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Cable networks for television signals, sound signals and interactive services –

Part 6-1: System guidelines for analogue optical transmission systems

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Part 6-1: System guidelines for analogue optical transmission systems

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

CABLE NETWORKS FOR TELEVISION SIGNALS, SOUND SIGNALS AND INTERACTIVE SERVICES –

Part 6-1: System guidelines for analogue optical transmission systems

FOREWORD

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IEC 60728-6-1, which is a technical report, has been prepared by technical area 5: Cable networks for television signals, sound signals and interactive services, of IEC technical committee 100: Audio, video and multimedia systems and equipment.

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

Enquiry draft	Report on voting
100/1078/DTR	100/1142A/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 the parts of the IEC 60728 series, under the general title *Cable networks for television signals, sound signals and interactive services*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result 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- withdrawn,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.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

Standards of the IEC 60728 series deal with cable networks for television signals, sound signals and interactive services including equipment, systems and installations for

- head-end reception, processing and distribution of sound and television signals and their associated data signals;
- processing, interfacing and transmitting all kinds of signals for interactive services using all applicable transmission media.

All kinds of networks like

- CATV-networks
- MATV-networks and SMATV-networks
- individual receiving networks

and all kinds of equipment, systems and installations installed in such networks, are within this scope.

The extent of this standardization work is from the antennas, special signal source inputs to the head-end or other interface points to the network up to the terminal input.

The standardization of any user terminals (i.e. tuners, receivers, decoders, multimedia terminals etc.) as well as of any coaxial and optical cables and accessories thereof is excluded.

CABLE NETWORKS FOR TELEVISION SIGNALS, SOUND SIGNALS AND INTERACTIVE SERVICES –

Part 6-1: System guidelines for analogue optical transmission systems

1 Scope

This part of IEC 60728 provides guidelines and procedures for determining the overall performance of optical transmissions systems used in cable networks for television signals, sound signals and interactive services. It is based on the requirements for optical equipment defined in IEC 60728-6 and should be used together with this standard. The information provided is meant to help field engineers and network planners (system designers) in planning and designing optical systems. Though this content is less dense than in a standard, basic knowledge about system parameters of cable networks is needed.

2 Normative references

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

IEC 60728-1, *Cable networks for television signals, sound signals and interactive services – Part 1: Methods of measurement and system performance*

IEC 60728-3, *Cable networks for television signals, sound signals and interactive services – Part 3: Active wideband equipment for coaxial cable networks*

IEC 60728-6, *Cable networks for television signals, sound signals and interactive services – Part 6: Optical equipment*

IEC 60793-2, *Optical fibres – Part 2: Product specifications – General*

IEC 61931, *Fibre optics – Terminology*

3 Terms, definitions, symbols and abbreviations

For the purposes of this document, the terms, definitions, symbols and abbreviations given in IEC 60728-1, IEC 60728-6 and IEC/TR 61931 apply.

3.1 Symbols

In addition to the symbols given in the above-mentioned references, the following graphical symbol is used in the figures of this technical report.

$\boxed{\text{WDM}}$	wavelength division multiplexer

3.2 Abbreviations

In addition to the abbreviations given in the above-mentioned references, the following abbreviations are used in this technical report.

2HD second harmonic distortion

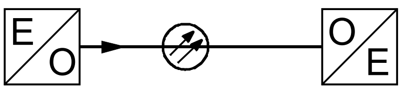
3HD	third harmonic distortion
DFB	distributed feedback
DWDM	dense wavelength division multiplex
IIN	induced intensity noise
IMD2	second-order intermodulation
IMD3	third-order intermodulation
IM-DD	intensity modulation – direct detection
I_r	equivalent input noise current density of an optical receiver
OMI	optical modulation index
MPI	multi-path interference
PMD	polarization mode dispersion
PMP	point-to-multi-point
PTP	point-to-point
RMS	root-mean-square
SBS	stimulated Brillouin scattering
WDM	wavelength division multiplexer

4 Topologies used for optical transmission systems in cable networks

The overall performance of optical transmission systems depends on many parameters and conditions. Separating the applications into different categories simplifies the step-by-step analysis and leads to a better overview. A logical way to build up these categories is to distinguish different network topologies because it can be assumed that the network architecture is always known in advance. Starting from this point of view the following five topologies can be identified as relevant for the user.

4.1 Point-to-point system

Point-to-point (PTP) systems consist of a single optical transmitter and a single optical receiver connected by a single line of fibre (Figure 1).



IEC 2154/06

Figure 1 – Point-to-point system

This configuration can typically be found in trunk-line feeding areas cabled with coax (HFC networks). Both wavelengths, 1 310 nm and 1 550 nm, are used for these systems. Most of the optical budget is consumed by the fibre attenuation (long-distance system). At 1 550 nm, optical amplifiers can be used to extend the range of this kind of system.

4.2 Point-to-multi-point system

In point-to-multi-point (PMP) systems, a single optical transmitter feeds more than one optical receiver. The receivers are connected to a main fibre via optical couplers and tap fibres as shown in Figure 2.

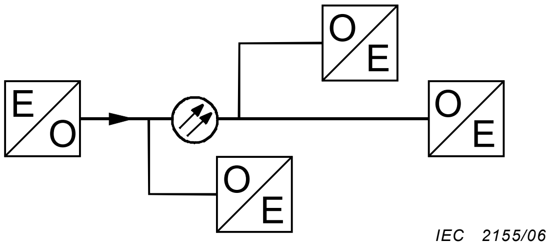


Figure 2 – Point-to-multi-point system

An alternative configuration for feeding more than one receiver from a single transmitter is to use an optical splitter at the transmitter node and individual fibres from the transmitter node to each receiver. This leads to a star topology, which should be treated as multiple PTP systems with a single transmitter.

PMP systems are typically used when different coaxial parts of a network shall be supplied with the same signal saving as much fibre as possible (optical distribution systems). Depending on the fibre lengths, both wavelengths are used. At 1 550 nm, optical amplifiers can be used to compensate for the fibre and splitting losses.

4.3 Multi-point-to-point system

Multi-point-to-point systems consist of at least two transmitters with different wavelengths sending their signals to a common receiver. The transmitter signals may be combined by an optical coupler or, if the link loss is critical, by a wavelength multiplexer (Figure 3).

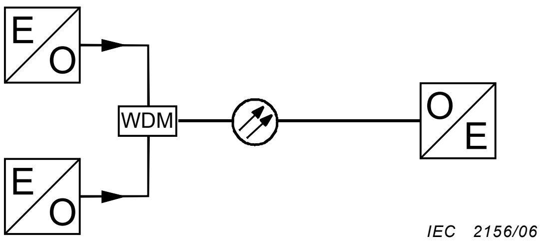


Figure 3 – Multipoint-to-point system

Since optical receivers usually have a very broad input wavelength range, the central wavelengths of the transmitters may be extremely different (for example, 1 310 nm and 1 550 nm). In order to avoid signal mixing in the receiver, the optical spectrums of the transmitters shall differ at least by the upper limit of the receiver's electrical frequency range. If only signals in the 1 550 nm wavelength range are used, optical amplifiers can be employed for extending the fibre length. Since all input signals of the system are provided at the same system output, different frequency ranges have to be used for modulating the transmitters.

This kind of topology is typically chosen if part of a network shall be provided with signals from different locations.

4.4 Real wavelength division multiplex system

Real wavelength division multiplex systems consist of at least two PTP systems operating on the same fibre. The transmitter signals are combined at the transmitter node with a wavelength multiplexer or, if the link loss is not critical, by an optical coupler. At the receiver node, the different signals are separated by another wavelength multiplexer and led to individual receivers (Figure 4).

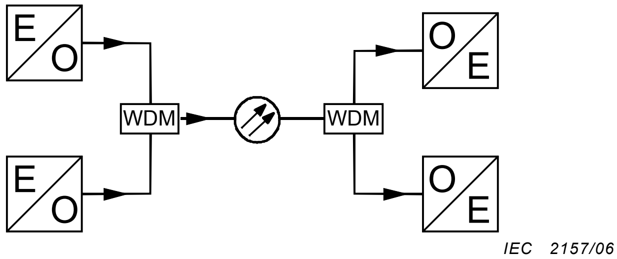


Figure 4 – Real wavelength division multiplex system

For only two different wavelengths, this configuration can be built up easily combining a 1 310 nm system and a 1 550 nm system. If wavelength dependent fibre losses cannot be tolerated, or more than two PTP systems have to be combined, closer spacing of the wavelengths shall be chosen (DWDM = dense WDM). This is usually done in the 1 550 nm wavelength range. Optical amplifiers can be used to achieve longer link lengths in this case. Care has to be taken to avoid overlapping of the transmitters spectrums. Narrow wavelength spacing means high efforts to control the transmitter wavelengths and high costs for the wavelength division multiplexers.

The main reason for using this configuration is to save fibres. This approach allows for the transmission of digital and analogue modulated signals over the same fibre.

4.5 Combinations

The basic configurations described above can be combined to more complex architectures. The best way of dealing with such complex structures is to split them up into their basic parts which could be treated separately.

5 Influences of equipment and fibre parameters on the system performance

The performance of analogue optical transmission systems depends not only on various equipment parameters but also on the properties of the fibre installation. Some of these parameters and properties interact in a way making it necessary to look at the transmission system at a whole. The interdependencies between the equipment and system properties and the performance parameters are shown in Table 1. The numbers in the table refer to the clauses of this technical report containing the relevant information.

Table 1 – Interdependencies between equipment and system properties and performance parameters

Equipment properties and effects		System performance parameters				
		C/N	**CSO**	**CTB**	**Flatness**	**Output level**
TX	OMI	Clauses 6 and 7	Clause 6, 8.2	Clause 6, 8.1	(Clause 9)	Clauses 6 and 10
	CSO		8.1			
	CTB			8.2		
	Line width	B.1.2				
	Chirping	7.2	C.3.7.1, C.3.7.2	C.4.1		
	RIN	Clause 7				
	Power	Clause 7				Clause 10
	λ	(7.3)				
	Flatness				Clause 9	
RX	I_r	Clause 7				
	CSO		8.1			
	CTB			8.2		
	Flatness				Clause 9	
	AGC range				Clause 9	Clause 10
OFA	F	7.4				
	Power	7.4				Clause 10
	Gain	7.4	(8.1.2)	(8.2)		
	λ	7.4				
Fibre	Dispersion		C.3.7.1, C.3.7.2	(8.2)		
	SBS	(7.2)	(8.1.2)	(C.4.3)		
	SPM		C.3.10			
	PMD		(8.1.1)			
	Loss	Clause 7				Clause 10
Passive	Return loss	(B.1.3)				
	PDL		(C.3.7.2)			
	Loss	Clause 7				Clause 10
X: relevant		(X): can be relevant				

This table can be used as an entry point and quick reference to the contents of this technical report.

6 Optical modulation index

The optical modulation index (OMI) is one of the most important parameters of analogue optical links. It shall be chosen very carefully in order to obtain the best carrier-to-noise ratio without getting too much distortion due to clipping effects (see C.3.3).

Working with OMIs two cases shall be considered: single wavelength systems and wavelength division multiplex (WDM) systems.

6.1 Single wavelength system

The definition of the OMI is very similar to the definition of the modulation index in ordinary AM modulation. An illustrative explanation of this definition is shown in Figure 5.

