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Fibre optic communication system design guides –

Part 8: Calculating dispersion penalty from measured time-resolved chirp data

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FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 8: Calculating dispersion penalty from measured time-resolved chirp data

FOREWORD

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IEC 61282-8, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

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

Enquiry draft	Report on voting
86C/686/DTR	86C/721/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 of 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 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- withdrawn,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

Dispersion penalty is a commonly used parameter of laser transmitters and is usually included as a specification for transmitters designed for 2,5 Gb/s and higher data rates. The value of the dispersion penalty is a function of the interaction of laser chirp, spectral width and fibre dispersion and will depend on the particular type of fibre.

Because the type and length of the fibre specified for a particular transmitter is fixed, the dispersion penalty is determined by the temporal characteristics of the transmitter chirp, which include the spectral characteristics of the laser.

As developers and manufacturers of laser transmitters are attempting to go to higher rates and longer distances, they are finding that chirp is limiting their ability to achieve a required dispersion penalty. Direct measurement of dispersion penalty requires two BER measurements over a reference receiver input range that yields BER values typically from 10^{-4} to 10^{-12}. This is typically a long measurement. Measuring time-resolved chirp (TRC) and calculating dispersion penalty can be a considerably shorter measurement.

This technical report describes the procedure for calculating dispersion penalty from TRC data.

FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 8: Calculating dispersion penalty from measured time-resolved chirp data

1 Scope

This part of IEC 61282 provides definitions of dispersion penalty and other related penalties. It describes the direct measurement of these penalties using a *BER* test set and the calculation of the penalties from time-resolved chirp (TRC) data. Annex A provides the theory for power penalty calculations.

The calculations are valid for all types of single longitudinal mode (SLM) laser transmitters intended for use in telecommunications applications at data rates of 2,5 Gbit/s and higher with NRZ modulation format. These include but are not limited to directly modulated DFB lasers, DFB lasers with integrated electro-absorption modulators, and DFB lasers with external Mach-Zehnder modulators. This technique is not suitable for multiple longitudinal mode (MLM) lasers or LEDs.

Chromatic dispersion induced power penalty values in this technical report are characteristics of the transmitter, which is considered to be the device-under-test (DUT). Other power penalty sources, such as nonlinear effects and amplifier noise are not covered by this document.

Since dispersion penalty for a transmission link depends on the transmitter, receiver and fibre, the dispersion penalty parameter for a transmitter is based on a specified fibre dispersion and receiver characteristic, which should be reported with the test results.

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 61280-2-8, *Fibre optic communication subsystem test procedures – Digital systems – Part 2-8: Determination of low BER using Q-factor measurements*

IEC 61280-2-10, *Fibre optic communication subsystem test procedures – Digital systems – Part 2-10: Time-resolved chirp and alpha-factor measurement of laser transmitters*

ITU-T Recommendation G.957, *Optical interfaces for equipments and systems relating to the synchronous digital hierarchy*

3 Terms and definitions

Power penalty measurements compare *BER* versus received power curves for two conditions. The first condition is a reference condition. The second condition introduces impairment. Changing the received power influences *BER* by altering the ratio of optical signal power to the receiver noise. Therefore it is useful, but equivalent, to express *BER* versus received power curves as *BER* versus *OSNR* curves, where this “optical signal to noise ratio” compares average optical signal power to all noise including the electrical noise of the receiver. Generally, the *OSNR*, based on average signal power, differs from the *SNR* of a digital signal, which is based on the average difference between the signal of the ‘1’ and ‘0’ bits, as described in IEC 61280-2-8.

3.1
dispersion penalty
apparent change in receiver sensitivity due to distortion of the signal waveform during its transmission over a path with a specified chromatic dispersion and minimal PMD. It is manifested as a shift of the system's *BER* curves from the fibre path to a no-fibre path:

– reference condition: DUT without dispersive fibre;

– impaired condition: DUT with specified fibre path

NOTE 1 It is normal that the impaired condition will shift the *BER* to a higher received power and yield a dispersion penalty that is a positive value. Under some conditions, for example, when fibre dispersion compensates for transmitter chirp, in the impaired condition, the *BER* curve will be shifter to a lower received power and yield a negative dispersion penalty.

