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Foreword

This ETSI Technical Report (ETR) has been produced by the Transmission and Multiplexing (TM) Technical Committee of the European Telecommunications Standards Institute (ETSI).

ETRs are informative documents resulting from ETSI studies which are not appropriate for European Telecommunication Standard (ETS) or Interim European Telecommunication Standard (I-ETS) status. An ETR may be used to publish material which is either of an informative nature, relating to the use or the application of ETSs or I-ETSs, or which is immature and not yet suitable for formal adoption as an ETS or an I-ETS.

Introduction

General

This ETSI Technical Report (ETR) on "Physical aspects of long-haul optical systems for 10 Gbit/s capacity" investigates the physical aspects of optical long-haul inter-office systems at 9,953 280 Gbit/s bit rate, including STM-64 systems of the Synchronous Digital Hierarchy (SDH). The transmission ranges to be covered are of the long-haul (L), very-long-haul (V) and ultra-long-haul (U) type. Because the transmission distance may be limited by fibre dispersion, the introduction of optical amplifiers (as booster-, line- and pre-amplifiers) and of various fibre dispersion accommodation techniques is proposed to enable optical 10 Gbit/s systems at longer distances, e.g. 80 km, 120 km or 160 km. This ETR considers especially different forms of linear chromatic fibre dispersion accommodation techniques and non-linear chromatic fibre dispersion accommodation techniques.

Nominal operating wavelengths of 10 Gbit/s systems are:

- 1 310 nm for the possible use of Semiconductor Optical Amplifiers (SOAs) or Praseodymium-Doped Fluoride Fibre Amplifiers (PDFFAs);

- 1 550 nm for use of Erbium-Doped Fibre Amplifiers (EDFAs) and possibly of SOAs.

Existing and emerging standards

According to the draft ITU-T Recommendation G.scs [29], STM-64 distances of the order of 20 km at 1 310 nm and 40 km at 1 550 nm are feasible for S-systems, whereas the order of 80 km (at 1 550 nm) is considered for long haul (L) systems and the order of 120 km for very long haul (V) systems. The general procedure of the standardization of optical interfaces will follow the guidelines of the ETS 300 232 [30] and the following emerging ITU-T recommendations:

- ITU-T draft Recommendation G.scs [29]: "Optical Interfaces for Single-Channel Systems with Optical Amplifiers (OAs) and without/with In-Line Amplifiers" and

- ITU-T draft Recommendation G.mcs [31]: "Optical Interfaces for Multi-Channel Systems with OAs and without/with In-Line Amplifiers".

New functional aspects, not included within the existing ITU-T Recommendation G.958 [32], will be covered in the ITU-T draft Recommendation G.lon: "Functional Characteristics of Interoffice and Long-Haul Line Systems Using Optical Amplifiers, including Optical Multiplexing", [33].

NOTE: Some of the techniques described in this ETR may be covered by existing or pending patents.

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1 Scope

The technical possibilities of 10 Gbit/s SDH long-haul systems at 1 310 nm and 1 550 nm wavelength are investigated, taking into account:

- intensity modulation (digital modulation) and optical Frequency-Shift-Keying /Amplitude-Shift-Keying (FSK/ASK) modulation or pure FSK modulation;
- different Time Division Multiplex (TDM) and Wavelength Division Multiplex (WDM) transmission procedures;
- the application of OAs in the form of Optical Fibre Amplifiers (OFAs) or SOAs; and
- methods for overcoming fibre dispersion limitations by Dispersion Accommodation (DA) techniques.

Constraints by, and relationships to existing and emerging standards will be pointed out, taking into account:

- compatibility with existing equipment;
- suitability for application in long repeatered systems using in-line amplifiers;
- ease of upgrade to higher capacity;
- maturity of technology; etc.

Soliton transmission has not been considered within the scope of this ETR.

2 References

This ETR incorporates by dated and undated reference, provisions from other publications. These references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this ETR only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

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3 Abbreviations

For the purposes of this ETR, the following abbreviations apply:

AM	Amplitude Modulation (i.e. optical intensity modulation)
APD	Avalanche Photo Diode
ASK	Amplitude Shift Keying
BA	Booster Amplifier
BER	Bit Error Ratio
CSMF	Conventional (ITU-T Recommendation G.652 [35] or "Standard" or "dispersion-unshifted") Single Mode Fibre
D	Dispersion
DA	Dispersion Accommodation
DCF	Dispersion Compensating Fibre
DGD	Differential Group Delay
DSF	Dispersion Shifted (ITU-T Recommendation G.653 [34]) Fibre
DST	Dispersion Supported Transmission
EA	Electro-absorption
EDFA	Erbium Doped Fibre Amplifier
E/O	Electrical/Optical converter
ETR	ETSI Technical Report
FDM	Frequency Division Multiplexing
FSK	Frequency Shift Keying
FWM	Four-Wave-Mixing
L	Length
LA	Line Amplifier
LD	Laser Diode
LT	Line Termination
MSI	Mid-system (Mid-point) Spectral Inversion
MZI	Mach-Zehnder-Interferometer
NRZ	Non Return-to Zero
OA	Optical Amplifier
O/E	Optical/Electrical conversion
O/E/O	Optical/Electrical/Optical transponder
OF	Optical Filter
OFA	Optical Fibre Amplifier
OFDM	Optical Frequency Division Multiplexing
O&M	Operation and Maintenance
O/O	Optical wavelength converter
OTDM	Optical Time Division Multiplexing
PA	Pre-Amplifier
PD	Photo Diode
PDFFA	Praseodymium Doped Fluoride Fibre Amplifier
PM	Phase Modulation
PMD	Polarization Mode Dispersion
r	bit rate
R	Reference point at the receiver side
S	Reference point at the transmitter side
SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy
SOA	Semiconductor Optical Amplifier
SPM	Self-Phase-Modulation
SRS	Stimulated Raman Scattering
STM	Synchronous Transport Module
TDM	Time Division Multiplexing
TF	Transmission Fibre
WDM	Wavelength Division Multiplexing
XPM	Cross-Phase-Modulation

4 Transmission aspects and multiplexing procedures

4.1 Transmission aspects

4.1.1 Fibre types

The two main types of single mode fibres deployed for the purpose of digital transmission are Conventional (sometimes called "standard") Single Mode Fibre (CSMF) described in I-ETS 300 227 [36] and Dispersion Shifted Fibre (DSF) described in I-ETS 300 228 [37]. The zero dispersion wavelength of the CSMF is located around 1 310 nm with attenuation values of 0,34 to 0,45 dB/km. The zero dispersion wavelength of the DSF is about 1 550 nm, where the attenuation is in the range of 0,2 to 0,25 dB/km. The combination of a rather low attenuation in the 1 550 nm wavelength region and of a lower dispersion value of /D/<3.5 ps/(nm.km) in the 1 525 to 1 575 nm range, e.g. /D/<2.7 ps/(nm.km) specified by one supplier, makes the DSF more suitable for single-channel long-haul transmissions at such high bit rates.

Since the CSMF type represents the majority of the world's deployed fibres, there are two proposals of 10 Gbit/s long-haul systems with high distances (80 km and 120 km), characterized by:

a) the use of 1 550 nm wavelength, of an EDFA as an OFA and of a DA technique for overcoming a fibre dispersion limitation of the CSMF due to a dispersion of about 16 to 20 ps/(nm.km); or

b) the use of 1 310 nm wavelength, of a PDFFA or as SOA without a DA technique.