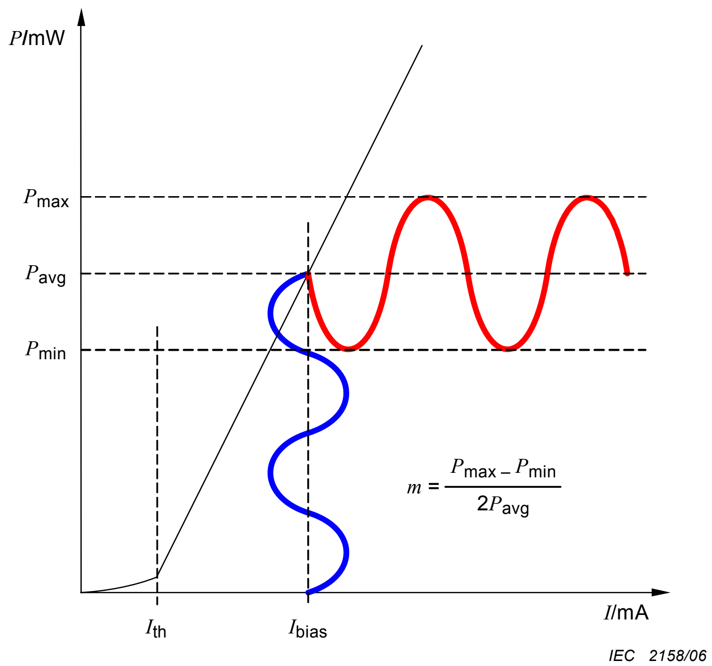


Figure 5 – Definition of OMI for an optical transmitter

The OMI is defined as

$$m = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} = \frac{P_{max} - P_{min}}{2 \cdot P_{avg}} \tag{1}$$

where

m is the optical modulation index;

P_{max} is the peak optical output power;

P_{min} is the minimum optical output power;

P_{avg} is the mean optical output power.

Laser currents below I_{th} lead to clipping, and the waveform of the optical output power becomes distorted. The OMI is more than 1 then.

This definition relates to a single channel and a sinusoidal signal. The same definition can also be used with QAM signals if the equivalent power is used to calculate a new peak value of the modulating current. However, the signals transmitted in cable networks are a mixture of a whole bunch of channels containing carriers with various modulation schemes. For each channel an individual OMI can be determined.

Since the peak-to-average ratio of combined signals decreases with the number of channels, the individual OMIs do not add up linearly to the total OMI. The total OMI for several channels is, instead, calculated by summing the powers of individual carriers

$$m_T = \sqrt{m_1^2 + m_2^2 + \ldots + m_N^2} \tag{2}$$

Provided that all channels have equal OMI the formula simplifies to

$$m_T = m\sqrt{N} \tag{3}$$

The total OMI is a practical value for making estimations of the maximum channel counts or for C/N calculations with a certain number of channels [6][1], but the peak-to-average ratio for relatively small numbers of channels can be surprisingly high, and clipping may occur at smaller total OMI values than in the case of more than 10 channels. For analogue carriers, m_T = 0,3 is a typical value for 1 310 nm directly modulated transmitter and m_T = 0,25 to 0,28 for externally modulated 1 550 nm transmitter.

6.2 WDM systems

In WDM systems outputs of optical transmitters are combined using wavelength division multiplexers or optical couplers. Thereby the average optical output powers add up resulting in a reduced OMI for the individual channels. For the combination of signals from two transmitters the resulting OMI of a channel can be calculated by

$$m = \frac{m_1 \cdot P_1}{P_1 + P_2} \tag{4}$$

where

m_1 is the OMI of the channel to be considered, transmitted by the first transmitter;

P_1 is the optical power of the first transmitter at the output of the combining device (optical coupler or WDM);

P_2 is the optical power of the second transmitter at the output of the combining device (optical coupler or WDM).

For more than two transmitters, the denominator shall be replaced by the sum of all powers at the output of the combining device. If the combined signal is fed to an optical receiver, the carrier-to-noise ratio at its output is lower than with a single optical signal due to the reduced OMIs. Therefore, multi-point-to-point systems are not very popular and true WDM systems with separate receivers for each wavelength are preferred in cable networks. Nevertheless, this configuration can be useful for adding narrowcast signals to broadcast signals in existing networks. As equation (4) shows, great care has to be taken by adjusting the power levels of the input signals.

6.3 Choosing the right input level at the transmitter

The OMI is directly related to the driving current of the laser hence to the input level of the transmitter. Therefore, choosing the right transmitter input level is crucial for any optical transmission link. Some manufacturers solved this problem by developing special driving amplifier with an automatic gain control (AGC) for their transmitters. This results in a broader input level range for achieving the optimum OMI. Nevertheless, even with this kind of solution, the input level should be chosen carefully in order to save the AGC range for unwanted changes in the level or the channel load.

---

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

IEC 60728-6 requires manufacturers to publish the required input level at which the required performance can be met (see 6.1.1 of IEC 60728-6). Starting from this level the optimum input level for a given channel load can be calculated, using the following procedure.

1) Check the count of channels related to the given reference input level stated in the data sheet of the optical transmitter. Since according to IEC 60728-6, all transmitters shall be designed for the frequency range 47 MHz to 862 MHz and all measurements shall be carried through using the channel allocation specified in IEC 60728-3, this count will usually be n_0 = 42.
2) Determine the effective channel load for the considered system. For the effective channel load the different levels of the channels to be transmitted shall be taken into account:

$$n_\mathrm{e} = \sum_n 10^{\frac{\Delta U_\mathrm{n}}{10}} \tag{5}$$

where ΔU_n is the deviation from the level of an analogue channel in dB.

With this effective channel load the target deviation ΔU from the reference input level can be calculated easily with

$$\Delta U = 10 \cdot \lg\left(\frac{n_\mathrm{e}}{n_0}\right) \text{ in dB} \tag{6}$$

3) If the OMI is given for the reference input level (m_ref), the OMI for the new channel load can be calculated with

$$m_\mathrm{e} = m_\mathrm{ref}\sqrt{\frac{n_0}{n_\mathrm{e}}} \tag{7}$$

This procedure should be used only when the number of channels (n_e and n_0) is higher than 10 (see 6.1). For lesser channel loads, significant deviations from the optimum OMI can occur.

7 Carrier-to-noise ratio

Noise in optical links can be divided into three different components: intensity noise, shot noise and thermal noise (Annex B). Intensity noise is noise associated with the generation of light in transmitters and optical amplifiers, shot noise appears in the receiver and thermal noise is a noise mechanism of the electrical amplifiers. The parameters needed for calculating the carrier-to-noise ratio of an optical link are either well known or shall be given in the data sheets of the equipment as required by IEC 60728-6.

7.1 Short-haul links with a single transmitter

The carrier-to-noise ratio for a single channel of an optical point-to-point link up to lengths of about L = 30 km can be calculated using equation (25) in 4.19 of IEC 60728-6:

$$C/N = 20\lg m - 10\lg(2B) - 10\lg\left(10^{-\frac{1}{10}RIN} + \left(\frac{2e}{rP_\mathrm{opt,RX}} + \frac{I_\mathrm{r}^2}{r^2 P_\mathrm{opt,RX}^2}\right)\right) \tag{8}$$

where

RIN is the relative intensity noise in dB/(Hz)$^{-1}$. This value shall be published in the data sheet of the optical transmitter;

m is the OMI of the channel to be considered. For the choice of the right OMI, see Clause 6;

$P_{\text{opt,RX}}$ is the optical power incident on the photodiode in W;

r is the responsivity of the photodiode in A/W;

B is the bandwidth in Hz;

e is $1{,}6 \times 10^{-19}$ C (charge of an electron);

I_{r} is the effective spectral noise current density in A/√Hz.

In point-to-multi-point systems this equation has to be used for each receiver, as different optical input powers shall be taken into account.

7.2 Long-haul point-to-point link

Long fibres can degrade the carrier-to-noise ratio of an analogue optical link. Using direct modulation, for example, with DFB lasers, multi-path interference is the main source for additional link noise. With externally modulated transmitters, care has to be taken to avoid signal degradation due to stimulated Brillouin scattering (SBS).

7.2.1 Long-haul links with DFB lasers

At fibre lengths above L = 20 km, multi-path interference should be taken into account for calculating the carrier-to-noise ratio. With equation (B.9) (see B.1.3), the carrier-to-noise ratio equation from equation (8) extends to

$$C/N = 20\lg m - 10\lg(2B) - 10\lg\left(10^{-\frac{1}{10}(RIN + RIN_{\text{IIN}})} + \left(\frac{2e}{rP_{\text{opt,RX}}} + \frac{I_{\text{r}}^2}{r^2 P_{\text{opt,RX}}^2}\right)\right) \qquad (9)$$

The main difficulty in applying this equation is to find the values needed for calculating RIN_{IIN} according to equation (B.9). The following hints may help to get reasonable results.

α The fibre's attenuation-per-unit length is usually known in dB/km (for example, 0,38 dB/km at λ = 1 310 nm or 0,18 dB/km at λ = 1 550 nm). For α the according (linear) attenuation coefficient shall be used (for example, $\alpha = \ln(10^{-0,38/10})$/km =0,0875/km at λ = 1 310 nm).

α_{S} The proportion of signal scattered per unit length is a parameter of the fibre and can be found in the fibre's data sheet. For standard single-mode fibre $\alpha_{\text{S}} \approx \alpha$ can be assumed.

S The fraction of scattering that is captured by the fibre is also a parameter of the fibre which can be found in data sheets. For standard single-mode fibre S = 0,001 5 is a common value.

η_{FM} The light source's chirping efficiency is usually not specified by the manufacturer of lasers and transmitters because it varies in a very large range from sample to sample. The measurement of this parameter is costly and the benefit is low. As a rule of thumb, η_{FM} = 250 MHz/mA to 500 MHz/mA can be used for standard DFB lasers at 1 310 nm.

I_{b}, I_{th} The bias current and the threshold current of the laser are set by the manufacturer of the transmitter and are usually not published in the data sheet. Common values are in the range $I_{\text{b}} - I_{\text{th}}$ = 40 mA to 60 mA for high-power DFB lasers used in long-haul systems.

7.2.2 Long-haul links with externally modulated transmitters

For long distances high optical power is needed in order to achieve sufficient input power at the receivers. With modern high-power DFB lasers up to $L \approx 40$ km can be achieved. For even longer distances the wavelength range at 1 550 nm shall be used where the fibre attenuation is significantly lower. Unless dispersion-shifted fibres or dispersion-flattened fibres are employed, directly modulated DFB lasers cannot be used anymore at these wavelengths because the laser's chirping and the dispersion of the fibre would cause too much distortion. Externally modulated transmitters are used instead.

Another advantage of using the wavelength range at 1 550 nm is that optical amplifiers are available. Using optical amplifiers as booster amplifiers, very high output powers up to several 100 mW could be achieved. Unfortunately, the small cross-section of single-mode fibre cores is not able to handle such powers. Non-linear effects of the fibre lead to distorted signals (Annex A). Several techniques have been developed for broadening the optical spectrum of externally modulated transmitters in order to increase the maximum power level. As a drawback, a certain loss in carrier-to-noise ratio at long fibre lengths due to increased multi-path interference shall be accepted. Unfortunately, without detailed knowledge about these techniques, there is no reliable method for predicting the C/N degradation to be expected. Therefore, IEC 60728-6 requires that the degradation shall not exceed 2,5 dB at a fibre length of L = 65 km. For different fibre lengths, the manufacturer shall be consulted or measurements shall be made.

7.3 Multiple transmitter systems (WDM)

If signals from optical transmitters working at different wavelengths are combined and fed to a single receiver, the optical modulation index decreases according to equation (4). With this resulting modulation index, equation (8) can be used for calculating the carrier-to-noise ratio. This works satisfactorily as long as the wavelengths of the transmitters are close together in the same range (1 310 nm or 1 550 nm). If different wavelength ranges are used (1 310 nm and 1 550 nm), the wavelength dependency of the responsivity of the photodiode shall be taken into account. This can easily be done by using an adapted equation for the optical modulation index of the combined signal:

$$m = \frac{m_1 \cdot P_1 \cdot r_1}{P_1 \cdot r_1 + P_2 \cdot r_2} \qquad (10)$$

where

m_1 is the optical modulation index (OMI) of the channel to be considered, transmitted by the first transmitter;

P_1 is the optical power at λ_1 of the first transmitter at the output of the combining device (optical coupler or WDM);

P_2 is the optical power at λ_2 of the second transmitter at the output of the combining device (optical coupler or WDM);

r_1 is the responsivity of the receiving photodiode at λ_1;

r_2 is the responsivity of the receiving photodiode at λ_2.