NOTE 2 Minimal PMD is a necessary condition because, for example, 0,6 ps PMD causes 0,1 dB power penalty for 40 Gb/s NRZ.

3.2
transmitter and dispersion penalty
TDP
apparent change in receiver sensitivity due to distortion of the signal waveform during its transmission over a path with a specified chromatic dispersion for a transmitter with a defined extinction ratio. It is manifested as a shift of the system's *BER*-curves for these two cases:

– reference condition: ideal transmitter (specified with maximum rise and fall times only) with the same extinction ratio as the actual DUT with no dispersive fibre in the path;

– impaired condition: DUT with specified fibre path

NOTE This parameter is defined in IEEE 802.3ae-2002, *10Gb/s Ethernet*. The IEEE standard does not specify a transmitter with the same ER as the DUT, but accomplishes the equivalent by specifying a measurement of optical modulation amplitude (OMA) as opposed to average power.

3.3
total transmitter power penalty
apparent change in receiver sensitivity due to distortion of the signal waveform during its transmission over a path with a specified chromatic dispersion for a transmitter with an infinite extinction ratio. It is manifested as a shift of the system's *BER*-curves for these two cases:

– reference condition: ideal transmitter with infinite extinction ratio;

– impaired condition: DUT with specified fibre path

4 Measuring dispersion penalty using a bit-error-ratio test set

Directly measuring dispersion penalty requires the setup of Figure 1. This figure is introduced to provide a context for the calculation of dispersion induced power penalty, which is the main topic of this document.

NOTE When dispersion induced power penalty is measured directly, care should be taken to use power levels that are low enough to avoid introducing penalties that can be induced by nonlinear effects.

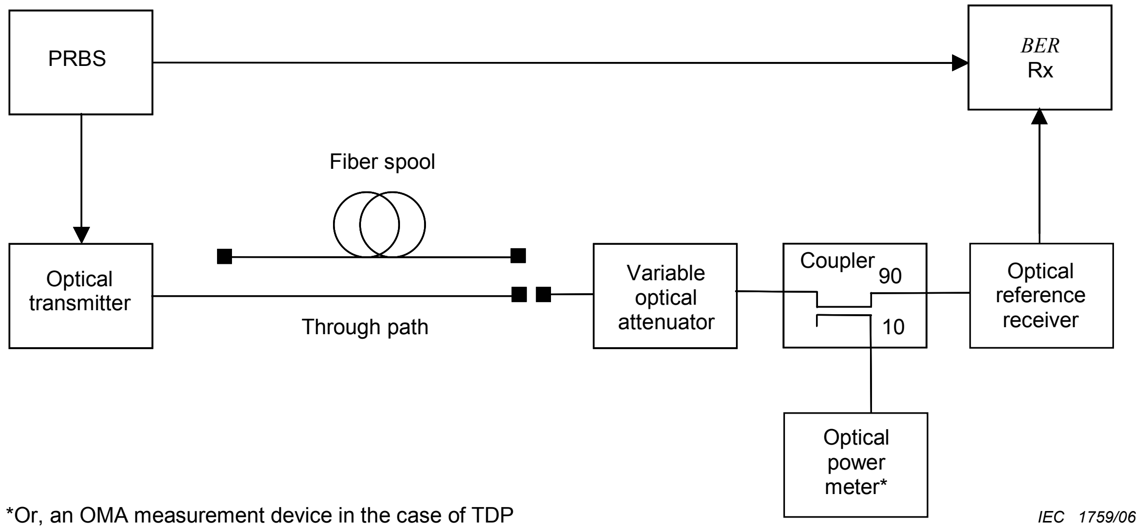

Figure 1 – Equipment setup for direct power penalty measurements

As described in Annex A, two sets of *BER* versus received power data are taken by varying the variable optical attenuator. The received power (or, equivalently, the *OSNR*) for the specified *BER* for the reference and impaired conditions, expressed in dB, are subtracted to obtain the penalty value. The particular reference and impaired conditions are given in 3.1.