Currently ITU-T Study Group 15 is studying a possible new fibre ITU-T draft Recommendation G.65x, being a non-zero dispersion fibre particularly for WDM applications, minimizing Four Wave Mixing (FWM) effects, described in more detail in subclauses 4.1.5 and 5.3.2 of this ETR. This new fibre type may be very useful in very long-haul networks.

4.1.2 Optical Fibre Amplifiers (OFAs)

Having reached a high level of maturity, OFAs for the 1 550 nm region (e.g. EDFA) have become an indispensable means to overcome attenuation problems. Their relatively high gain (typically 10 to 30 dB), high optical output power (+10 to +15 dBm in the case of single-pumping and +13 to +17 dBm in the case of double-pumping; in specific cases even up to +20 dBm), and low noise figure (3 to 4 dB) allow them to be used as:

- optical Booster Amplifiers (BAs) in order to increase transmitter output power;
- optical Pre-Amplifiers (PAs) in order to enhance receiver sensitivity; and
- optical Line Amplifiers (LAs) in order to compensate the accumulating fibre loss of optical paths with more than one section.

BAs are a simple means to enhance link lengths, since no optical filters or low noise figures are required. However, the relatively high output power gives rise to non-linear optical effects in glass fibres, which can lead to severe signal distortions mainly due to Self-Phase-Modulation (SPM) effects in single-channel systems and additionally Cross-Phase-Modulation (XPM) and FWM in multichannel systems. Such non-linear optical distortion effects are discussed more in detail within draft ITU-T draft Recommendation G.OA3 [38].

Care should be taken when using high output powers for several reasons, e.g. optical safety, damage of fibre end faces due to contamination or non-linear effects.

Further enlargement of link ranges can be achieved by implementing a PA just before the receiver photodiode and thus improving receiver sensitivity. In this case a narrowband optical filter between PA and the photodiode is recommended, which may need an active regulation of its transmission wavelength.

A third step to reduce the number of regenerators (regenerative repeaters) in a long-haul transmission system is done by the installation of LAs (optical non-regenerative repeaters). In most cases, special measures have to be developed in order to obtain Operation & Maintenance (O&M) facilities for such line amplifiers, e.g. by introduction of an optical supervisory channel, which will be described within the emerging draft ITU-T draft Recommendation G.lon [33].

OFAs have also been demonstrated for the 1 310 nm region. PDFFAs have been reported with output powers of up to +18 dBm, gain values of 32 dB and noise figures of 6 dB, but their realization is much more complex than that of EDFAs.

4.1.3 Semiconductor Optical Amplifiers (SOAs)

The system improvements, described in subclause 4.1.1, may also be realized in the 1 310 nm and 1 550 nm regions by applying SOAs. Preliminary implementations of a 1 310 nm SOA indicate: +13 dBm saturation output power, 27 dB polarization-independent gain, 60 nm spectral width, and 7 dB noise figure (see [28]).

In contrast to OFAs, the behaviour of the input-to-output power of SOAs is non-linear. This means that such amplifiers have to be operated outside the saturation regime in order to avoid extinction ratio degradation. Other points of SOAs, needing further consideration, are related to their possible polarisation dependence as well as to a certain lack of experience and maturity.

4.1.4 Fibre dispersion

The total dispersion of a transmission fibre with specific fibre Dispersion (D) and Length (L) is characterized by the product D*L. Due to the spectral bandwidth of a modulated optical signal (baseband modulation spectrum and additional chirp) dispersion effects lead to a distortion of the transmitted signal. In the case of an intensity-modulated signal without chirp, first order dispersion effects lead to a limitation of the link ranges (according to [1]):

$$L_{max} \mu \frac{1}{D * r^2}$$; with r = bit rate.

For small dispersion values D (|D | < 0.1 ps/(nm.km)), third and higher order dispersion effects have to be considered in order to calculate the dispersion limited link range (see [1]). For an intensity-modulated optical signal at 10 Gbit/s, the limit for the product D*L is about 1 000 ps/nm for a system degradation of 1 dB. This results in a theoretical transmission distance of 60 km with CSMF (D = 17 ps/(nm.km) at 1 560 nm) or 1 000 km (with transmission systems including line amplifiers) with DSF (D = 1 ps/(nm.km) at 1 560 nm). Various DA techniques are proposed in clause 5 in order to extend link ranges above these conventional dispersion-limited distances.

4.1.5 Non-linear fibre effects

Mainly because of the advent of EDFAs and of their high output powers, the optical power-density in glass fibres reaches levels, where non-linear effects in the fibre are no longer negligible. The most relevant effect in single-channel transmission systems is the SPM effect. The Stimulated Brillouin Scattering (SBS) threshold can be substantially raised by 'dithering' the laser current, i.e. modulation of the optical wavelength signal by a low frequency. Multichannel transmission systems give rise to XPM and FWM effects.

Multichannel transmission with many channels occupying a large total bandwidth may also suffer from Stimulated Raman Scattering (SRS). Even if the Raman threshold is not reached, the non-linear Raman crosstalk may cause severe eye-closure.

The signal distortions caused by non-linear effects cannot be generally looked upon as destructive for the transmitted signal. SPM effects induced in the anomalous dispersion regime of fibre (D>0) can compensate for dispersion effects (see [1]). The FWM effect can be used to realize a DA technique by phase conjugation of the optical signal. The positive application of SPM and FWM effects as non-linear DA techniques is described in subclause 5.3. The non-linear fibre effects as negative distortions are described more in detail in draft ITU-T draft Recommendation G.OA3 [38].

4.2 Multiplexing procedures

4.2.1 TDM-multiplexing procedures according to SDH rules and/or practice

In this case, multiplexing is completely managed by electronic components providing a byte-interleaved STM-64 SDH output signal. Considering the state of the art and of electronic components, it is a possible way to achieve a 9,953 280 Gbit/s transmission capacity and provides flexibility, add-drop facilities, cost, effectiveness and even further upgrading possibilities towards optical multichannel systems. The input signals can be STM-1, STM-4 or STM-16 signals. The new SDH level of byte-interleaved STM-64 was introduced into the ITU-T Recommendation G.707 [39].

4.2.2 Multiplexing procedures not corresponding to SDH rules and/or practice

4.2.2.1 4 x STM-16 with Optical/Electrical (O/E) conversion, electrical multiplexing, Electrical/Optical (E/O) conversion

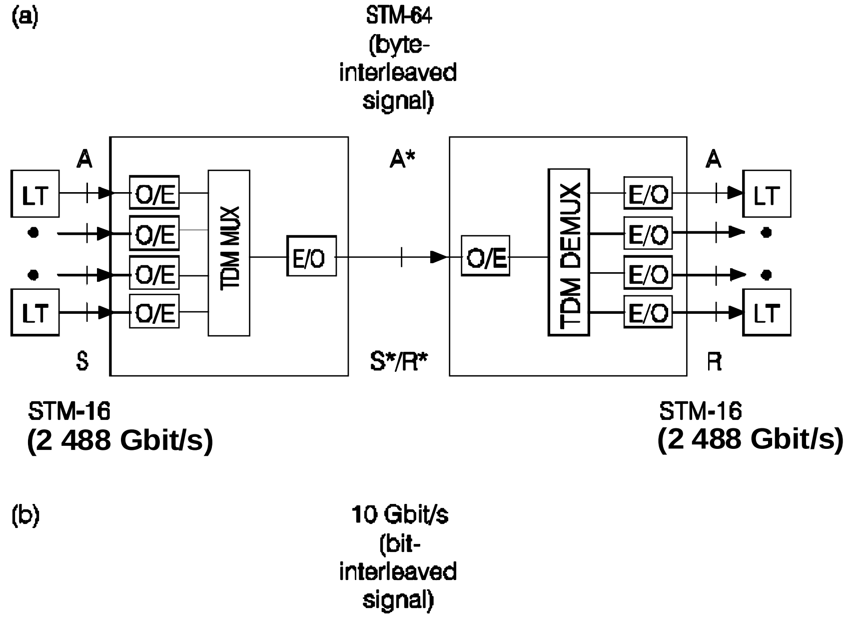
Due to the definition of STM-N signals, conventional bit-by-bit (bit-interleaved) multiplexing schemes are not capable of combining STM-N signals into signals with STM format of higher order.

