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TECHNICAL REPORT

Fibre optic communication system design guides – Part 4: Accommodation and utilization of non-linear effects

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 4: Accommodation and utilization of non-linear effects

FOREWORD

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IEC/TR 61282-4, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

This second edition cancels and replaces the first edition, published in 2003, and constitutes a technical revision.

This edition includes the following significant technical change with respect to the previous edition:

– clarifications on the compensation for nonlinear impairments with digital signal processing.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86C/1166/DTR	86C/1189/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 61282 series, published under the general title *Fibre optic communication system design guides*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 4: Accommodation and utilization of non-linear effects

1 Scope

This part of IEC 61282, which is a technical report, is intended to describe physically and analytically non-linear effects in fibre optic systems, their impact on system performance, and ways of minimizing the effects or using them to advantage. It contains some of ITU-T Recommendation G.663 [1] [1] with additional material. More details on applications are considered in [2] and networks in [3].

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60793-1 (all parts), *Optical fibres – Part 1: Measurement methods and test procedures*

IEC 60793-2 (all parts), *Optical fibres – Part 2: Product specifications*

IEC/TR 61292-3, *Optical amplifiers – Part 3: Classification, characteristics and applications*

3 Abbreviations and symbols

3.1 Abbreviations

BER	bit-error ratio
DCF	dispersion compensating fibre
DWDM	dense wavelength division multiplexing/demultiplexing
EDFA	erbium-doped fibre amplifier
FWHM	full width at half-maximum
FWM	four-wave mixing
FPM	four-photon mixing
IL	insertion loss
MI	modulation instability
OA	optical amplifier
OFA	optical fibre amplifier
ORL	optical return loss
OTDR	optical time-domain reflectometer
PDC	passive dispersion compensator
PDL	polarization dependent loss

[1] Figures in square brackets refer to the bibliography.

PMD	polarization mode dispersion
Rg	regenerator
RMSW	root-mean-square width
Rx	receiver
SBS	simulated Brillouin scattering
SLM	single longitudinal mode
SMF	single-mode fibre
SOA	semiconductor optical amplifier
SPM	self-phase modulation
SRS	simulated Raman scattering
TDM	time-division multiplexing
Tx	transmitter
XPM (CPM)	cross-phase modulation

3.2 Symbols

A_{eff}	(fibre) effective area in µm^2
c	speed of light in a vacuum in km/s or nm/ps
D	chromatic dispersion coefficient in ps/nm-km
f	signal (modulation) frequency in GHz
g	non-linear gain coefficient
I	light intensity in µW/µm^2
L_{eff}	(fibre) effective length in km
n	phase (refractive) index
N	group index
n_0	linear (phase) index
n_2	non-linear (phase) index
S	(chromatic) dispersion slope in ps/nm^2-km
subscript $_{\text{B}}$	Brillouin scattering
subscript $_{\text{P}}$	pump signal
subscript $_{\text{R}}$	Raman scattering
subscript $_{\text{S}}$	Stokes signal
t	time in ps to s
v_{g}	group velocity (speed) in km/s or nm/ps
v_{p}	phase velocity (speed) in km/s or nm/ps
z	distance coordinate along fibre in km
α	(power) attenuation coefficient in np/km or dB/km
β	propagation wave number in km^{-1}
Γ	non-linearity coefficient in W^{-1} or mW^{-1}
λ	light vacuum wavelength in nm to µm
φ	optical phase
ν	optical frequency in THz
ω	optical circular frequency in THz

4 General

4.1 System trends leading to non-linear effects

The market demand for new advanced telecommunications services has driven the rapid increase of system bandwidth, and, for some applications, longer system distances.

Greater bandwidth has been addressed in two ways. One way is by increasing the channel bit-rate, accomplished with optoelectronic time-division multiplexing (TDM) and various types of signal encoding. Another way is by increasing the number of channels, accomplished with channel multiplexing, such as polarization division multiplexing or (more commonly) by dense wavelength division multiplexing (DWDM). Bandwidth limitations of the optical fibre cable can be overcome with various dispersion management techniques.

Longer distances, defined to be the optical path lengths between 3R regenerators, can be achieved by two methods. One method is by increasing the span length, where a span is defined to be the optical path between optical amplifiers (OAs). A longer span length may be attained with fibre cable of lower attenuation coefficient and with fibre optic passive components having lower loss. The span length may also be increased with increased launched channel power from the output of the OA at the beginning of the span or with lower allowed power at the input of the OA at the end of the span. Another method of increasing the optical path length is to increase the number of spans. This increases the number of OAs, but improvements can be limited by amplifier noise degradation.

There are a number of interactive trade-offs in system design. For example, increasing the bit-rate reduces the span length by requiring higher received power or by requiring lower link dispersion. The latter may be addressed by dispersion compensation, but this introduces losses. Increasing the number of channels in DWDM systems also reduces span length due to optical multiplexing and demultiplexing losses. The loss limitations of a span can be overcome with OAs, but these introduce noise.

4.2 Optical amplifiers and non-linearities

An OA accepts a modulated signal at its input and emits an essentially identically shaped signal at its output. However, the optical power is higher (desired), and there is some additional noise (not desired). This technical report is concerned with the effects of higher power on the fibre and the implications for system design. These non-linear effects are so-called because they are not linearly proportional to launched power into the fibre or to the fibre length in either absolute units or in dB units. They are affected primarily by characteristics of the optical signal (power, optical spectrum, modulation, state of polarization), of the optical fibre (effective area, effective length, gain coefficients, non-linear index, dispersion, dispersion slope, polarization mode dispersion), and of system aspects such as distance between regenerators and the number and spacing of channels in DWDM systems. Power levels as low as several mW can induce non-linear effects.