5 Obtaining time-resolved chirp data

The measurement of time-resolved chirp is described in IEC 61280-2-10. As described in that standard, the measured result is an array of instantaneous optical power versus time, $P(t)$, and of instantaneous optical frequency versus time, $\Delta f(t)$. The transmitter stimulus is a pseudo-random binary sequence, PRBS, to simulate transmitter behaviour with actual data.

In order to adequately describe the transmitter behaviour, the PRBS must be sufficiently long to include strings of consecutive ones and zeros adequate to measure any intersymbol effects of the transmitter. For example, a maximal length sequence of $2^7 - 1$ bits sufficiently represents intersymbol interference effects up to ±3 bits, and is available in all standard pattern generators. Shorter patterns can be used as long as they satisfy the criteria of equal probability of occurrence of each bit pattern within the range of the intersymbol interference. Additionally, the time resolution must be sufficient to capture the transient nature of $P(t)$ and $\Delta f(t)$. Typically, a resolution that provides more than 30 points per bit period is adequate.

Figure 2 shows a plot of data that is suitable for calculating the power penalties described in Clause 6. This data is for a 9,95328 Gbit/s NRZ signal. The time range is 12,8 ns and there are 4 096 points of display resolution. This provides 32 points per bit period.

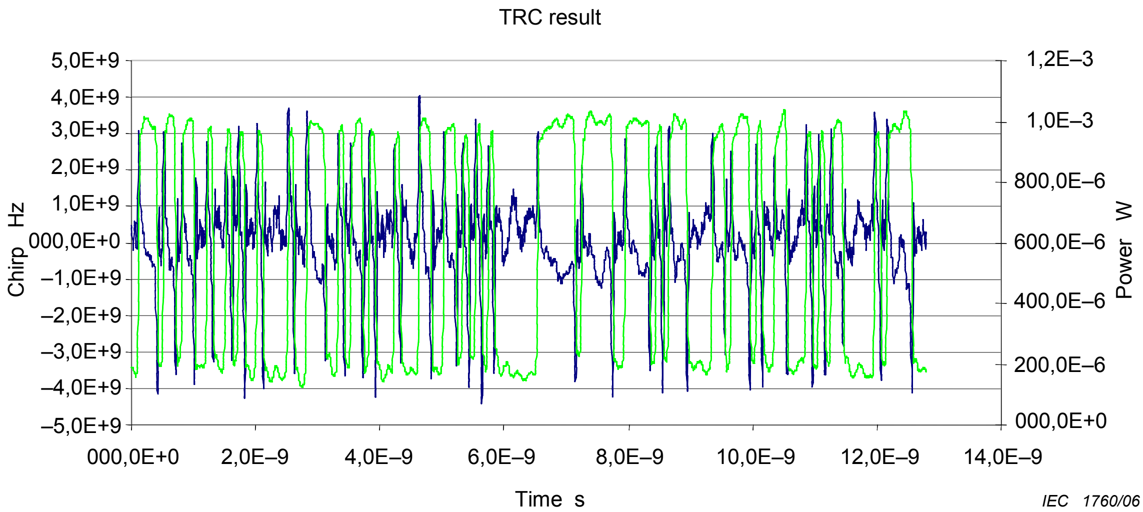

Figure 2 – Typical TRC data suitable for dispersion penalty calculations

6 Calculating dispersion penalty from time-resolved chirp data

The TRC data, as represented in Figure 2, is a complete description of the transmitted signal. By Fourier transforming, adding the effect of chromatic dispersion, inverse-Fourier transforming, and analysing the *BER* by adding noise, the dispersion penalty may be calculated. The following is a detailed description of the algorithm.

6.1 Calculate *BER* for a particular condition

(1) Integrate $\Delta f(t)$ to obtain phase, $\phi(t)$.

$$\phi(t) = \int 2\pi\Delta f(t)dt \quad (1)$$

(2) Calculate complex electric field array

$$E(t) = \sqrt{P(t)}e^{j\phi(t)} \quad (2)$$

(3) Perform fast Fourier, transform, *FFT*.

$$S_{\text{in}}(f) = FFT[E(t)] \quad (3)$$

(4) Add chromatic dispersion.

$$S_{\text{out}}(f) = S_{\text{in}}\text{e}^{j\pi d^2} \quad (4)$$

where d is dispersion in s/Hz, related to D in ps/nm by

$$d(\text{s/Hz}) = -D(\text{ps/nm}) * 10^{-3} * \frac{\lambda_0{}^2}{c}$$

where λ_0 is in meters, the 10^{-3} converts the ps/nm to s/m, and the final term converts 1/m to –1/Hz.