If optical STM-16 signals are converted to electrical signals, a processing in the electrical domain may be done in two ways:

a) by rearranging the bits of the signals in a form that, after multiplexing them in a 4 * 1 - multiplexer, a genuine byte-interleaved STM-64 signal is obtained; and

b) by simply bit-interleaving the four STM-16 streams, leading to a 10 Gbit/s signal, which does not obey the rules of SDH.

System (a) is not very attractive but leads to a real STM-64 signal, whereas (b) is technically easier, but leads to a 'non-standard 10 Gbit/s signal'. In both cases, future upgrading of the single-channel transmission system towards a multichannel WDM system with e.g. 4 wavelengths, each operating at 10 Gbit/s, can be achieved at a later date by the insertion of optical wavelength multiplexers and demultiplexers.



a) with byte-interleaved signals (STM-64)
b) with bit-interleaved signals 10 Gbit/s

Figure 1: TDM MUX-DEMUX for 10 Gbit/s system

4.2.2.2 4 x STM-16 with optical multiplexing (WDM or OFDM)

This configuration (see figure 2) corresponds to a 4-channel WDM system with 4-channel optical wavelength multiplexer and demultiplexer to provide 10 Gbit/s capacity. A constraint is that only channels with different wavelengths which match the specified channels of the multiplexer/demultiplexer can be combined. The impact of non-linear effects arising in multichannel systems depends upon the various parameters of the transmission systems, so that no general assertions may be given. However, in most cases, non-linear effects are no more likely to be the primary limitation of system performance than in the case of single channel systems. One advantage of using multichannel transmission is its greater insensitivity to dispersion of the transmission fibre due to the lower individual channel bit rate. The dispersion-limited link range is around 1 000 km over CSMF for individual channel rates at STM-16, permitting the utilization of line amplifiers to achieve very long system lengths without dispersion accommodation. This must be compared to a link range of only 60 km at STM-64 over CSMF without dispersion accommodation. For practical realization, a conventional 1:4-splitter may be used instead of a special wavelength-multiplexing-coupler. On the receiver side, however, some filter function will be required.

A specific form of WDM is Optical Frequency Division Multiplexing (OFDM). Both methods are principally equal; the denomination "OFDM" is primarily used in cases where a set of optical frequencies (derived from optical wavelengths) is multiplexed by Frequency Division Multiplexing (FDM) or coherent-multi-carrier techniques or Phase Locked Loop locking of laser sources.

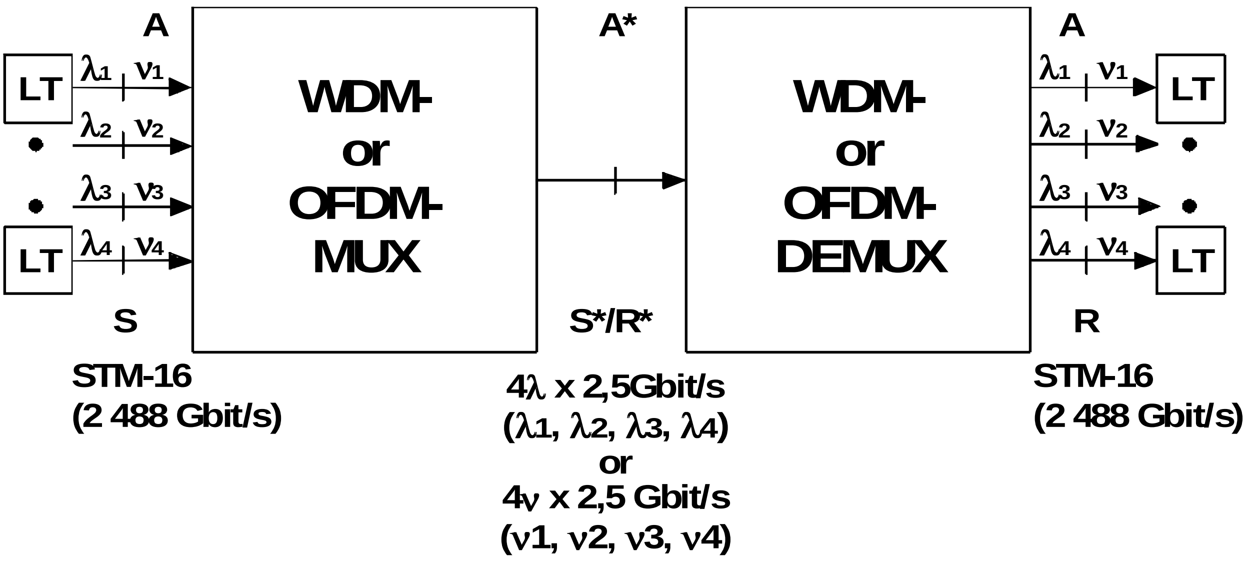


Figure 2: WDM- or OFDM - MUX/DEMUX for 10 Gbit/s system

4.2.2.3 4 * STM-16 with optical multiplexing (WDM) and Optical/Electrical/Optical (O/E/O) transponders

A 4-wavelength * STM-16 system (see figure 3) with O/E/O transponders or Optical/Optical (O/O) wavelength converters uses WDM multiplexing/ demultiplexing procedures with 4 different wavelengths (l_1,...,l_4) of 4 STM-16 channels, whereas the station side interfaces are all of the same wavelength l_0, preferably of the intraoffice interface type of ETS 300 232 [30]. The output signal of the WDM multiplexer is compatible with the signal generated according to subclause 4.2.2.2.

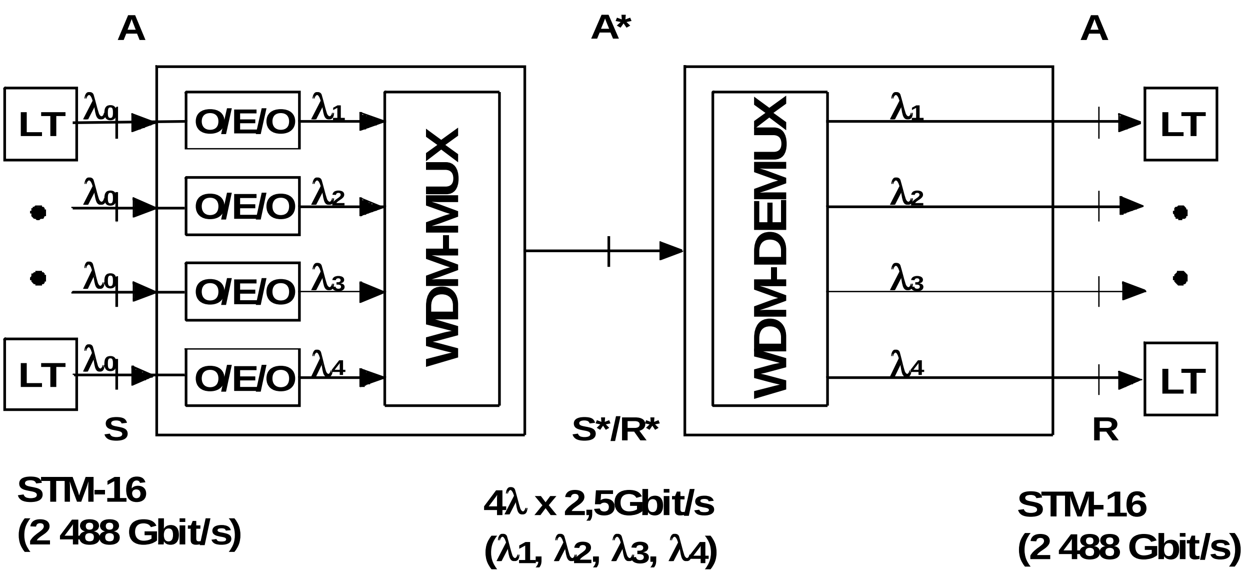


Figure 3: WDM- MUX/DEMUX with optical/electrical/optical transponders for 10 Gbit/s system