7.4 Transmission systems with optical fibre amplifier

With optical fibre amplifiers the range of optical transmission systems can be increased significantly. The major drawback of optical amplifiers is that they add noise to the amplified signal. Therefore, only a very limited number of optical amplifiers can be cascaded in optical cable networks.

The amount of added optical noise is expressed as a noise figure, which has a similar definition to the noise figure of electrical amplifiers. With a known noise figure, the carrier-to-noise ratio of an optical transmission system including an optical amplifier can be calculated according to equation (11).

$$C/N = 20\lg m - 10\lg(2B) - 10\lg\left(10^{-\frac{1}{10}(RIN)} + \frac{2h\nu}{P_{\mathrm{in}}}\left(10^{\frac{F}{10}} - \frac{1}{G}\right) + \left(\frac{2e}{rP_{\mathrm{opt,RX}}} + \frac{I_{\mathrm{r}}^2}{r^2 P_{\mathrm{opt,RX}}^2}\right)\right) \qquad (11)$$

where

RIN	is the relative intensity noise of the optical transmitter in dB(Hz)$^{-1}$. This value shall be published in the data sheet of the optical transmitter;
m	is the OMI of the channel to be considered. For choice of the right OMI, see Clause 6;
$P_{\mathrm{opt,RX}}$	is the optical power incident on the photodiode in W;
r	is the responsivity of the photodiode;
B	is the bandwidth of the considered transmission channel in Hz;
e	is $1{,}6\cdot10^{-19}$ C (charge of an electron);
I_{r}	is the effective spectral noise current density in A/√Hz;
F	is the noise figure of the optical amplifier in dB. This value depends on the optical input power. Therefore, manufacturers shall publish the noise figure as a function of the optical input power;
$G = P_{\mathrm{out}}/P_{\mathrm{in}}$	is the power gain of the optical amplifier;
h	is $6{,}62\cdot10^{-34}$ Js (Planck's Constant);
	is the frequency of the light signal in Hz. Because of the high frequency of light signals, the wavelength in the vacuum is commonly used instead: $\nu = c_0/\lambda$.

If optical amplifiers are cascaded, equation (11) is not useful. A better approach is to consider the added noise as an increase of the RIN.

$$RIN_{\mathrm{out}} = 10\lg\left(10^{-\frac{1}{10}(RIN_{\mathrm{in}})} + \frac{2h\nu}{P_{in}}\left(10^{\frac{F}{10}} - \frac{1}{G}\right)\right) \qquad (12)$$

where

RIN_{out}	is the relative intensity noise of the output signal in dB(Hz)$^{-1}$;
RIN_{in}	is the relative intensity noise of the input signal in dB(Hz)$^{-1}$.

With this equation the increase of the RIN can be calculated step by step for each optical amplifier passed. For the last part of the system the resulting RIN_{out} can be inserted in equation (8) for determining the carrier-to-noise ratio from end to end.

8 Linearity

Non-linear distortion in cable networks leads to intermodulation of the transferred signals. Due to the regular spacing of channels, intermodulation products add up at certain frequencies (Annex C). The ratio of the carriers to the cumulated distortion products is called CSO for second-order distortion and CTB for third-order distortion. Both parameters are expressed in dB. In some documents negative values and the unit dBc are used in order to point out that the cumulated distortion products are below the carrier. Throughout this report and in IEC 60728-6, only positive values are used.

Unlike C/N the calculation of CSO and CTB values is difficult because several aspects shall be considered.

- The amount of non-linear distortion depends on the channel allocation used.
- The linearity of active devices depends on the frequency.
- Laser clipping is a very strong source of distortion. Precise calculations can only be made if all signals are well known as a function of time or if statistical methods can be applied.
- CSO and CTB depend on the load of the active devices (number and level of channels).
- Strictly speaking CSO and CTB are defined for un-modulated carriers only.
- It is hardly possible to predict how intermodulation products from different sources add up on a certain frequency. Sometimes even compensation can be observed. The results depend on the phase of the different intermodulation products, which in turn depend on the phase of the input signals and the phase behaviour of the active device's internal distortion sources which both are usually unknown.

For most relations only assumptions can be made. Their accuracy largely depends on the applicability of statistical methods. Therefore, calculated CSO and CTB values can deviate significantly from measured results.

8.1 Composite second order (CSO)

The symmetrical characteristic line of externally modulated transmitters leads to very low second-order distortion. So, CSO is mainly a problem of transmitters containing directly modulated lasers. Deviations between samples of the same laser charge are significant. Therefore, additional pre-distortion circuits are often employed to achieve CSOs good enough for cable networks. As stated above, the CSO of an optical system cannot reliably be calculated from the CSOs of the TX and the RX due to the fact that the laws of statistics cannot be applied. Therefore, the following procedures may only be understood as guidance for rough estimations.

8.1.1 CSO of 1 310 nm systems

In the 1 310 nm wavelength range, fibre dispersion can be neglected on short hauls up to approximately L = 25 km. For this kind of system, only the distortion of the transmitter and the receiver and the influence of the channel allocation shall be considered.

a) Make sure that the CSO values of both the transmitter ($CSO_{\mathrm{CLC,TX}}$) and the receiver ($CSO_{\mathrm{CLC,RX}}$) are given for the IEC frequency map as required in 4.12 of IEC 60728-6.

b) The CSO for the whole link can be estimated out of the single CSO values with

$$CSO_{\mathrm{CLC}} = k \cdot \lg\left(10^{\frac{1}{k}CSO_{\mathrm{CLC,TX}}} + 10^{\frac{1}{k}CSO_{\mathrm{CLC,RX}}}\right) \tag{13}$$

where k = 15 for unlocked carriers and k = 20 for locked carriers.

NOTE Sometimes the CSO value is already given in the data sheets of the manufacturers for the whole link.

c) Calculate the maximum number of beats n_{act} for the actual frequency map. The maximum number of second order beats for the full IEC frequency map according to IEC 60728-3 is n_{CLC} = 22 at f = 48 MHz. With these beat counts the resulting CSO_{res} can be calculated with

$$CSO_{\mathrm{res}} = CSO_{\mathrm{CLC}} + 10\lg\frac{n_{\mathrm{act}}}{n_{\mathrm{CLC}}} \tag{14}$$

This procedure can also be applied to externally modulated transmitters. Since the CSO of this kind of transmitter is usually high, calculated results are even less reliable.

At fibre lengths L > 25 km CSO can be deteriorated due to interaction of chromatic dispersion and laser chirping. The CSO contribution of this effect can be calculated by applying equation (50) of C.3.7.1. The main difficulty with this procedure is that in most cases neither the precise wavelength of the laser nor the true dispersion of the fibre at this wavelength is known because both vary in certain ranges. With a transmitter wavelength of λ = (1 310 ± 10) nm as required in 6.1.3 of IEC 60728-6 and the standard fibre specified in IEC 60793-2, the resulting dispersion range is D = 0 ps/(nm km) to 2 ps/(nm km).

Other sources of second-order distortion can be neglected for 1 310 nm systems. CSO caused by laser chirping and polarization-mode dispersion (PMD) and polarization-dependent loss shall be kept low as described in C.3.7.2. Laser clipping shall be avoided by choosing the right optical modulation index (6) and the power available by directly modulated lasers at this wavelength range is not high enough to reach the threshold for non-linearities of the fibre like Brillouin scattering or self-phase modulation.

Both the inherent CSO of the devices and the CSO caused by the interaction of laser chirping and chromatic dispersion are frequency dependent. That means equation (14) has to be applied to all frequencies within the band where second order beats occur, if the combined CSO shall be calculated. For the superposition of both CSOs the following equation can be used:

$$CSO_{\mathrm{SYS}}(f) = k \cdot \lg\left(10^{\frac{1}{k}CSO_{\mathrm{res}}(f)} + 10^{\frac{1}{k}CSO_{\mathrm{D}}(f)}\right) \tag{15}$$

where

$CSO_{\mathrm{res}}(f)$ is the CSO of combined transmitter and receiver at the frequency f;

$CSO_{\mathrm{D}}(f)$ is the CSO caused at the frequency f by laser chirping and dispersion;

$CSO_{\mathrm{SYS}}(f)$ is the resulting CSO of the system at the frequency f;

k is 15 for unlocked carriers and k = 20 for locked carriers.

8.1.2 CSO of 1 550 nm systems

The wavelength range at 1 550 nm differs from 1 310 nm in the following three ways.

- Optical amplifiers with high output powers are available.
- The standard fibre has high chromatic dispersion at this wavelength.
- Due to the low fibre attenuation, higher distances can be achieved.

At short distances and with dispersion-shifted fibre, directly modulated lasers can be used as transmitters. These systems can be treated the same way as 1 310 nm systems (8.1.1), but with the chromatic dispersion valid for this wavelength range. For distances exceeding a few kilometres, externally modulated transmitters with controlled chirping are used at this wavelength in order to avoid second-order distortion due to the interaction of chirping and fibre dispersion. Other advantages of this kind of transmitter are their inherent good second-order linearity and the missing of a hard clipping limit. Nevertheless, the optical modulation index shall also be chosen very carefully in order to avoid excessive distortion.

Due to the controlled chirping, the methods of C.3.7.1 cannot be applied for externally modulated transmitters. The CSO degradation of the signal due to fibre dispersion is instead required to be less than 2 dB at a fibre length of L = 65 km. As a rule of thumb, linear interpolation can be used for other fibre lengths. For more precise values measurements shall be made. The CSO of the combination of the transmitter and the receiver can be calculated in the same way as for 1 310 nm systems using equations (13) and (14).

With the use of optical amplifiers, the power limit for the non-linear behaviour of the fibre can be exceeded easily at the 1 550 nm wavelength range. The controlled chirping of externally modulated transmitters is used to push this limit as high as possible. In practice Brillouin scattering and self-phase modulation shall be avoided. That means the power calculated with equation (A.4) shall not be exceeded.

Appropriate optical amplifiers do not add up to the system's CSO significantly. The main cause of non-linear distortion from optical amplifiers is their optical gain slope, which is kept low by the manufacturers. Therefore, the method of calculation described in C.3.6 is not needed in practice and no publication of the necessary parameter is required in IEC 60728-6.

8.2 Composite triple beat (CTB)

As far as clipping effects can be neglected directly modulated lasers show very good third-order linearity. Therefore, CTB is usually not a problem for optical transmitters based on this kind of light source. Externally modulated transmitters are based on Mach-Zehnder modulators, which exhibit a very poor third-order linearity. Additional pre-distortion circuits are needed to achieve CTBs good enough for cable networks. As stated above, the CTB of an optical system cannot reliably be calculated from the CTB of the TX and the RX due to the fact that the laws of statistics cannot be applied. Therefore, the following procedure may only be understood as guidance for rough estimations.

a) Make sure that the CTB values of both the transmitter ($CTB_{\mathrm{CLC,TX}}$) and the receiver ($CTB_{\mathrm{CLC,RX}}$) are given for the CENELEC frequency map as required in IEC 60728-6.

b) The CTB for the whole link can be estimated out of the single CTB values with

$$CTB_{\mathrm{CLC}} = k \cdot \lg\left(10^{\frac{1}{k}CTB_{\mathrm{CLC,TX}}} + 10^{\frac{1}{k}CTB_{\mathrm{CLC,RX}}}\right) \qquad (16)$$

where k = 15 for unlocked carriers and k = 20 for locked carriers.