One class of non-linear effects is stimulated scattering of the signal. Stimulated Brillouin scattering limits the power transmitted through the fibre by scattering some light backwards in the fibre. Stimulated Raman scattering mainly causes forward crosstalk in a DWDM system.

Another class of non-linear effects is phase-shifting of the signal. This leads to self-phase modulation and modulation instability that produce distortion even on a single channel, or to cross-phase modulation and four-wave mixing that introduce interference between channels. These interact with chromatic dispersion to degrade or enhance system performance. Soliton formation is another related effect.

4.3 Background and notation

4.3.1 Wavelength and frequency

These simple concepts are essential in discussing advanced optical transmission systems. One can interchangeably talk about the vacuum wavelength λ in nm and optical frequency ν in THz (10^{12} Hz or 1 000 GHz). The optical frequency is not to be confused with the signal modulation frequency f or the signal bit-rate B. By using the speed of light in a vacuum c, one can change between wavelength and frequency through the fundamental relation:

$$\lambda(\text{nm}) \times \nu(\text{THz}) = c(\text{nm/ps}) \quad \text{where} \quad c \approx 299{,}792{,}458 \text{ nm/ps} \tag{1}$$

The fundamental mode of a single-mode fibre has a phase (refractive) index n, which is dimensionless, with a value around 1,46 in silica fibre. It decreases as the wavelength of light increases and details depend upon the refractive index profile of the fibre and the characteristic of the fundamental mode. The wavelength of light in a fibre decreases to $\frac{\lambda}{n}$ and the speed of the light decreases to $\frac{c}{n}$, but the light's frequency ν does not change.

Examples of the wavelength/frequency correspondence from Equation (1) are shown in the two left columns of Table 1 for several significant wavelengths of interest. Note that as the (vacuum) wavelength increases, the frequency decreases.

For DWDM systems it is important to be able to relate wavelength and frequency in terms of differences. These differences describe channel widths and separations. From Equation (1), two wavelengths separated by $\Delta\lambda$ may be related to the frequency separation $\Delta\nu$ by

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta\nu}{\nu} \tag{2}$$

The fractional changes in wavelength and frequency are the same, though of opposite sign (important in later discussions of chirp). This can also be written as

$$-\frac{\Delta\lambda}{\Delta\nu} = \frac{\lambda^2}{c} = \frac{c}{\nu^2} \tag{3}$$

and examples of the correspondence in wavelength and frequency spreads are shown in the two right columns of Table 1. For a communications engineer, dealing in frequency, which is related to information content, is more natural than dealing with wavelength. Note that a constant frequency spread has a larger wavelength spread at longer wavelengths.

It is sometimes convenient to use the notation $\beta(\omega) = \frac{2\pi}{\lambda} n(\omega)$ for the propagation wave number in the material. It depends upon the circular frequency $\omega = 2\pi\nu$, so Equation (1) is

$$\omega n(\omega) = c\beta(\omega) \tag{4}$$

4.3.2 Various velocities

It is important to distinguish between two types of velocities in optical fibre. The phase of an optical wave, as written in $e^{i\phi}$, is

$$\phi = \beta z - \omega t = 2\pi\left(\frac{nz}{\lambda} - \nu t\right) \tag{5}$$

where

z is the distance along the fibre;

t is the time.

For a point of constant phase along the optical wave, $d\phi = 0 = \beta dz - \omega dt$, so dz/dt is the phase velocity (actually “speed”) given by

$$v_p = \frac{\omega}{\beta(\omega)} = \frac{c}{n(\nu)} \tag{6}$$

Table 1 – Correspondence of wavelength and frequency

Wavelength nm	**Frequency** THz	**1 nm spread** GHz	**100 GHz spread** nm
1 260,000 (nominal lower limit due to cut-off)	237,931	188,8	0,530
1 310,000 (nominal zero dispersion for category B1 fibre)	228,849	174,7	0,572
1 395,000 (nominal water peak)	214,905	154,1	0,649
1 550,000 (nominal zero dispersion for category B2 fibre)	193,414	124,8	0,801
1 552,524 (ITU grid reference)	193,100	124,4	0,804
1 625,000 (nominal upper limit due to attenuation)	184,448	113,5	0,881

Although the optical subcarrier travels at the phase velocity, this is not the primary interest of a communications engineer. The subcarrier is modulated to produce an analogue or digital signal. The more slowly varying signal envelope and its associated energy travel at the group velocity.

$$v_g = \left(\frac{d\beta}{d\omega}\right)^{-1} = \frac{c}{N} \tag{7}$$

is the group velocity. Here

$$N = n - \lambda\frac{dn}{d\lambda} = n + \upsilon\frac{dn}{d\upsilon} \tag{8}$$

is the group index. (For silica fibre in the wavelength regions of interest, this is slightly larger than the phase index because the wavelength derivative is positive.) These “group” quantities describe the speed at which energy and information (such as pulses) travel down the fibre. Also, this index is the appropriate one for the pulses generated by an optical time-domain reflectometer (OTDR). The group index can easily be measured as the time delay of a pulse or the phase shift of an RF modulation, both for a known physical length of fibre.