4.2.2.4 4 x STM-16 with Optical Time Division Multiplexing (OTDM)

OTDM can realize the bit-oriented multiplexing of the incoming STM-16 signals into a 10 Gbit/s data-stream, which does not match the STM-64 standard. Similar to the electrical signal processing, the multiplexing and demultiplexing procedures can be done in the optical domain with nonlinear optical components, control systems and under consideration of polarization fluctuations (see [9]). Pure optical multiplexing or demultiplexing needs sophisticated optical components such as pulse generators, optical switches and polarization-insensitive components or techniques (see [9]). Optical demultiplexing can also be realized with cascaded Mach-Zehnder-Interferometers (MZIs) (see [6] and [7]). Due to the higher bandwidth of OTDM-signals, dispersion-induced distortions are more severe than with the other multiplexing schemes, generally resulting in shorter link ranges. The OTDM procedure is more difficult than electrical TDM (subclause 4.2.1) and WDM (subclauses 4.2.2.2 and 4.2.2.3).

5 Linear and non-linear dispersion accommodation techniques

5.1 General

Extending transmission ranges beyond existing dispersion-induced limits has become a crucial aspect for 10 Gbit/s transmission systems. Manifold activities in this field aim at minimizing this influence e.g. by using pre-chirp techniques, specific dispersion compensation fibres, or by Mid-System Spectral Inversion (MSI, also called phase conjugation). Others use dispersion to support the transmission such as solitons or dispersion-supported transmission. Most of these are valuable techniques to optimize a single transmission system with given path length, fibre parameters and bit rate, but not all of them are compatible to each other.

In the following subclauses various methods to overcome the limitation to some extent are considered. The link lengths of transmission systems with or without dispersion accommodation techniques strongly depend on the fibre type (CSMF or DSF) and on the operating wavelength in relation to the zero dispersion wavelength. Further details concerning simulation parameters are given in subclause 5.5. **A direct comparison of the achievable link ranges given below with different DA techniques is not yet possible, because the dispersion penalties are not yet defined for the various systems.**

5.2 Linear Dispersion Accommodation (DA) techniques

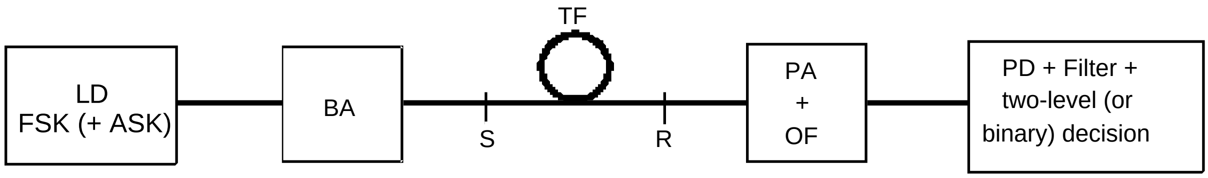
The values of link lengths are for 10 Gbit/s single-channel transmissions at 1 550 nm wavelength.

5.2.1 Dispersion Supported Transmission (DST) method

The aim of the DST method is to overcome the chromatic fibre dispersion limit of e.g. 10 Gbit/s optical signals in a CSMF with typical chromatic dispersion of 16 - 20 ps/(nm.km) at 1 550 nm, without requiring additional components like external modulators, interferometers or optical dispersion compensation elements. However, this DA technique requires matching of the systems parameters (on both the transmitter and receiver side) to the dispersion value of the transmission path. Using a BA in the optical transmitter, two stand-alone optical amplifiers in the link and a PA in the optical receiver, a 10 Gbit/s optical signal could be transmitted via a 253 km optical inter-office link. A repeaterless transmission at 10 Gbit/s could be extended up to 182 km CSMF using a high power BA and PA. The mean optical power with BA was +19 dBm; the receiver sensitivity with PA was: -24,6 dBm at Bit Error Ratio of $1*10^{-9}$ (see [18]).

In the ideal case, a purely frequency modulated signal is transmitted over a dispersive fibre of sufficient length and is thereby converted into a three-level ASK signal (see [17]). In the receiver a two-level decision circuit or an ideal integrator provides the demodulated NRZ signal (Non Return to Zero). Practical realization of this DA technique uses direct modulation of the transmitter laser, thus producing a FSK signal along with an amount of residual ASK. The FSK amount is responsible for partly compensating dispersion effects. The residual ASK allows a conventional binary decision circuit to be used. A low-pass electrical filter of lower order (e.g. 1st order low-pass filter) in the receiver compensates the fibre dispersion, which is reported to exhibit high-pass-related characteristics (see [15] and [19]), provided the modulation index of the intensity modulation is small and the signal is carried as a combined frequency and amplitude modulation.

The system parameters have to be tuned to the total fibre dispersion for optimized performance, however, only a coarse tuning is necessary, e.g. the whole range from 0 km to 160 km CSMF can be covered with 3 fixed filter parameter settings. With the parameters of the DST simulation in subclause 5.5.1 a link range of about 150 - 250 km has been predicted in table 1 of subclause 5.5.5.



LD	Laser Diode
TF	Transmission Fibre
OF	Optical Filter
PD	Photo Diode
S	reference point at the transmitter side
R	reference point at the receiver side

Figure 4: Physical configuration of the DST technique

Besides using an appropriate laser, a DST can also be realized with two separate components for modulating the optical signal in amplitude and frequency, respectively. By means of direct modulation of a semiconductor laser to obtain frequency modulation and additionally an external modulator (e.g. Electro-Absorption (EA) modulator or MZI) chirp can be applied to an ASK optical signal.

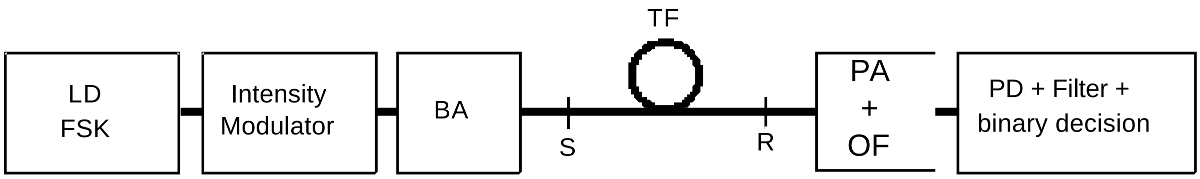


Figure 5: Physical configuration of the DST with separated amplitude and frequency modulation

5.2.2 AM & PM (Amplitude Modulation and Phase Modulation) and linear prechirp technique

Investigations showed, that similar to applying frequency chirp to an ASK signal, a phase modulator can induce phase modulation such that it partly compensates dispersion effects (see subclause 5.5.2 for simulation parameters). Transmission can also be done without Amplitude Modulation (AM), so that a three level ASK signal can be detected by the receiver. Typical achievable link ranges are similar to those achieved by DST. A typical applied phase change for a 'zero' to 'one' transition of the data and vice versa is 0,4 p radians for a fibre length of 120 km. Adjustment of the phase change to the total fibre dispersion is required for optimization. The commercial availability of high speed phase modulators and the relative low phase-shift required makes this technique a promising one. The potential of link range is about 150 - 250 km. The phase-shift is the only parameter to be adjusted. When involving the SPM effect, the transmitter output power has to be optimized too.