NOTE Sometimes the CTB-value is already given in the data sheets of the manufacturers for the whole link.

c) Calculate the maximum number of beats n_{act} for the actual frequency map. The maximum number of third-order beats for the CENELEC frequency map according to IEC 60728-3 is n_{CLC} = 283 at f = 599,25 MHz. With these beat counts the resulting CTB_{SYS} can be calculated with

$$CTB_{\mathrm{SYS}} = CTB_{\mathrm{CLC}} + 10\lg\frac{n_{\mathrm{act}}}{n_{\mathrm{CLC}}} \qquad (17)$$

This procedure can also be applied to directly modulated transmitters. Since the CTB of this kind of transmitter is usually high, calculated results are even less reliable.

Other sources of third-order distortions fall into two categories. The first category has only a weak impact on the system's CTB and can therefore be neglected in most cases:

- interaction of laser chirping and dispersion (C.4.1);
- third order distortion of optical amplifiers (C.3.6).

The second category must be avoided in practical systems:

- laser clipping (C.4.2);
- Brillouin scattering (C.4.3);
- self-phase modulation (C.3.5).

9 Flatness

Unlike coaxial cables, optical fibres do not have any impact on the flatness and the slope of the system amplitude frequency response. Therefore, only the flatness of the transmitter and the receiver shall be taken into account.

Lasers exhibit constant efficiencies over a very broad frequency range. This leads to very flat frequency responses of optical transmitters, which are deteriorated by internal transformers and pre-distortion circuits only.

Optical receivers have a much higher ripple due to internal amplifiers, gain control and the impedance matching circuits at the photodiode. The gain control normally has a wide range in order to achieve a certain electrical output level at different optical input levels and OMIs. Influencing the internal return losses the position of the gain control could have some impact on a receiver's flatness. Therefore, manufacturers shall investigate the whole gain range and specify the worst-case flatness.

Because only two devices contribute to the total flatness of an optical transmission system, no statistical methods can be used for summing up the single flatnesses, as it is often done for coaxial networks. On the other hand, the specified flatness values of the transmitter and the receiver do not add up linearly in most cases because they have their minimum and maximum gain of the amplitude frequency response at different frequencies. Dealing with single devices only, the standard IEC 60728-6 does not help with this problem. A good practice is to have a closer look at the amplitude-versus-frequency response diagrams, if available. Many manufacturers also specify the total flatness for combinations of their own transmitters and receivers.

10 Output level

The available electrical output level of optical transmission systems depends on the OMI and the total optical attenuation. The manufacturers of optical receivers are required to publish the reference output (see 6.3.1 of IEC 60728-6) which allows calculation of the available output level under real conditions. The reference output level is obtained at maximum gain of the receiver with an optical input power of $P_{\text{opt,RX}}$ = 0 dB(mW) and m = 0,05. Any AGC has to be turned off. Starting from this value the electrical output level of the receiver can be calculated for any other optical input power and OMI.

$$U_{\text{out}} = U_{\text{ref}} + 2P_{\text{opt,RX}} + 20\lg\frac{m}{0{,}05} \qquad (18)$$

where

U_{out} is the available electrical output level in dB(μV);

U_{ref} is the reference output level in dB(μV);

$P_{\text{opt,RX}}$ is the actual optical input power in dB(mW);

m is the actual optical modulation index.

It has to be taken into account that the result is valid for turned-off AGC only. AGCs are often designed in such a way that a mean gain is obtained in the turned-off state. In such cases the maximum available electrical output level is higher with the AGC turned on, by the amount of remaining gain of the AGC range.

In WDM systems where multiple optical transmitters work on the same optical receiver, equation (10) shall be used to get the right OMI.

Annex A
(informative)

Brillouin scattering in optical fibres

Stimulated Brillouin scattering is typically the first optical non-linearity encountered in lightwave systems using external modulators and single-mode optical fibres. SBS, related to vibrational excitation modes of silica, partly converts the transmitted signal in the fibre to a backward scattered one and thus sets a limit to the total fibre injected power. A photon of the incident field (often called the pump) is annihilated to create a photon (a Stokes photon) at the downshifted Stokes frequency and an acoustic phonon with the right energy and momentum to conserve the energy and the momentum. The frequency shift ν_B in the backward direction is given by

$$\nu_B = \frac{2n\nu_A}{\lambda_P} \tag{A.1}$$

where

n is the refractive index of the fibre core;

ν_A is the acoustic velocity (5 960 m/s in silica);

λ_P is the pump wavelength (wavelength of the incident field).

For standard single-mode fibres and wavelengths in the 1 550 nm range the result is $\nu_B \approx 11{,}5$ GHz.

The growth of the Stokes wave is characterized by the Brillouin-gain coefficient $g_B(\nu)$ whose peak value occurs at $\nu = \nu_B$. The Brillouin-gain spectrum is given by

$$g_B(\nu) = \frac{(\Delta\nu_B/2)^2}{(\nu-\nu_B)^2 + (\Delta\nu_B/2)^2}\, g_B(\nu_B) \tag{A.2}$$

where

$\Delta\nu_B$ is the spectral width of the Brillouin-gain spectrum;

$g_B(\nu_B)$ is the maximum Brillouin-gain coefficient (typically 4,6 x 10^{-11}m/W) given by

$$g_B(\nu_B) = \frac{2\pi n^7 p_{12}^2}{c\lambda_p^2 \rho_0 \nu_A \Delta\nu_B} \tag{A.3}$$

where

p_{12} is the longitudinal elasto-optic coefficient;

ρ_0 is the material density.

The threshold power P_{th} where the Brillouin appears is given by

$$P_{th} = \frac{21 A_e K}{g_B(\nu_B) L_e} \frac{\Delta\nu_L \otimes \Delta\nu_B}{\Delta\nu_B} \tag{A.4}$$

where

K	is a parameter depending on the polarization ($1 \leq K \leq 2$), generally $K = 2$ for random polarization state;
A_e	is the effective core area;
$\Delta\nu_L$	is the laser line width;
L_e	represents the effective interaction length, given by $L_e = \frac{1 - e^{-\alpha L}}{\alpha}$ where α is the fibre attenuation coefficient and L the fibre length;
$\otimes$	denotes convolution of the laser linewidth $\Delta\nu_L$ and the Brillouin bandwidth $\Delta\nu_B$: for Gaussian profiles, $\Delta\nu_L \otimes \Delta\nu_B = (\Delta\nu_L{}^2 + \Delta\nu_B{}^2)^{1/2}$, for Lorentzian profiles, $\Delta\nu_L \otimes \Delta\nu_B = \Delta\nu_L + \Delta\nu_B$.

Generally, when the laser is not modulated, $\Delta\nu_L < \Delta\nu_B$, assuming a Lorentzian profile,

$$P_{th} = 21 \frac{A_e K}{g_B(\nu_B) L_e} \tag{A.5}$$

In practice, the laser is modulated in intensity and (for Gaussian or Lorentzian profiles) $\Delta\nu_L \gg \Delta\nu_B$, P'_{th} is given by

$$P'_{th} = \frac{21 A_e K}{g_B(\nu_B) L_e} \frac{\Delta\nu_L}{\Delta\nu_B} \quad \Rightarrow \quad P'_{th} > P_{th} \tag{A.6}$$

Annex B
(informative)

Noise sources of optical transmission systems

For special calculations it is helpful to have a better understanding of the influences from different noise sources. In this annex, these noise sources are considered separately and the equations used in Clause 7 are derived.

B.1 Intensity noise

Intensity noise is a parameter of the transmitter and it determines the maximum achievable C/N in the link. Intensity noise is originated from the optical interference between the stimulated laser signal and spontaneous emissions generated within the laser cavity [1]. Intensity noise is usually specified as relative intensity noise (RIN) value and is expressed in dB(Hz)$^{-1}$ then. RIN is the ratio of the optical noise power density to the mean power of the optical carrier. In the electrical domain, this is expressed as the ratio between the mean square of the noise current density i and the square of the average current I_{DC}.

$$RIN = 10\lg\left(\frac{<i^2>}{I_{\mathrm{DC}}^2}\right) \qquad \text{(B.1)}$$

For the bandwidth of interest B the relative intensity noise current is then given by

$$I_{RIN} = I_{\mathrm{DC}}\sqrt{10^{RIN/10} \cdot B} \qquad \text{(B.2)}$$

Three other noises like mechanisms exist that are usually treated the same way as intensity noise: amplifier spontaneous emission (ASE) in optical amplifiers, PM/AM noise and multi-path interference (MPI).

B.1.1 Amplified spontaneous emission (ASE)

ASE noise originates from spontaneous emission of exited rare earth ions in the optical amplifier. Noise mechanisms in optical amplifiers are quite complicated and this topic is not given further treatment in this document.

The calculation of optical amplifier noise is derived from the definition of the noise figure. It is possible to make calculations with assumptions closer to physics but these calculations are not as practical as this one. In addition, the calculations based on measured noise figures give results that are more accurate.

The noise figure of optical amplifiers can be measured in the electrical domain and is calculated using equation (B.3). A reference to a suitable method of measurement is given in 4.20 of IEC 60728-6.

$$F = 10\lg\left(\left(\frac{m^2}{2B \cdot 10^{\frac{C/N_{\mathrm{out}}}{10}}} - \frac{m^2}{2B \cdot 10^{\frac{C/N_{\mathrm{in}}}{10}}}\right)\frac{P_{\mathrm{in}}}{2h\nu} + \frac{P_{\mathrm{in}}}{P_{\mathrm{out}}}\right) \qquad \text{(B.3)}$$

where

m	is the optical modulation index;
B	is the noise bandwidth;
h	is Planck's constant;
ν	is the frequency of light;
P_{in}	is the optical powers measured at the input;
P_{out}	is the optical powers measured at the output;
C/N_{in}	is the carrier-to-noise ratio measured in the electrical domain at the input;
C/N_{out}	is the carrier-to-noise ratio measured in the electrical domain at the output.

Because the interest is on the noise added by the optical amplifier, C/N_{in} is assumed to be infinite. With this simplification, the equation becomes

$$F = 10\lg\left(\frac{m^2}{2B\cdot 10^{\frac{C/N_{\mathrm{out}}}{10}}}\cdot\frac{P_{\mathrm{in}}}{2h\nu}+\frac{P_{\mathrm{in}}}{P_{\mathrm{out}}}\right) \tag{B.4}$$

With m = 1 the ratio between noise and the maximum signal output power can be solved for B = 1 Hz noise bandwidth as

$$\frac{1}{10^{\frac{C/N}{10}}} = \left(10^{\frac{F}{10}} - \frac{P_{\mathrm{in}}}{P_{\mathrm{out}}}\right)\cdot\frac{4h\nu}{P_{\mathrm{in}}} \tag{B.5}$$

This is equivalent to $2\cdot RIN_{\mathrm{OA}}$. Dividing by two and using equation (B.2) this can be converted to an equivalent noise current in the receiver, which can be given by

$$I_{\mathrm{OA}} = I_{\mathrm{DC}}\cdot\sqrt{\left(10^{\frac{F}{10}} - \frac{P_{\mathrm{in}}}{P_{\mathrm{out}}}\right)\cdot\frac{2h\nu}{P_{\mathrm{in}}}\cdot B} \tag{B.6}$$

B.1.2 PM/AM-conversion

Dispersion in a fibre results in a phase modulation to amplitude modulation conversion (PM/AM). Phase modulation spreads the optical spectrum and the dispersion causes some parts of the signal to propagate with higher velocity than the others. This early or late arrival can be seen as a variation in the amplitude at reception. When the phase modulation is due to the phase noise of the optical carrier, the resulting variation in amplitude is noise. Therefore, the narrower the laser linewidth the smaller the amount of resulting noise. PM/AM conversion can be neglected in the 1 310 nm window close to zero dispersion wavelength but is a problem in the 1 550 nm transmission window where the dispersion is high in standard fibres.

