the receiver to avoid overload.
2) Configure the tributary input of the transmitter in the loop-back mode and connect the PRBS-generator to the first tributary input.
3) Synchronize the transmitter to the recovered clock by configuring the timing source for the aggregate signal as T3 (external clock input).
4) Calibrate the two-beam interferometer in accordance with IV.3. Lock the interferometer to the quadrature point A.
5) Adjust the time delay on the digital oscilloscope until the framing bytes A1 A2 of the SDH overhead is displayed on the oscilloscope. Record the trace of the transition from the A1 to the A2 byte (11110110 to 00101000) and store the trace as $V_A(t)$.
6) Lock the interferometer to the quadrature point B.
7) Store the trace of the data on the oscilloscope as $V_B(t)$.

IV.5 Data processing

The chirp parameter is determined by the sum and the difference between $V_A(t)$ and $V_B(t)$. Therefore the variables $V^+(t)$ and $V^-(t)$ are defined:

$$V^+(t) = \frac{V_A(t) + V_B(t)}{2}$$

$$V^-(t) = \frac{V_A(t) - V_B(t)}{2}$$

The time varying intensity P(t) of the transmitter is proportional to $V^+(t)$. The chirp parameter is calculated as:

$$\alpha(t) = 2 \times FSR \times \frac{V^+(t) \times \arcsin \dfrac{V^-(t)}{V^+(t)}}{\dfrac{\partial V^+(t)}{\partial t}}$$

P(t) and α(t) are calculated and plotted on the same graph. The chirp parameter of the transmitter is defined as the value of α(t) calculated at the time where the intensity P(t) is half-way between the level representing the "0" and the "1" symbols of the data.

IV.6 Examples and interpretation of data

In Figure IV.3, an example of the measured result of the two traces $V_A(t)$ and $V_B(t)$ is shown measured on a PRBS signal with a bit rate of 10 Gbit/s.

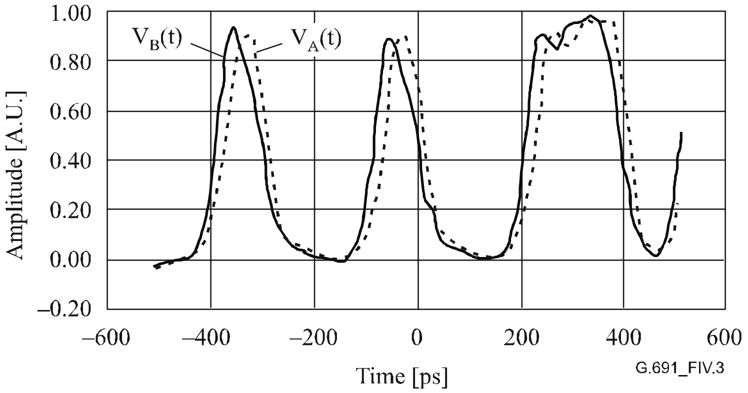


Figure IV.3/G.691 – Data traces of a 10 Gbit/s PRBS signal measured with the interferometer adjusted to the quadrature points A and B, respectively

Figure IV.4 shows a plot of the calculation of P(t) and α(t) as described in clause IV.5.

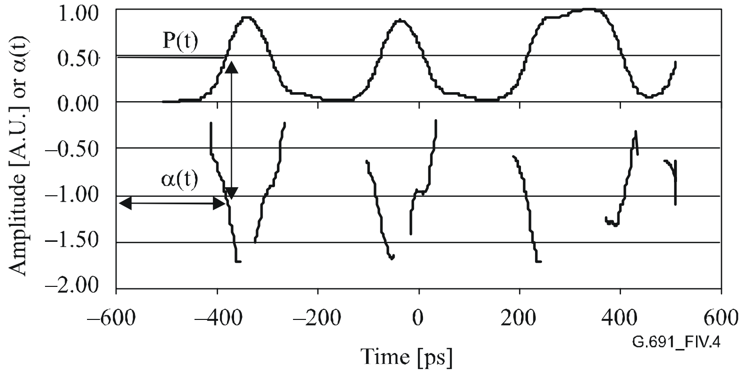


Figure IV.4/G.691 – Plot of the calculated values for P(t) and α(t); The arrows show how to find the chirp parameter

The chirp parameter can be calculated on the leading and the trailing edges of the data pulses. In Figure IV.4 the identification of the chirp parameter is shown for the first leading edge of the pulses in the trace. The chirp parameter varies slightly depending on the position of the pulse in the trace. The minimum and the maximum chirp parameter over the pattern shall be within the specified limits for the system.

How the chirp parameter influences the system performance is for further study. Whether the chirp parameter is to be calculated on the leading or trailing edge, as an average, or as a worst case is also for further study.

Appendix V

Upgradability considerations

One example of upgrades to higher bit rates is from an STM-16, line-amplified single-channel system to STM-64. A 640-km-long STM-16 regenerating span with seven line amplifiers, for example, can be upgraded to STM-64 by replacing the line amplifier at the middle with a regenerator while the rest of the line amplifiers and their span remain unchanged. Figure V.1 shows this upgrade.

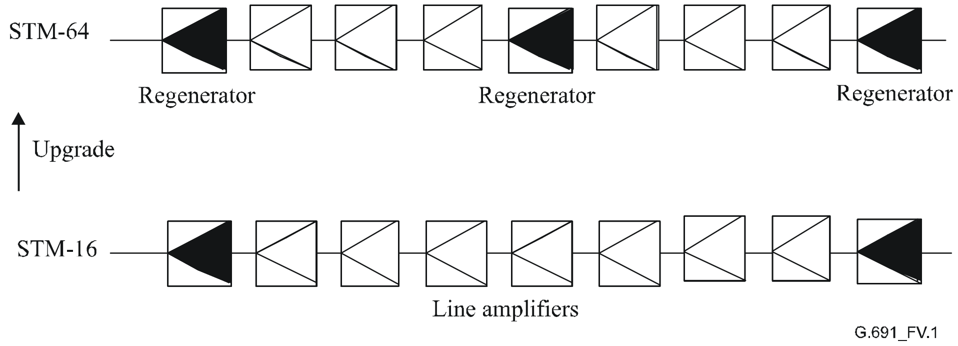


Figure V.1/G.691 – An example of upgrading from STM-16 to STM-64

Upgrades from STM-4 to STM-16 would have no practical merit because STM-4 systems with line amplifiers would not be cost effective unless the line amplifier cost is greatly reduced.

SERIES OF ITU-T RECOMMENDATIONS

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

Printed in Switzerland
Geneva, 2006