Realization is also possible with MZI used as intensity modulators and phase-shifters simultaneously, when the phase shifts in both arms are asymmetric (see [3]). Chirp in conventional laser diodes or EA modulators is generally not adjustable to arbitrary values, so that suitable devices have to be specified for the transmission systems.

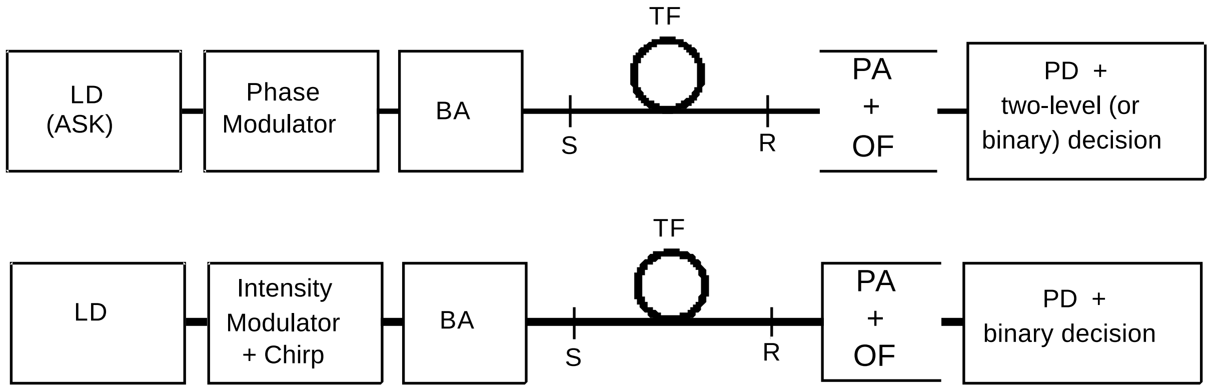


Figure 6: Physical configurations of the AM & PM and pre-chirp techniques

5.2.3 Multi-level modulation schemes (i.e. quaternary ASK and duo-binary modulation)

Multi-level modulation schemes with n>2 can reduce the bandwidth of the optical signal spectrum and thereby suffer less distortions from dispersion. The transmitter needs data signal processing. A linear external modulator showing good linearity is recommended. In the receiver, multiple thresholds for the decision circuit(s) are necessary. No fitting of system parameters to the dispersion properties of the transmission fibre is necessary. Simulations resulted in link ranges of about 200 km with a 4-level ASK modulation and 3 dB eye-closure (see subclause 5.5.3 for simulation parameters). A special case of this DA technique is the 'duo-binary' transmission proposed in (see [5]). Hereby, special electrical filtering of the data signal spectrum in the transmitter leads to a three-level optical signal with reduced bandwidth and thus suffers less dispersion distortion. In the receiver, two decision circuits along with simple digital signal processing are required for demodulation. Simulations resulted in link ranges comparable to the 4-level ASK modulation system at 3 dB eye-closure (see subclause 5.5.4 for simulation parameters).

With this DA technique emphasis is laid on linearity requirements of the analog circuits, which are more stringent compared to the binary modulation schemes.

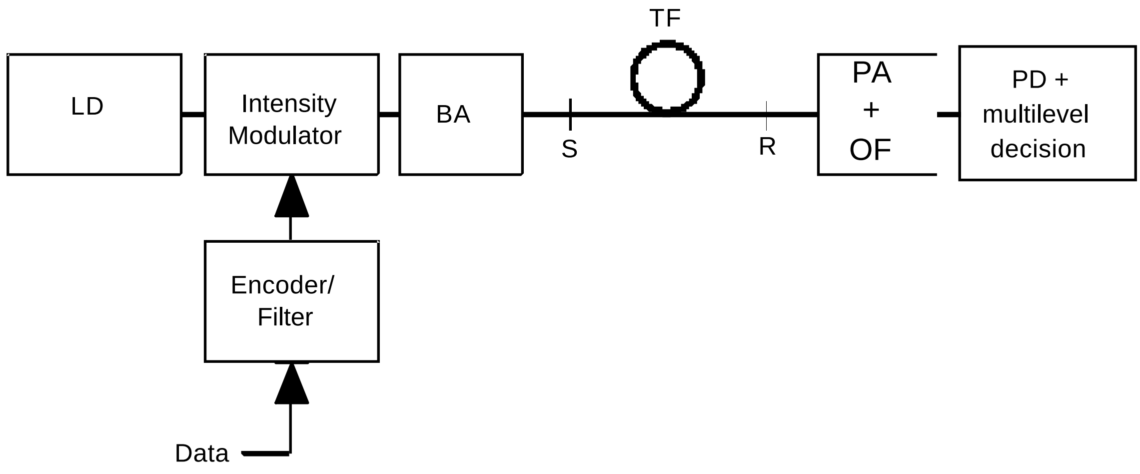


Figure 7: Physical configuration of the multi-level modulation technique

5.2.4 Dispersion compensating optical elements

Straightforward dispersion compensation can be done by inserting dispersion compensating elements into the transmission line. The following subclauses describe several types of optical elements for dispersion accommodation.

5.2.4.1 Dispersion Compensating Fibre (DCF)

Dispersion compensation can be done by inserting DCF into the transmission line. Suitable locations of the DCF may be at one of the fibre ends (Line-Terminations, LT) or even on both ends of the transmission fibre. However, the use of DCF at the output side of a high power source may lead to induced non-linear effects which could degrade the linear dispersion compensation effect. The length of the DCF has to be matched to the fibre length which needs compensation and the additional loss by inserting the DCF has to be taken into account. For instance a transmission distance of 100 km CSMF needs compensation of 40 km of CSMF, thus tolerating a penalty of 1 dB resulting from 60 km uncompensated fibre at 10 Gbit/s and 1 550 nm. The dispersion compensation of –680 ps/nm at 1 550 nm can be realized with DCF exhibiting an additional insertion loss of 6.5 dB (commercially available fibre, e.g. with -105 ps/(nm dB)). The length of the additional DCF is about 20 % of the compensated fibre length (CSMF at 1 550 nm). DCFs are currently being specified in ITU-T draft Recommendation G.671 [40]. Another dispersion compensating fibre technique has been demonstrated which uses a higher order fibre mode to provide much higher negative dispersion as a function of unit length. This technique, however, does require conversion between the fundamental and higher order mode and back again.

The technique of providing dispersion compensation by inserting DCF into transmission line gives a straightforward means to upgrade existing single-channel transmission systems (i.e. with CSMF) towards higher bit rates in the transmission fibre. A disadvantage is that the optical amplifiers (BA and PA) first have to overcome DCF losses, before they can act on the TF losses.