The intensity noise induced by the PM/AM-conversion can be estimated from

$$RIN_{\mathrm{PM/AM}} = 10\lg\left(2\cdot\Delta\omega\cdot\left(\frac{D\cdot\lambda^2\cdot L}{2\cdot\pi\cdot c_0}\right)^2\cdot(2\cdot\pi\cdot f)^2\right) \tag{B.7}$$

where

$\Delta\omega$ is the linewidth of the laser;

D is the dispersion coefficient of the fibre;

λ is the wavelength of the light;

L is the length of the fibre;

c_0 is the speed of light in the vacuum;

f is the frequency of interest.

The equivalent noise current in the receiver is then

$$I_{\mathrm{PM/AM}} = I_{\mathrm{DC}} \cdot \sqrt{2 \cdot \Delta\omega \cdot \left(\frac{D \cdot \lambda^2 \cdot L}{2 \cdot \pi \cdot c_0}\right)^2 \cdot (2 \cdot \pi \cdot f)^2 \cdot B} \tag{B.8}$$

B.1.3 Multi-path interference (MPI, fibre noise)

MPI occurs in the case of double reflection. Twice-reflected light arrives later to the receiver than the main signal. This causes interference between the signals. If the double reflection distance is greater than the coherence length of the laser, the interference occurs as noise. Discrete reflections in cable networks are typically very small so that double Rayleigh back-scattering with a return loss of $a_r \approx 30$ dB in long fibres is the dominating effect. In this case the reflections are not discrete but the resulting noise phenomenon has the same nature. This noise caused by double Rayleigh back-scattering is called induced intensity noise (IIN). As Rayleigh scattering is greater in the 1 310 nm transmission window, the IIN is more of a problem in 1 310 nm systems than in 1 550 nm systems.

An approximation to calculate the effect of IIN is given in equation (B.9). This approximation is based on an infinite number of discrete reflections and is valid for light with Gaussian spectral distribution. Therefore, this equation should not be used for externally modulated transmitters using SBS suppression techniques.

$$RIN_{\mathrm{IIN}} \approx 10 \lg\left(\frac{4}{\pi} \cdot \left[\frac{S^2 \cdot \alpha_{\mathrm{S}}^2}{4 \cdot \alpha^2}\left(2 \cdot \alpha \cdot L - 1 + e^{-2 \cdot \alpha \cdot L}\right)\right] \cdot \frac{1}{\eta_{\mathrm{FM}}(I_{\mathrm{b}} - I_{\mathrm{th}})\mu}\right) \tag{B.9}$$

where

α is the fibre's attenuation per unit length;

α_{S} is the proportion of signal scattered per unit length;

S is the fraction of scattering that is captured by the fibre;

η_{FM} is the light source chirping efficiency;

I_{b} is the bias current of the laser;

I_{th} is the threshold current of the laser;

μ is the total RMS modulation index according to equation (B.10).

$$\mu = \frac{m_{\mathrm{T}}}{\sqrt{2}} \tag{B.10}$$

where m_{T} = is the total OMI as described in Clause 6.

The according equivalent noise current in the receiver can be written as

$$I_{\text{IIN}} \approx I_{\text{DC}} \cdot \sqrt{\frac{4}{\pi} \cdot \left[\frac{S^2 \cdot \alpha_{\text{S}}^2}{4 \cdot \alpha^2} \left(2 \cdot \alpha \cdot L - 1 + e^{-2 \cdot \alpha \cdot L} \right) \right] \cdot \frac{1}{\eta_{\text{FM}} (I_{\text{b}} - I_{\text{th}}) \mu} \cdot B} \tag{B.11}$$

B.2 Shot noise of the receiver

Shot noise is a noise component originating from the statistical variation in the arrival of the photons at the receiver. The magnitude of the shot noise is given by

$$I_{\text{shot}} = 2 \cdot I_{\text{DC}} \cdot e \cdot B \tag{B.12}$$

where

I_{DC} is the mean current of the photodiode;

e is $1{,}6 \times 10^{-19}$ C (charge of an electron);

B is the considered bandwidth.

B.3 Thermal noise

Thermal noise originates from thermal movement in the structure of the matter. Thermal noise power is constant over any given bandwidth, and it only varies with temperature. The noise power delivered by any resistor can be calculated by:

$$N_{\text{th}} = 4 \cdot k \cdot T \cdot B \tag{B.13}$$

The equivalent noise current is

$$I_{\text{th}} = \sqrt{\frac{4 \cdot k \cdot T \cdot B}{R}} \tag{B.14}$$

The equivalent noise currents of optical receivers are much higher due to the noise added by internal amplifier stages. The real values are commonly published as equivalent input noise current density expressed in $\text{pA/(Hz)}^{1/2}$.

B.4 Carrier-to-noise ratio

With the definition of OMI (6) and the noise currents from above it is possible to calculate the carrier-to-noise ratio (*C/N*) of the whole link. *C/N* is usually expressed in decibels. It can be determined for the detected signal in the electrical domain without taking into account the responsivity of the receiver. The *C/N* can be defined through the currents as

$$C/N = 20 \cdot \lg \left(\frac{I_{\text{signal}}}{I_{\text{total noise}}} \right) \tag{B.15}$$

where

$$I_{\text{signal}} = I_{\text{DC}} \cdot m \cdot \frac{1}{\sqrt{2}} \tag{B.16}$$

$$I_{\text{total noise}} = \sqrt{I_{\text{RIN}}^2 + I_{\text{shot}}^2 + I^2{}_{th} + I_{\text{OA}}^2 + I_{\text{AM/PM}}^2 + I_{\text{IIN}}^2} \tag{B.17}$$

Annex C
(informative)

Non-linear distortion in optical transmission systems

C.1 Non-linear product definition

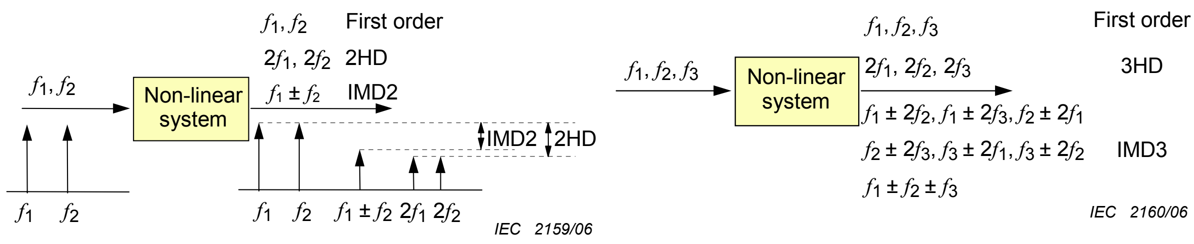
The association of all un-modulated carrier frequencies, regularly spaced by 7 MHz (VHF band) or 8 MHz (UHF band), and passing through non-linear components, creates additional frequencies. This behaviour is best explained by Volterra series expansion, which allow the theoretical calculation of the evolution *y(t)* of a signal *x(t)* passing through a non-linear component. The Volterra series expression is:

$$\begin{aligned} y(t) = {} & \frac{1}{1!}\int_{-\infty}^{+\infty} h_1(\tau_1).x(t-\tau_1)\,d\tau_1 + \frac{1}{2!}\iint h_2(\tau_1,\tau_2).x(t-\tau_1).x(t-\tau_2)\,d\tau_1\,d\tau_2 \\ & + \ldots + \frac{1}{n!}\iint..\int h_n(\tau_1,\tau_2,\ldots,\tau_n).x(t-\tau_1).x(t-\tau_2)\ldots x(t-\tau_n)\,d\tau_1\,d\tau_2\ldots d\tau_n \end{aligned} \tag{C.1}$$

where $h_n(\tau_1,\tau_2,\ldots,\tau_n)$ is the n^{th} order Volterra kernel (the n^{th} order impulse response of the non-linear system under study). Taking as a hypothesis that $x(t)$ is a sum of pure sinusoids of the same amplitude and applying multidimensional Fourier transform to $y(t)$, we obtain the following expression:

$$\begin{aligned} y(t) = {} & \left.\begin{aligned} & a\left|\underline{H}_1(\omega_1)\right|.\cos(\omega_1 t+\varphi_1+\beta_1(\omega_1)) + a\left|\underline{H}_1(\omega_2)\right|.\cos(\omega_2 t+\varphi_2+\beta_1(\omega_2)) \\ & + a\left|\underline{H}_1(\omega_3)\right|.\cos(\omega_3 t+\varphi_3+\beta_1(\omega_3)) + \ldots \end{aligned}\right\}\text{1. order} \\ & \left.\begin{aligned} & + \frac{a^2}{2}\left|\underline{H}_2(\omega_1,\omega_1)\right|.\cos(2\omega_1 t+2\varphi_1+\beta_2(\omega_1,\omega_1)) \\ & + \frac{a^2}{2}\left|\underline{H}_2(\omega_2,\omega_2)\right|.\cos(2\omega_2 t+2\varphi_2+\beta_2(\omega_2,\omega_2)) + \ldots \\ & + \frac{a^2}{2}\left|\underline{H}_2(\omega_1,-\omega_1)\right|.\cos(\beta_2(\omega_1,-\omega_1)) + \ldots \\ & + a^2\left|\underline{H}_2(\omega_1,\omega_2)\right|.\cos((\omega_1+\omega_2)t+\varphi_1+\varphi_2+\beta_2(\omega_1,\omega_2)) \\ & + a^2\left|\underline{H}_2(\omega_1,-\omega_2)\right|.\cos((\omega_1-\omega_2)t+\varphi_1-\varphi_2+\beta_2(\omega_1,-\omega_2)) + \ldots \end{aligned}\right\}\text{2. order} \\ & \left.\begin{aligned} & + \frac{a^3}{4}\left|\underline{H}_3(\omega_1,\omega_1,\omega_1)\right|.\cos(3\omega_1 t+3\varphi_1+\beta_3(\omega_1,\omega_1,\omega_1)) + \ldots \\ & + \frac{3}{4}a^3\left|\underline{H}_3(\omega_1,\omega_2,\omega_2)\right|.\cos((\omega_1+2\omega_2)t+\varphi_1+2\varphi_2+\beta_3(\omega_1,\omega_2,\omega_2)) + \ldots \\ & + \frac{3}{2}a^3\left|\underline{H}_3(\omega_1,\omega_2,\omega_3)\right|.\cos((\omega_1+\omega_2+\omega_3)t+\varphi_1+\varphi_2+\varphi_3+\beta_3(\omega_1,\omega_2,\omega_3)) + \ldots \end{aligned}\right\}\text{3. order} \\ & + \ldots\text{etc} + \text{all combinations of indexes and sign.} \end{aligned} \tag{C.2}$$

Cable network distortion characterization is generally described in terms of second and third orders (higher distortion products are generally negligible) related to that theory. Figure C.1 shows basic IMD2 (second-order intermodulation), 2HD (second harmonic distortion), IMD3 and 3HD definitions.