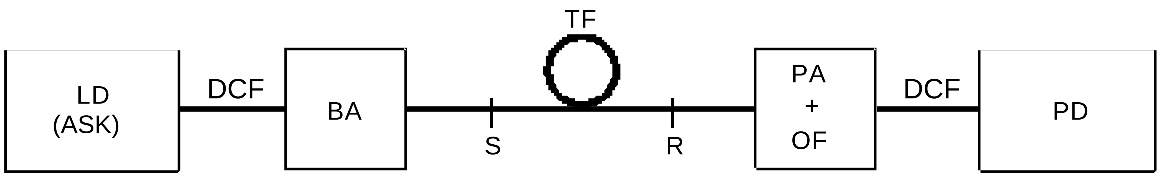


Figure 8: Physical configuration of the DCF technique

5.2.4.2 Concatenated asymmetrical Mach-Zehnder-Interferometers (MZI)

Concatenated asymmetrical MZI show wavelength-tunable dispersive characteristics and can be used in the transmission line for DA (see [16]). The fabrication can be done as an integrated-optic dispersion equalizer on a planar waveguide circuit, resulting in a compact device. Tuning of the asymmetrical interferometer arms is necessary and is realized in (see [16]) by thermo-optic phase control. First experiments resulted in the dispersion compensation of 20 km of CSMF at 1 550 nm by using 12 MZI-elements.

In principle other filter types, e.g. Fabry-Perot filters, can be used for the same purpose.

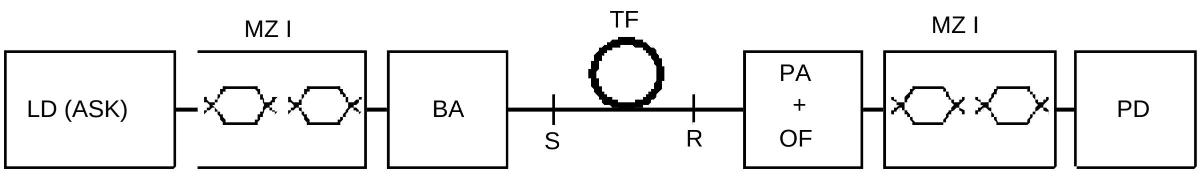


Figure 9: Physical configuration of the DA by implementation of concatenated asymmetrical MZI

5.2.4.3 All fibre devices for chromatic dispersion compensation

A few all fibre devices have been proposed in recent years to achieve efficient dispersion compensation (see [27]), with the advantage of inherently low insertion loss, although additional loss can be incurred for reflective devices that need optical circulators.

Unchirped fibre gratings have been proposed for dispersion compensation but the two requirements, dispersion and bandwidth (the bandwidth of the device must be large enough to cover the signal bandwidth) are most often contradictory in such systems: the narrower the resonance, the larger the dispersion.

To overcome this problem, devices where the resonant frequency varies along the coupler have been conceived; this results in a propagation delay along the device that is a function of frequency.

Three all fibre devices have been proposed: linearly chirped Bragg gratings, linearly chirped intermodal couplers and linearly tapered two-dissimilar-cores fibres.

In the chirped fibre grating the larger frequency component is coupled at the input end of the filter to a counterpropagating mode, while the smaller one is coupled to this mode at the output end. By coupling energy between two modes that have different group velocities, in such a way that the coupling location varies with frequency, a propagation delay as a linear function of frequency is achieved.

For the intermodal coupler and two core fibre, the delay is acquired because the larger component is coupled at the input end of the filter to a guided mode that has a smaller group velocity while the smaller one is coupled to this mode at the output end. These last two solutions do not require optical circulators.

5.3 Non-linear dispersion accommodation techniques

5.3.1 Self-Phase Modulation (SPM)

Intensity modulation with high transmitter output power induces SPM effects in the glass fibre. Preliminary theoretical system investigations resulted in an SPM supported transmission with link ranges up to some 150 km, using reasonable optical power levels of +10 ... +15 dBm (see subclause 5.5.5 for simulation parameters). Reduction of the link range is possible without performance degradation, i.e. no readjustment of the system parameters is required. In (see [12]) the link range of a 10 Gbit/s transmission system could be raised from 50 km to 107 km over CSMF at 1 550 nm by implementing a BA. An experiment similar to the latter resulted in a link range of 130 km with an optimized value of +12 dBm for the BA output power, thus confirming the theoretical system investigations.

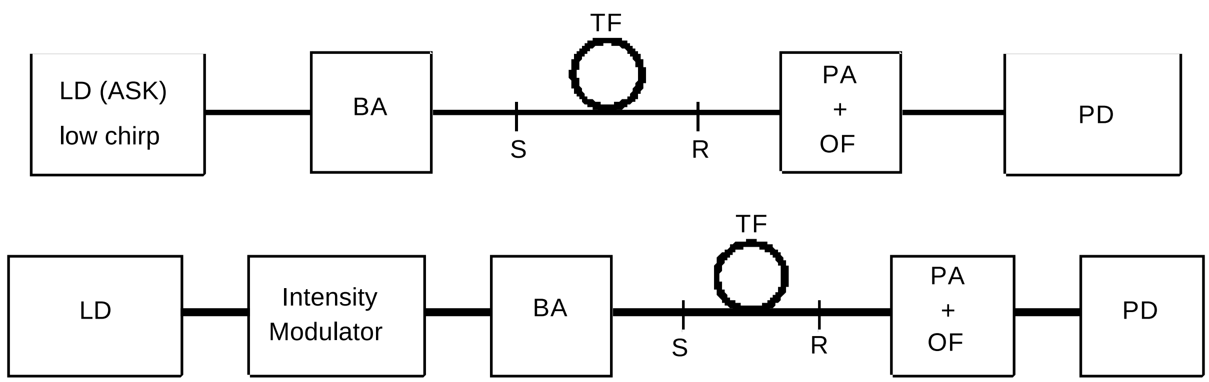


Figure 10: Physical configurations of the nonlinear optical technique by inducing SPM effects

5.3.2 Four-Wave-Mixing (FWM) or Midsystem Spectral Inversion (MSI)

MSI is a technique based on the FWM effect, which compensates not only the first order dispersion effects, but also reduces the distortions caused by nonlinear SPM effects (see [13]). Dispersion effects can be compensated for link ranges far greater than 10 000 km and thus enabling direct modulation of the transmitter laser. First experimental setups resulted in transmission of 10 Gbit/s over 360 km CSMF (see [8]) and 100 Gbit/s over 50 km CSMF (see [14]). The MSI DA technique is transparent to the modulation format and is relatively tolerant towards unprecise wavelength adjustments of the data channels. A major practical restriction is the fact, that the MSI unit has to be placed with adequate accuracy (e.g. some ± 20 km for 10 Gbit/s over CSMF at 1 550 nm) at that location of the optical transmission line, where the dispersion value is half of the total dispersion value. Since the FWM effect is polarization-sensitive, suitable measures have to be used in order to handle polarization fluctuations (see [14] and [20]). The MSI may be realized within a DSF or more compact within a SOA.

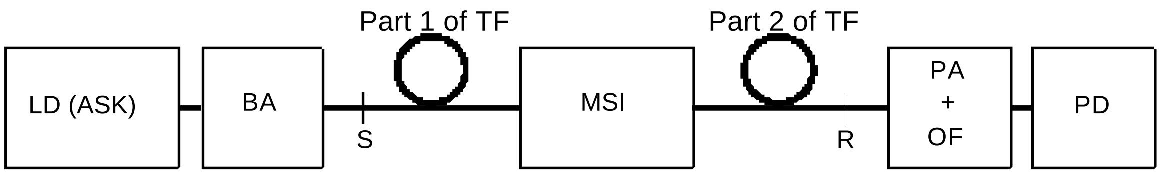


Figure 11: Physical configuration of the midsystem spectral inversion (MSI) technique

5.4 Evaluation and comparison of DA techniques

A comparison of the various DA Techniques and some specific remarks are summarized in table 1. Here, various DA techniques are considered separately and related transmission ranges are given for unregenerated 10 Gbit/s CSMF systems, but with many line amplifiers. Table 2, however, considers repeaterless 10 Gbit/s CSMF and DSF systems (without line amplifier or O/E/O regenerator), where also a mixing of DA techniques is shown.

5.4.1 Considerations for unregenerated systems utilizing line amplifiers

It is the aim of terrestrial unregenerated 10 Gbit/s long haul systems with CSMF, 1 550 nm wavelength and DA technique to extend the regenerator distances by using optical line-amplifiers. Regenerator and amplifier target distances are subject to ETSI and ITU-T standardization. Simulation results and preliminary experimental results of 10 Gbit/s long-haul systems with various DA techniques are given in table 1. DST, external AM and PM modulation, multi-level modulation techniques and/or SPM could be used for realizing regenerator distances (including line amplifiers) up to the order of 300 km. Utilization of other DA techniques, like DCF, MSI and/or WDM, could potentially permit regenerator distances of the order of 1 000 km to be realized.

Some dispersion accommodation schemes need to be tuned or adjusted to the amount of dispersion to be compensated. For example, the DST needs to match its frequency deviation, the prechirp technique needs to adjust the amount of chirp, and the SPM tunes the output power. Further, the MSI needs to be positioned at the middle of the link, and the amount of dispersion (i.e. the length) of a compensating fibre (or other passive device) needs to be matched to the link length.

NOTE: The values given in table 1 are examples based upon published experimental results, which do not guarantee appropriate performance under all conditions. The experiment boundary conditions are not known and might not be compatible between the various experiments.

5.4.2 Considerations for repeaterless systems without line amplifiers

If a long length of a repeaterless 10 Gbit/s system with CSMF or DSF at 1 550 nm wavelength and linear DA technique is required, table 2 indicates regenerator section lengths without an optical line amplifier between 100 km and 250 km. Repeaterless systems with DSF are longer than those with CSMF. DST, external modulation and DCF techniques can be used separately or in a mixed form.

However, all mentioned DA techniques can be applied to the L- and V-type STM-64 systems with line lengths of 80 km and 120 km, respectively, as are in discussion within the emerging ITU-T draft Recommendation G.scs (Part A) [29].

5.5 Simulation results

This subclause gives an overview of the relevant transmission system parameters used in the simulation programs in order to obtain the results given in clause 5. In all the simulations, noise effects (e.g. amplified spontaneous emission, shot noise) and variations of the fibre parameters (e.g. attenuation, dispersion) have been neglected. Pattern length was varied from 32 bits up to 128 bits. No LAs were used. Optical power levels refer to mean optical power. Only single-channel transmission systems have been considered.

NOTE: The simulation boundary conditions are not known and might not be compatible between the various examples given. Furthermore the simulations might not reflect realistic circumstances. Therefore simulations results should be interpreted with some care.

5.5.1 Parameters of the DST simulation:

Data rate:	10 Gbit/s
Transmission Fibre:	CSMF
Fibre Attenuation:	0,2 dB/km
Zero Dispersion Wavelength:	1 310 nm
Dispersion Slope:	0,09 ps/(nm^2.km)
Operation Wavelength:	1 549 nm
Dispersion at Operation Wavelength:	+17 ps/(nm.km)
Adiabatic Laser Chirp:	5 GHz
Alpha Factor:	2
AM Index:	20 %
Transmitter Power:	+12 dBm
Receiver Electrical Filter:	R.C. low-pass with f_{3dB} = 1 GHz

5.5.2 Parameters of the AM & PM simulation:

Data rate:	10 Gbit/s
Transmission Fibre:	CSMF
Fibre Attenuation:	0,2 dB/km
Zero Dispersion Wavelength:	1 310 nm
Dispersion Slope:	0,09 ps/(nm^2.km)
Operation Wavelength:	1 550 nm
Dispersion at Operation Wavelength:	+17,08 ps/(nm.km)
Modulation Phase Shift:	0,2 p rad...0.5 p radians
AM Index:	20...100 %
Transmitter Power:	+12 dBm
Receiver Electrical Filter:	5th order Bessel low-pass with f_{3dB} = 5,5 GHz

5.5.3 Parameters of the quaternary simulation:

Data rate:	10 Gbit/s
Transmission Fibre:	CSMF
Operation Wavelength:	1 550 nm
Dispersion at Operation Wavelength:	+17 ps/(nm.km)

5.5.4 Parameters of the duo-binary simulation:

Data rate:	10 Gbit/s
Transmission Fibre:	CSMF
Operation Wavelength:	1 550 nm
Dispersion at Operation Wavelength:	+17 ps/(nm.km)

5.5.5 Parameters of the SPM supported transmission simulation:

Data rate:	10 Gbit/s
Transmission Fibre:	CSMF
Fibre Attenuation:	0,2 dB/km
Zero Dispersion Wavelength:	1 310 nm
Dispersion Slope:	0,09 ps/($nm^2 \cdot$km)
Operation Wavelength:	1 549 nm
Dispersion at Operation Wavelength:	+17 ps/(nm.km)
AM Index:	75 %
Transmitter Power:	+12 dBm
Receiver Electrical Filter:	5th order Bessel low-pass with f_{3dB} = 8 GHz

Table 1: Comparison of various techniques and transmission ranges

Parameters: 10 Gbit/s over CSMF at 1 550 nm (D = 17 ps/(nm.km))

		Chirp- and pre-chirp	**Multi-level modulation**	**Dispersion compensating optical elements**			**Self-phase modulation**	**Midsystem spectral inversion**	**Wavelength Division Multiplexing**
	DST **Figures 4 + 5**	**AM & PM** **Figure 6**	**duo-binary modulation** **Figure 7**	**DCF** **Figure 8**	**Concatenated asymmetrical MZI** **Figure 9**	**All fibre devices**	**SPM** **Figure 10**	**MSI (FWM)** **Figure 11**	**4*STM-16 WDM**
Link range without O/E/O regenerative repeater (simulation)	150 - 250 km	150 - 250 km	150 - 250 km	potentially >1 000 km	potentially >100 km	for further study	100 - 200 km	potentially >1 000 km	>1 000 km
Verification in 10 Gbit/s system (experiment)	253 km [18] (101,102,50) or 182 km [18]	180 km [21] (with Prechirp, external modulation and DCF)	100 km [5], 138 km [2]	360 km [25] (3x120) or 150 km [22]	demonstration of 201 ps/nm dispersion on a BW of 27,5 GHz [16]	270 km CSMF fibres, 10 Gbit/s direct modulation, including 1 LA. [26]	204 km [10] (without LA, with pre-chirp ASK + MZM)	560 km [11] (2x280)	
Adjustment to fibre dispersion	coarse adjustment of transmitter or/and receiver	transmitter; adjustment of DCF	no	adjustment of DCF (tuned length)	element tuned to fibre length & wavelength	element tuned to fibre length and wavelength	adjustment of transmitter launch power and chirp	adjustment of location & spectral inversion	no
Remarks		Modulator with additional loss		DCF causes additional loss	- potential use in WDM systems - limited up to 10 Gbit/s - prototype level 4,8 dB loss	- application of axially non uniform strain - chirped fibre grating	can be combined with other DA techniques	to be placed at mid-system of the transmission fibre	relatively insensitive to fibre dispersion

Table 2: Comparison of repeaterless 10 Gbit/s systems with linear Dispersion Accommodation (DA) techniques