(a) Second order (b) Third order

Figure C.1 –Distortion of Volterra series expansion

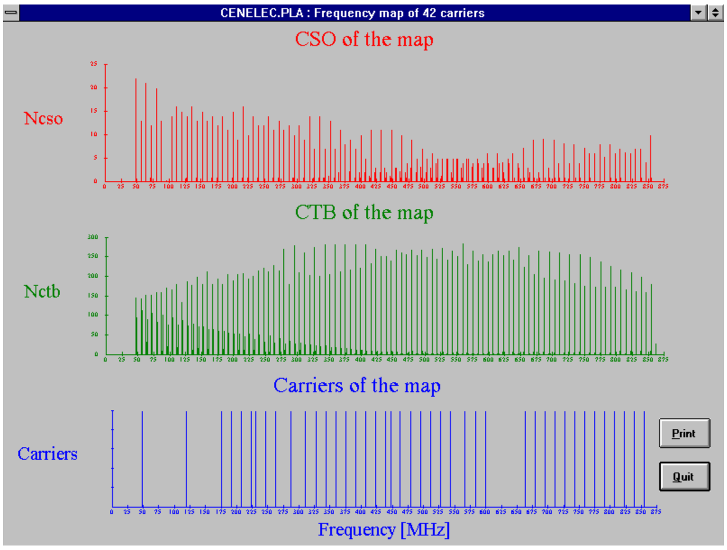
C.2 Non-linear products weighting

In the Volterra relation, IMD2 components have a unitary coefficient of multiplication while HD2 have a ½ coefficient. To characterize distortions of commercial systems, a spectrum analyser is used. It measures the RMS power in the resolution bandwidth. To take this into account, the Volterra equation has to be re-written in power terms, taking as unitary reference the IMD2 component for second-order weighting calculation, and the IMD3 for third-order weighting calculation. This leads to the following weightings.

Table C.1 – Weightings of HD2, HD3, IMD2 and IMD3

	Frequency combination	Weighting		Frequency combination	Weighting
Second order	$2f_i$	1/4	Third order	$3f_i$	1/36
	$f_i \pm f_j$	1		$2f_i \pm f_j$	1/4
				$f_i \pm f_j \pm f_k$	1

Due to the regular spacing of carriers in cable network frequency plans (IEC or others), several weighted distortions superpose at the same frequency. Their resulting influence can be high as shown in Figure C.2, which also emphasises the fact that second-order distortions are worst at band edges while third-order distortions are worst in the middle of the frequency range. The evolution of the global weight versus frequency gives an idea about which distortion frequencies affect a cable network channel, thus degrading picture quality.



IEC 2161/06

Figure C.2 – Weighted second- and third-order distortion repartition for the 42 carriers frequency allocation map defined in Table C.1 of IEC 60728-3 (software window capture)

C.3 Distortion generators in direct modulation cable network transmissions

There are several sources of non-linearities in an intensity modulation – direct detection) (IM-DD) analogue transmission system. Some depend on the laser (chirping induced, clipping) while others depend on the fibre (Brillouin effect, self-phase modulation) or the amplification devices. On a general basis, receivers are considered to be linear as long as their electrical amplifiers are well designed and used.

C.3.1 Laser chirping and chromatic dispersion

The dispersion is a phenomenon in which the velocity of propagation of an electromagnetic wave is wavelength-dependent. Chromatic dispersion means that light of different wavelengths have different indices of refraction. As a result, the light of different wavelengths travels at different speeds, and so takes different lengths of time to travel the same distance.

The fibre is a dispersive medium characterized by its chromatic dispersion coefficient D in ps/(nm·km) which varies with wavelength. A good system design is to use a laser source the emission wavelength λ_c of which is close to the fibre zero dispersion wavelength in order to minimize dispersion effects.

Distributed feedback (DFB) lasers are usually intensity-modulated by varying the drive current, which results in a corresponding change in optical output power. Unfortunately, because the changing current causes changes in the semiconductor refractive index, the laser mode frequency varies as well. The intensity modulation is mostly accompanied by frequency modulation in semiconductor laser (chirping effect). Due to AM-FM conversion effects, the linewidth of the source increases (chirping of the emitted central wavelength) and associated to dispersion, non-linearity distortions may occur at the fibre output. Under a multichannel modulation, the laser output intensity $P(t)$ is represented as

$$P(t) = \eta(I_{\mathrm{b}} - I_{\mathrm{th}})\left(1 + m\sum_{i=1}^{N}\sin(2\pi f_i t + \varphi_i)\right) \qquad \text{(C.3)}$$

where

η is the slope efficiency of the laser;

I_b is the bias current of the laser;

I_{th} is the threshold current of the laser;

m is the optical modulation index;

f_i are the carrier frequencies of the N channels;

φ_i are the phase offsets of the N channels.

The chirping of a DFB laser is represented by

$$\Delta\lambda(t) = -\frac{\lambda_C^2}{c_0}\eta_{FM}(I_b - I_{th})\, m \sum_{i=1}^{N} \sin(2\pi f_i t + \varphi_i) \quad (C.4)$$

where

λ_c is the centre wavelength;

c_0 is the light velocity in vacuum;

η_{FM} is the FM response of the laser diode.

The chromatic dispersion D of fibre causes the difference in delay time which depends on $\Delta\lambda(t)$. The difference $\Delta t_d(t)$ is expressed by using fibre length L as follows:

$$\Delta t_d(t) = -DL\Delta\lambda(t) \quad (C.5)$$

The received waveform $P_r(t')$ at time $t' = t + \Delta t_d(t)$ at the end of the fibre is given by

$$P_r(t') = P(t' - \Delta t_d(t)) = P(t) \quad (C.6)$$

neglecting the attenuation of the fibre.

Assuming that distortions are small, $P_r(t')$ is obtained as:

$$P_r(t) = P(t' - \Delta t_d(t'))\left\{1 - \frac{d\Delta t_d(t')}{dt'}\right\} \quad (C.7)$$

Developing the last equation into Bessel functions, it is easy to find harmonic and inter-modulation distortions.

C.3.2 Laser chirping and PMD

Polarization-mode dispersion (PMD) arises in single-mode fibre when the combined effects of non-circular symmetric internal stresses and irregular waveguide geometry created during manufacture cause the two polarization modes of the waveguide to propagate with different group velocities (Figure C.3).

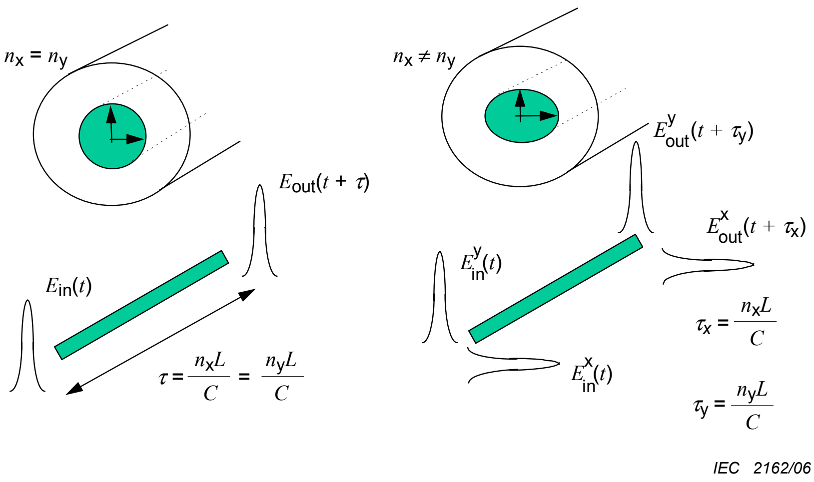


Figure C.3 – Polarization-mode dispersion in single-mode fibre

The fibre PMD fluctuates with time because it is dependent on the polarization mode coupling in the fibre, which is sensitive to ambient temperature and mechanical perturbations.

Two different PMD-related mechanisms generate second-order distortion [4].

a) Interaction of PMD and laser chirp generates CSO in fibres with coupling between the polarization modes, which scales with the square of the distortion frequency f_d.

b) Interaction of PMD, laser chirp, and polarization-dependent loss (PDL) generates CSO independently of the distortion frequency. The PMD of the fibre converts the frequency modulation of the signal into polarization modulation. The change in polarization is then converted to amplitude modulation when the signal traverses a polarization-dependent loss element, giving rise to non-linear components in the detected signal.

The distortions (CSO) from these two polarization-dependent effects interacting with the laser chirping can be minimized by choosing fibres and components with low PDL and PMD.

C.3.3 Laser clipping

The law between injected current and optical output power under static conditions (Figure C.4) shows a threshold. In order to work with the laser in stimulated emission, modulating current shall be higher than the threshold.

The amplitude distribution of the driving multi-channel current or voltage can be approximated by a Gaussian distribution if the number of channels N >> 1. Clipping starts to occur when $N \cdot m$ > 1, where N is the number of channels and m the OMI.

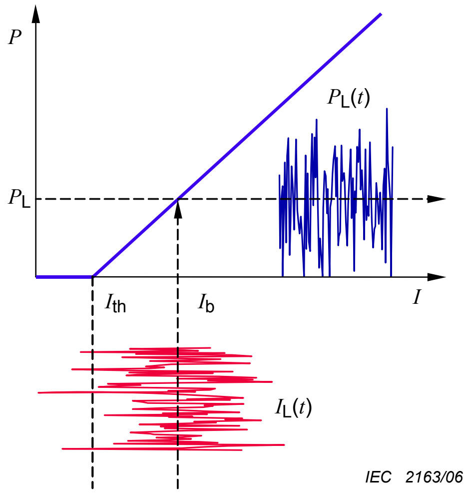


Figure C.4 – Static curve of a laser showing the clipping effect

The clipping distortion is largely a function of the standard deviation of the amplitude distribution of the driving signal:

$$\mu = \frac{\sigma}{I_b} = m\sqrt{\frac{N}{2}} = \frac{m_T}{\sqrt{2}} \quad \text{(C.8)}$$

It is a very strong distortion generator. Under high clipping driving current situation, even higher order (fourth, fifth) intermodulations shall be taken into account.

C.3.4 Brillouin scattering

Brillouin scattering (Annex A) is an inelastic process in which part of the power is lost from an optical wave and absorbed by the transmission medium while the remaining energy is re-emitted as a wave of lower frequency. SBS sets a limit to the total fibre injected power. The process can be thought of as the conversion of an incident photon into a lower energy scattered photon plus an acoustical phonon. Since the frequency of an optical wave is proportional to its energy, the photon produced by the scattering event has a lower frequency than the incident photon and propagates in the opposite direction of the input wave.

The Brillouin scattering process can become non-linear in optical fibres due to high optical intensity in the core and the long interaction lengths afforded by these waveguides. SBS occurs when the optical power launched into the fibre exceeds a threshold level (Figure C.5 [13]).

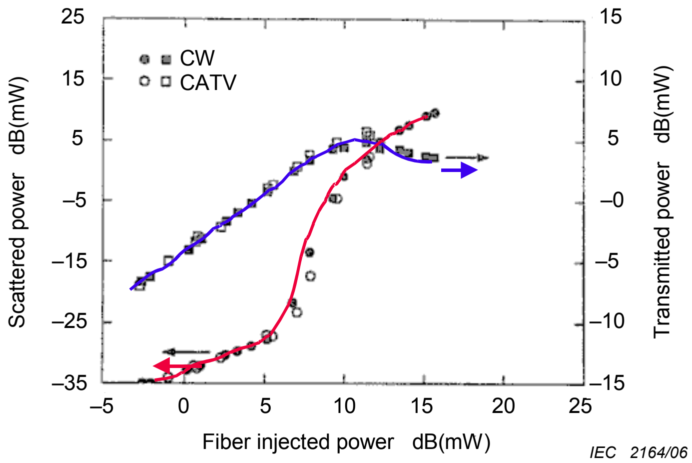


Figure C.5 – Transmitted and back-scattered power in the range of the Brillouin threshold

As shown in Annex A, the Brillouin threshold depends on the line width of the optical transmitter. For un-modulated DFB lasers, Brillouin scattering occurs in the 1 550 nm range already at several milliwatts. Therefore, the spectrum of optical transmitters with an external modulator is broadened, for example, through additional phase modulation. The modulation frequency for the phase modulation shall be at least twice the maximum modulation frequency of the Mach-Zehnder modulator in order to avoid intermodulation products falling into the frequency band of the cable network.

C.3.5 Self-phase modulation

The self-phase modulation (SPM) is a fibre non-linearity caused by the intensity-dependent non-linear change in refraction index of the fibre. In general, the refractive index of a medium is intensity-dependent. Under most conditions this can be neglected except when the pulse intensity becomes large.