DA Technique		Implementation of DA Function DA_S	Implementation of DA Function DA_R	Transmission Fibre/Span	Reference
(A) System with CSMF at 1 550 nm (repeaterless)					
(A1)	DST method (FSK/ASK conversion)	- FSK modulation of LD	- ASK reception of PD	CSMF 182 km	[18]
(A2)	Prechirp LD + external modulation + DCF method	- prechirp LD - external modulation ($LiNbO_3$) - DCF and - OF	- DCF - OF	CSMF 180 km	[21]
(A3)	DCF method	- optical isolation - DCF	- variable attenuation - DCF (2x) - OF (2x)	CSMF >150 km	[22]
(A4)	Chirped gratings	chirped Bragg gratings + optical circulator	Chirped Bragg gratings + optical circulator	CSMF 270 km including 1 LA	[26]
(B) System with DSF at 1 550 nm (repeaterless)					
(B1)	External modulation + DCF within DSF/DCF TF	- FM-modulated LD - external modulation	- DCF - OF	DSF/DCF (90/190 km) 280 km	[24]
(B2)	External modulation method	- sinusoidal-modulated LD - external modulation	- OF	DSF 252 km	[23]
(B3)	Prechirp LD + external modulation + DCF method	- prechirp LD - external modulation ($LiNbO_3$) - DCF and - OF	- DCF - OF	DSF 215 km	[21]

DST = Dispersion Supported Transmission
DCF = Dispersion Compensating Fibre (with negative dispersion)
DSF = Dispersion Shifted Fibre (with low dispersion) (I-ETS 300 228 [37] or ITU-T Recommendation G.653 [34])
CSMF = Conventional Single Mode Fibre (optimized at 1 310 nm) (I-ETS 300 227 [36] or ITU-T Recommendation G.652 [35])
OF = Optical Filter
TF = Transmission Fibre

6 Polarization Mode Dispersion (PMD) effects

6.1 Physical characteristics

Polarization Mode Dispersion (PMD) is seen as different propagation delays for various polarization modes supported by the single-mode fibre. The PMD value is the delay variation between minimum and maximum delay, which are associated with two orthogonally polarized eigenmodes. This difference in group velocity is caused by geometric core ellipticity and by mechanical asymmetric thermal stress, which are both intrinsic effects created in the manufacturing process. However, external effects like torsion and bending will also affect the fibre birefringence locally but in a random manner, and the resulting mode coupling between the two eigenmodes will tend to counteract the build-up of PMD. This is the reason to two generally observed characteristics of PMD in single mode fibres:

1) the PMD value for a single-mode fibre cable usually can not be predicted by measuring the PMD value of the spooled fibre before cabling, since the full intrinsic PMD will not be brought out until the fibre rests with minimum stress in the cable;

2) for a short length of fibre (meters) PMD will be proportional to the length, while for a long length of fibre (kilometres, exceeding the mode coupling length) PMD will be proportional to the square root of the length. It should be noted, that the PMD value at long lengths is a statistical property with Maxwellian probability density function.

6.2 System impact

PMD in an optical fibre can be characterized by its mean differential group delay t, where the mean represents an average over either time or optical frequency. At any particular frequency w and time T, the fibre has an instantaneous Differential Group Delay (DGD) t. For an input pulse with a narrow optical spectrum, there are two possible input states of polarization called principal states of polarization. When the input pulse is in one or the other of these principal states of polarization, the pulse will travel down the fibre with no distortion. The group delays of pulses launched into the two principal states differ by t.

When the input pulse is in a polarization state that is a superposition of the two principal states, the output pulse can be approximated by the sum of two pulses with different group delays. When there is no polarization filter at the receiver, the detected output pulse shows distortion characterized by the size of the DGD. For a given t, this distortion is largest when the energy of light launched into each of the two principal states is equal.

The differential group delay is referred to as a first order effect. The first order PMD effect is the same as propagation through a birefringent fibre. In this case the differential group delay t is independent of optical frequency. However, in most cases, t varies with optical frequency, and when t varies significantly over spectral width of the input pulse, higher order PMD effects can occur. When the change in t over the spectral width of the pulse is not too large, the higher order PMD effects can be dominated by second order effects.

There are two kinds of second order effects: pulse broadening and mode mixing. When light is launched into either of the two principal states, in the first order they propagate down the fibre unchanged. However, in the second order, the pulse can be broadened or compressed, exactly as a pulse is broadened or compressed when propagating through a dispersive fibre. Thus there can be significant output pulse distortion even when the pulse is launched into a principal state.

The mode mixing effect arises because the description in terms of principal states of polarisation is no longer valid, when the DGD t varies significantly over the range of the input pulse optical spectrum. At each optical frequency, the fibre has a unique set of principal polarization states. So if light is launched into a principal state defined at the centre of the input pulse spectrum, there are spectral components away from the centre optical frequency that consist of a mixture of principal states at that frequency. Thus in this case it is impossible to launch all the energy of the pulse into one principal state, which results in distortion of the output pulse.

The distortion of the output pulse is a result of a combination of first and higher order PMD effects, and depends on the input state of polarization. When the input pulse spectral width is sufficiently narrow, the higher order effects are dominated by second order effects: dispersive broadening and polarization mode mixing.

For the specification of a 10 Gbit/s optical transmission system, the tolerable maximum PMD value of the optical path has to be considered. Measurements at lower bit rates (600 Mbit/s and 2,5 Gbit/s) have shown, that the PMD penalty is negligible for PMD values less than or equal to 1/10 of the bit period. By extrapolating this result to 10 Gbit/s bit rate, the specification for a maximum value is 10 ps, resulting in a PMD penalty of less than 0,5 dB for a receiver with PIN-photodiode and less than 1 dB for a receiver with an Avalanche Photo-Diode (APD) or where an Optically Amplified Receiver (OAR) is used. Example: a fibre with a 0,5 ps/√km PMD in a 10 Gbit/s system will allow up to a 400 km fibre length for a 10 ps mean differential group delay, if only PMD is to be considered.

7 Relationship to existing and emerging standards

- The new SDH level of STM-64 at 9,953 280 Gbit/s was introduced and accepted for ITU-T Recommendation G.707 [39] at the ITU-T SG15/WP3 meeting, Geneva, September 1993 [COM 15-R E-8, Oct. 1993];

- the ETSI TM1 Working Group 2 activity on '10 Gbit/s Optical System Technologies' has identified 'linear and non-linear DA techniques' applied for 10 Gbit/s long-haul systems and a general DA function for standardizing these techniques in SDH systems and SDH equipments. However, the introduction into already existing ITU-T Recommendations G.957 [41] and G.958 [32] is not possible, because these Recommendations have just been accepted and cannot be changed in the near future;

- the physical aspects of 10 Gbit/s (STM-64) optical interoffice line systems with OAs (BA, LA, PA) as well as linear and non-linear DA techniques, influencing optical interfaces, will now be introduced into ITU-T draft Recommendation G.scs [29]. The physical aspects and the optical interfaces of 10 Gbit/s optical interoffice line systems using WDM will be described in ITU-T draft Recommendation G.mcs [31]. Both ITU-T draft Recommendations contain the actual optical interface specifications derived from the physical considerations in this ETR;

- the functional aspects of 10 Gbit/s (STM-64) optical interoffice line systems with OA and DA, and/or optical multiplexing functions will be introduced into ITU-T draft Recommendation G.lon [33];

- a new fibre type with a low, non-zero dispersion in the 1 550 nm window could minimize negative FWM effects in long-haul multi-channel systems. This new fibre type is currently under consideration in ITU-T Study Group 15 for a possible new fibre ITU-T draft Recommendation G.65x [42];

- ITU-T draft Recommendation G.671 [40] transmission characteristics of passive optical components are being specified, e.g. the attenuation and the PMD of DCFs in the 1 550 nm wavelength region.

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