Through the non-linear refractive index, n_2, the modulated intensity of the beam induces a modulation of the refractive index of the fibre material. This leads to phase modulation and subsequent frequency modulation of the optical field. With chromatic dispersion, the higher optical frequencies travel faster than the lower optical frequencies, thereby distorting the optical power wave envelope and generating non-linear distortions.

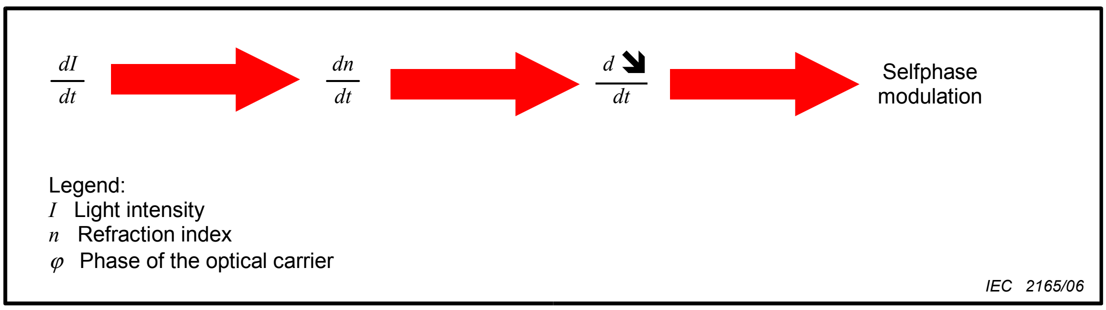


Figure C.6 – Cause of self-phase modulation

The typical manifestation of the self-phase modulation is CSO distortion at the upper frequency band.

C.3.6 Optical amplifiers

The distortion introduced by an optical amplifier employing a transmitter with chirp such as a directly modulated laser rises from the non-flatness of the optical gain spectrum. A change in the signal level, resulting in a change in the drive current applied to the laser, causes a slight change in the laser operating wavelength (chirping). Due to the non-flatness of the gain (gain tilt), this causes a change in optical power. Thus different signal levels will undergo different gains and the original waveform will be distorted. It is mainly a second-order distortion generating process.

C.3.7 Second-order modelling

C.3.7.1 Laser chirping and chromatic dispersion

After calculations for multi-channel distortion, the CSO analytic expression is [5], [4]:

$$CSO = 20\,\mathrm{lg}(a \cdot m \cdot \omega_\mathrm{d}) + 10\,\mathrm{lg}(I_\mathrm{b} - I_\mathrm{th}) \tag{C.9}$$

with

$$a = DL\frac{\lambda_c^2}{c_0}\eta_\mathrm{FM}(I_\mathrm{b} - I_\mathrm{th}) \tag{C.10}$$

where

η_FM is the FM response of the laser diode [MHz/mA] (which also depends on f_d);

D is the chromatic dispersion coefficient [ps/(nm*km)];

f_d is the distortion frequency;

I_b is the bias current of the laser [A];

I_th is the threshold current of the laser [A];

m is the optical modulation index (OMI);

L is the fibre length.

As an immediate analysis of the formulae, it appears that second-order distortions are worst for long links and for high frequencies. As an example, Figure C.7 shows the result of the CSO computation versus the length of the link with the following realistic parameters (λ_c = 1 550 nm, c_o = 3 10^8 m/s, $I_\mathrm{b} - I_\mathrm{th}$ = 20 mA, η_FM = 300 MHz/mA, L = 25 km, ω_d = 2•π •830,5 MHz, N_CSO = 11, m = 0,05). One can observe the benefit of using a laser wavelength close to the zero of dispersion of the fibre.

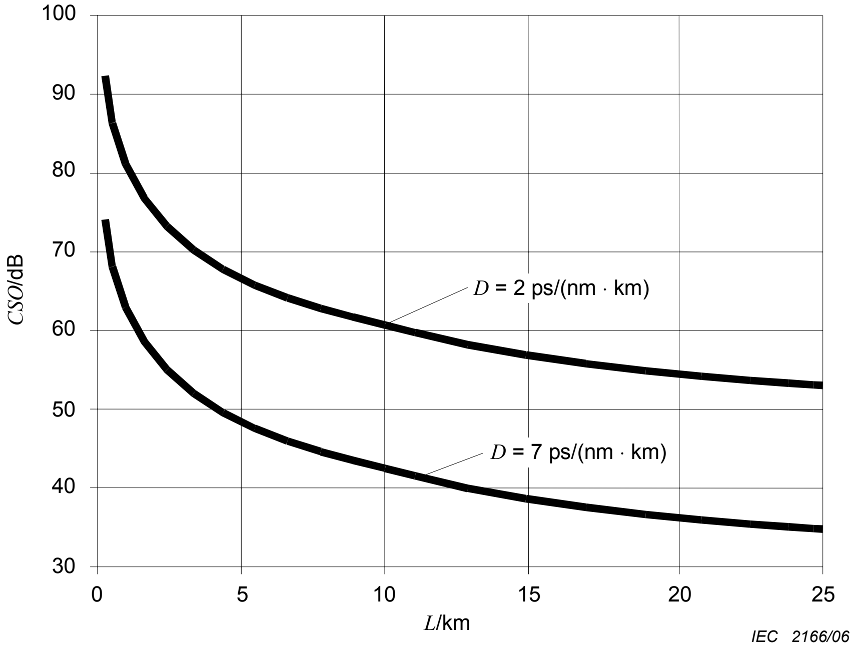


Figure C.7 – CSO caused by laser chirping and chromatic dispersion

C.3.7.2 Laser chirping and PMD

The average value of PMD generated CSO in an analogue multichannel system is defined by [11]:

$$< CSO >_{\mathrm{PMD}} = N_{\mathrm{CSO}} \gamma^2 m \left\{ \frac{\pi^2 \omega_{\mathrm{d}}^2 < \Delta\tau >^4}{256} + \frac{\pi \Delta T^2 < \Delta\tau >^2}{48} \right\} \tag{C.11}$$

where

ω_{d}	is the distortion frequency;
m	is the amplitude of sinusoidal intensity modulation emerging from the laser;
$\gamma = 2\pi\eta_{\mathrm{FM}}(I_{\mathrm{b}} - I_{\mathrm{th}})$	is the chirp parameter that relates to the change in laser output frequency due to the change in laser output power;
N_{CSO}	is the product count, equal to the number of mixing products contributing to a distortion peak;
$\Delta\tau$	is the maximum difference in propagation time for waves launched with perpendicular polarizations;
ΔT	is the polarization-dependent loss defined as the difference between maximum and minimum transmission loss, $\Delta T \leq 1$.

NOTE Quantities in parenthesis <> are average values over time.

In designing cable networks, a safety margin of at least 10-15 dB should be incorporated between $\langle CSO \rangle_{\mathrm{PMD}}$ and $CSO_{\max}$ to be sure that the temporal $\langle CSO \rangle_{\mathrm{PMD}}(t)$ stays below $CSO_{\max}$.

Figure C.8 [12] shows the value of $\langle CSO\rangle_{PMD}$ with increasing PMD in the case of no PDL with the following parameters:

N_{CSO} = 6,25 λ = 1 310 nm f_d = 504,25 MHz m = 5 %

$(I_b - I_{th})$ = 30 mA η_{FM} = 500 MHz/mA

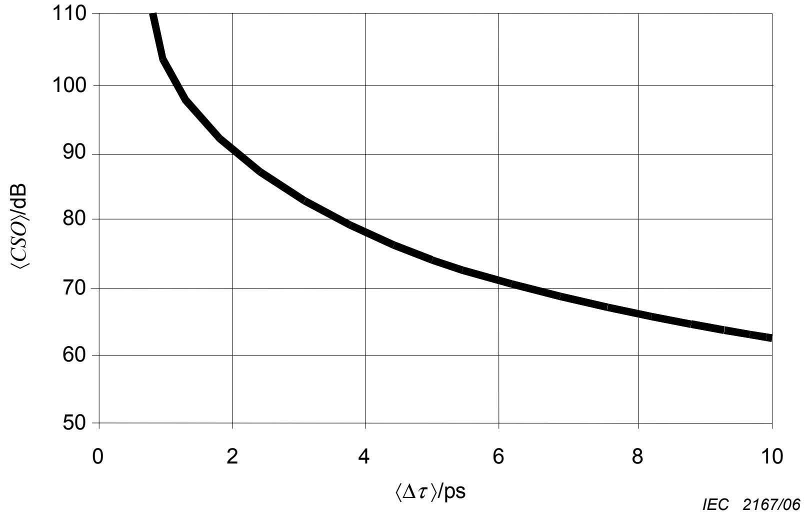


Figure C.8 – CSO degradation without PDL

If $CSO_{max} \geq 60$ dB is wanted, the rule of thumb imposes $\langle CSO\rangle_{PMD} \geq 75$ dB. To achieve this, the PMD $\langle\Delta\tau\rangle$ should be ≤5 ps. The PMD of standard production single-mode fibre is about 0,04 ps/√km. Therefore, the PMD does not degrade real analogue transmissions by itself.

Figure C.9 shows the value of $\langle CSO\rangle_{PMD}$ with increasing PMD in the case of PDL = 0,5 dB (ΔT = 0,11), for two frequencies.

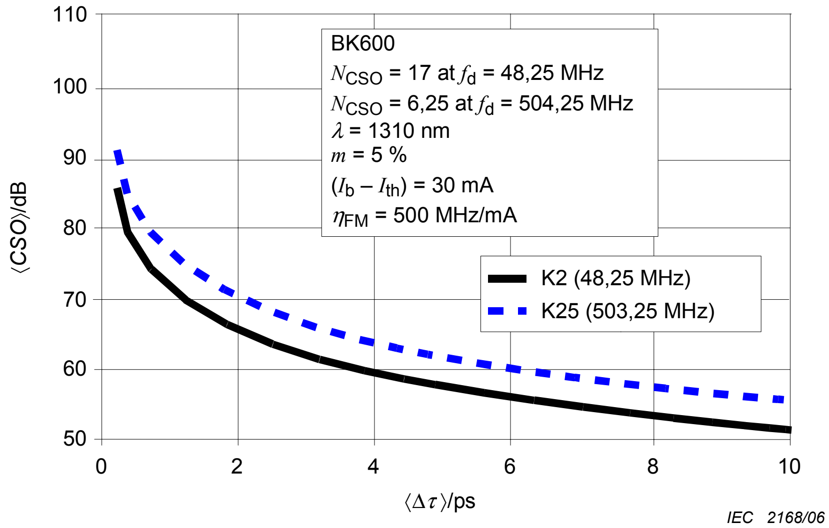


Figure C.9 – CSO degradation with PDL = 0,5 dB [12]

To keep $CSO_{\mathrm{max}} \geq 60$ dB, $\langle CSO\rangle_{\mathrm{PMD}} \geq 75$ dB is needed. To achieve this, the PMD $\langle\Delta\tau\rangle$ should be $\leq 0{,}3$ ps. The maximum length of the link is therefore 56 km. PDL is an important parameter, which has to be kept as low as possible.

C.3.8 Laser clipping

The carrier-to-intermodulation product ratio at the frequency f_{d} ($C/IMP_{f_d}^{(n)}$) with n = 2 for CSO, is given by the following equation [4]):

$$C/IMP_{f_d}^{(n)} = \frac{(4N)^{n-1}\pi\left(\chi^{(1)}n!\right)^2 e^{\left(1/\mu^2\right)}}{H_{n-2}^2\left(1/\sqrt{2\mu}\right)N_{f_d}^{(n)}} \tag{C.12}$$

where

$N_{f_d}^{(n)}$ is the product count for the n^{th}-order terms that contribute at frequency f_{d};

N is the number of carriers;

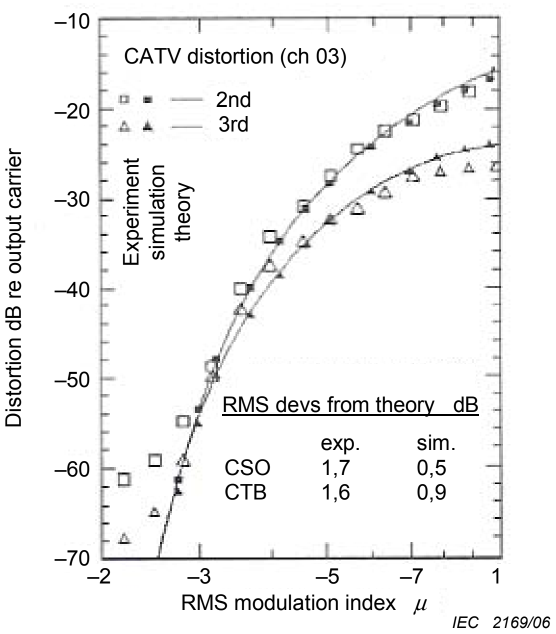
μ is the total RMS modulation index as defined in equation (B.10);

H_n is the Hermite polynomial;

$\chi^{(1)}$ accounts for the compression of the fundamental carriers because of the non-linear transfer function

$\chi^{(n)} = \dfrac{1}{\mu^{n+1}n!\sqrt{2\pi}}\displaystyle\int_{-\infty}^{+\infty} g(x)e^{\left(-\frac{x^2}{2\mu^2}\right)}H_n\left(\frac{x}{\mu}\right)dx$ with $g(x)$ the ideal transfer function (static curve).

Figure C.10 [4] shows with good agreement the comparison between simulation and experiment.



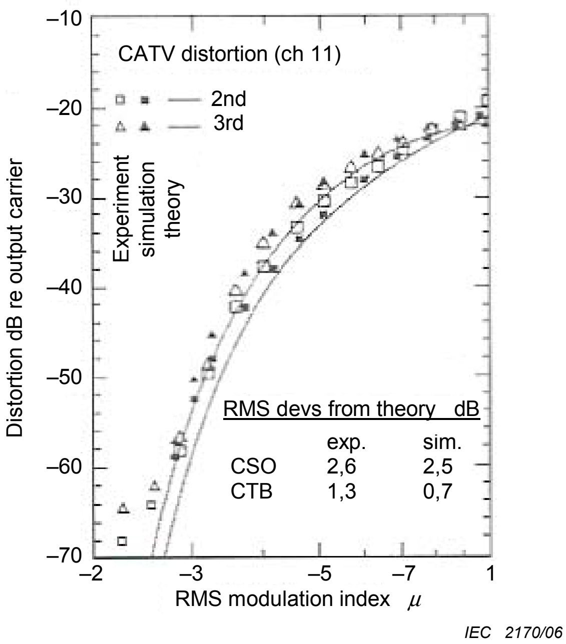


Figure C.10 – Simulated and measured intermodulation due to laser clipping

C.3.9 Brillouin scattering

The effects of SBS on CSO are defined by [4]:

$$CSO = 10 \cdot \lg \left[N_{\text{CSO}} \cdot \left(\frac{(1-\sigma) \cdot m}{4 \cdot \sigma} \right)^2 \right] \tag{C.13}$$

where

N_{CSO} is the weighted number of *CSO* components at the distortion frequency;

m is the optical modulation depth

$$\sigma = \sqrt{1 - \frac{R_{\text{bs}}}{0{,}85}}$$

for standard fibre. R_{bs} is the ratio of backscattered optical power to injected optical power (Annex A).

C.3.10 Self-phase modulation

Without additional phase modulation, the analytic form of the CSO distortion due to SPM is [4], [7], [8]:

$$CSO = 10 \cdot \lg \left\{ N_{CSO} \cdot \left(\frac{1}{2} m \cdot \beta_2 \cdot f_{\text{d}}^2 \cdot \frac{2\pi n_2 P_{\text{in}}}{\lambda A_{\text{eff}}} \cdot \frac{\alpha L - 1 + e^{-\alpha L}}{\alpha^2} \right)^2 \right\} \tag{C.14}$$

where

N_{CSO} is the weighted number of *CSO* components at the distortion frequency;

P_{in} is the average optical power entering the fibre section;

A_{eff} is the effective fibre core area;

m is the optical modulation index;

α is the fibre attenuation;

$\beta_2 = \mathrm{d}^2\beta/\mathrm{d}\omega^2$ with β the chromatic dispersion (β_2 is related to D by $\beta_2 = -D\,\lambda^2/(2\pi c)$ and is about -22 ps²/km on a standard fibre at 1550 nm for D = 17 ps /nm/km);

f_{d} is the frequency of the CSO distortion;

L is the fibre length;

n_2 ($\approx 3.10^{-20}$ m²/W) is the power-dependent non-linear refractive index.

C.3.11 Optical amplifiers

The CSO distortion induced by optical amplifiers is given in power units, after electrical detection and expressed in dB below carrier, by [9], [10]:

$$CSO = 20 \lg \left\{ \sqrt{N} \frac{\left[\frac{dG(P_0, \lambda)}{d\lambda} \right]_{\lambda_0}}{2G(P_0, \lambda_0)} \frac{\lambda_{\text{chirp}}}{\sqrt{n}} \right\} \tag{C.15}$$

where

λ_0	is the average signal wavelength;
P_0	is the average input power;
N	is the number of second-order intermodulation products;
$\left[\frac{dG(P_0,\lambda)}{d\lambda}\right]_{\lambda_0}$	is the optical amplifier's gain tilt (the gain variation experienced by the wavelength modulated signal);
n	is the total number of channels;
λ_{chirp}	is the full width at half maximum (FWHM) of laser light chirping linewidth due to modulation.

For negative gain-slope values (in the wavelength domain), the second-order distortion generated by the interaction of laser chirp and optical amplifier gain-slope tends to be π radians out of phase with the intrinsic second-order distortion of the DFB laser. In this case the CSO generated by the transmitter laser is reduced by the gain-slope of the optical amplifier. Positive gain-slope values will increase the system CSO values [12]. The CSO at the optical amplifier's output is calculated by adding or subtracting the second-order distortions on amplitude basis, with the sign of the gain slope:

$$CSO_{\text{OA,output}} = \left(\sqrt{CSO_{\text{DFB}}} \pm \sqrt{CSO_{\text{OA}}}\right)^2 \qquad \text{(C.16)}$$

C.4 Third-order modelling

C.4.1 Laser chirping and chromatic dispersion

As for CSO, it is also possible to find an analytical formulation to express the third-order distortion caused by laser chirping and chromatic dispersion. Unfortunately, in the CTB case, there is no direct relation with the computed N_{CTB} weighting value, therefore the equation is the following [5].

$$CTB = 20\lg\left[a^2 m^2 K_{\text{CTB}}\right] \qquad \text{(C.17)}$$

with

$$a = DL\frac{\lambda_c^2}{c_0}\eta_{\text{FM}}(I_{\text{b}} - I_{\text{th}}) \qquad \text{(C.18)}$$

where

η_{FM}	is the FM response of the laser diode [MHz/mA] (which also depends on f_{d});
D	is the chromatic dispersion coefficient [ps/(nm*km)];
I_{b}	is the bias current of the laser [A];
I_{th}	is the threshold current of the laser [A];
m	is the optical modulation index (OMI);
L	is the fibre length;
K_{CTB}	is a parameter representative of the third order which depends on the contributing frequencies at distortion frequency of interest.

Generated CTB due to the impact of laser chirping and chromatic dispersion are generally 20 dB below CSO values generated by the same phenomenon.

C.4.2 Laser clipping

The carrier to intermodulation product at frequency f_d ($C/IMP_{f_d}^{(n)}$) with n = 3 for CTB, is given by the following equation:

$$C/IMP_{f_d}^{(n)} = \frac{(4N)^{n-1}\pi\left(\chi^{(1)}n!\right)^2 e^{\left(1/\mu^2\right)}}{H_{n-2}^2\left(1/\sqrt{2\mu}\right)N_{f_d}^{(n)}} \tag{C.19}$$

where

$N_{f_d}^{(n)}$ is the product count for the nth-order terms that contribute at frequency f_d;

N is the number of carriers;

μ is the normalized total RMS modulation index;

H_n is the Hermite polynomial;

$\chi^{(1)}$ accounts for the compression of the fundamental carriers because of the non-linear transfer function;

$\chi^{(n)} = \frac{1}{\mu^{n+1}n!\sqrt{2\pi}}\int_{-\infty}^{+\infty} g(x)e^{\left(-\frac{x^2}{2\mu^2}\right)}H_n\left(\frac{x}{\mu}\right)dx$ with $g(x)$ the ideal transfer function (static curve).

C.4.3 Brillouin scattering

The effect of SBS on CTB is defined by [4]:

$$CTB = 10\cdot\lg\left[N_{\mathrm{CTB}}\cdot\left(\frac{(1-\sigma)\cdot 3\cdot m^2}{16\cdot\sigma}\right)^3\right] \tag{C.20}$$

where

N_{CTB} is the weighted number of *CTB* components at the distortion frequency;

m is the optical modulation depth

$$\sigma = \sqrt{1-\frac{R_{\mathrm{bs}}}{0.85}}$$

for standard fibre, R_{bs} is the ratio of back-scattered optical power to injected optical power (Annex A).

C.5 "Summation" of distortion products

As indicated above, due to the regular spacing of carriers, different sources of intermodulation contribute with their own weight to CSO or CTB.

In a real analogue transmission schemes, the modulators usually are not phased-locked, and their carrier frequencies deviate a few kHz from the nominal frequencies. This implies a spreading in frequency of the intermodulation contribution around the calculated distortion frequency f_d.

This results in a random dispersion in frequency. That is the reason why quite a large resolution bandwidth filter is used to perform CSO and CTB measurements, in order to integrate all intermodulation power contributions. Figure C.11 shows an enlargement of a CTB. Different contributions are clearly distinguishable.

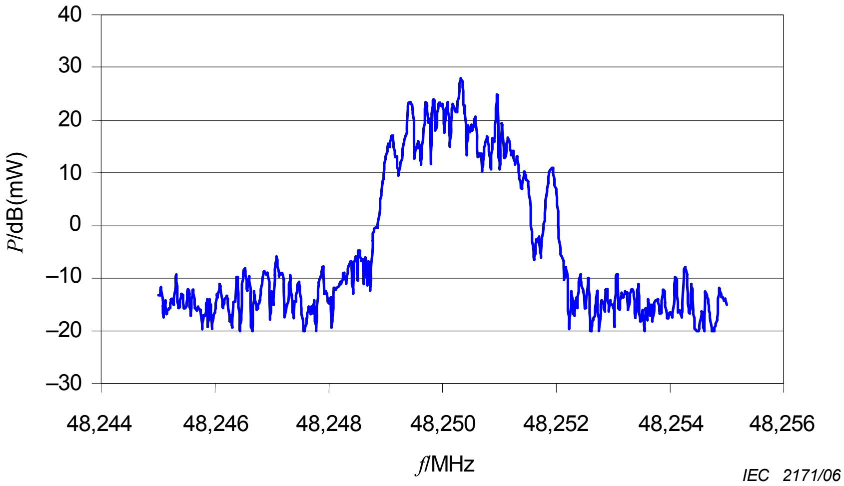


Figure C.11 – Zoom on a CTB

Due to the randomness of the process, it is not possible to reliably calculate the total CSO or CTB of an optical system as contributions from different origins do not add up either on amplitude (20·lg) or on power (10 lg). As an effective rule of thumb, 15 lg is commonly used.

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