(5) Perform inverse *FFT* and compute signal magnitude.

$$P(t) = \left|FFT^{-1}S_{\text{out}}(f)\right|^2 \quad (5)$$

(6) Filter $P(t)$ by the appropriate filter function to emulate optical receiver performance. The filter function is typically a fourth-order Bessel-Thompson filter as described in ITU-T Recommendation G.957:

$$\{H(p)\}^{-1} = \frac{1}{105}\left(105 + 105y + 45y^2 + 10y^3 + y^4\right), \quad (6)$$

where $y = 2{,}1140p$, $p = j\dfrac{\omega}{\omega_r}$, $\omega_r = 1{,}5\pi f_0$, and f_0 is the bit rate.

(7) Extract phase of the clock by finding maximum and minimum of $d[P(t)]/dt$.

NOTE An alternative approach is to calculate the bit phase for which the maximum eye opening occurs and then set that to the sampling time.

(8) Sort $P(t)$ into logical (0) and logical (1) samples by utilizing clock phase and setting a decision threshold. The amplitude threshold is typically set to the average power and the time threshold at one-half the bit period. (A more sophisticated approach might use an optimization routine to find the point of lowest *BER* for each condition.)

(9) Now calculate the *BER* for each sample, based on the distribution of the individual sample power levels caused by noise over the prescribed *OSNR* range, by assuming that the dominant noise contribution is receiver noise with a symmetric Gaussian distribution, so that the individual density function can be described in terms of the value *P(t)* at the time threshold and the standard deviation of the distribution σ. The relationship between σ and *OSNR* is given by

$$OSNR = \left(\langle P_{\text{logical(1)}}\rangle + \langle P_{\text{logical(0)}}\rangle\right)/2\sigma, \quad (7)$$

assuming the same σ for the logical (0) and logical (1) states and using the average power $\langle P\rangle$ over all of the respective bits for both logical states.

For each OSNR value and each sample i, compute:

$$BER_i = \int_V^{\infty}(DensityFunction_i)dP, \quad (8)$$

for logical (0) samples and

$$BER_i = \int_{-\infty}^{V}(DensityFunction_i)dP, \quad (9)$$

for logical (1) samples, where V is the amplitude threshold separating logical (0) and logical (1) values.

NOTE 1 If the intersymbol interference is sufficiently large, the calculation may not yield *BER* values at the required level for the prescribed *OSNR* range.

NOTE 2 This assumes that the noise is symmetric and the same for ones as for zeroes. When optical noise associated with ASE dominates some modification to the calculation taking this into account should be considered. This calculation is beyond the scope of the current document. The approach taken here should be considered as a transmitter test while the full treatment including optical noise is a broader indication of full system performance (see Clause 1).

(10) Calculate the total *BER* for each *OSNR* value as the average of the individual *BER* for all samples.

6.2 Calculate dispersion penalty

(1) Using the procedure of 6.1, calculate *BER* versus *OSNR* for the reference condition (no dispersion). Set d = 0 in Equation (4). Plot as described Annex A.

(2) Again, using the procedure of 6.1, calculate *BER* versus *OSNR* for the impaired condition (with fibre dispersion). Set d in Equation (4) to the value for the particular fibre type and length and operating wavelength. Plot as described in Annex A.

(3) At the specified BER, from the corresponding $OSNR$ values (expressed in dB), calculate dispersion penalty (expressed in dB):

Dispersion penalty = $OSNR_{\text{impaired}} - OSNR_{\text{reference}}$ (10)

6.3 Calculate transmitter and dispersion penalty

(1) Using the procedure of 6.1, calculate BER versus $OSNR$ for the impaired condition (with fibre dispersion). Plot as described in Annex A.

(2) Calculate BER versus $OSNR$ for the reference condition from the following equation:

$$BER \cong \frac{e^{-\left(Q^2/2\right)}}{Q\sqrt{2\pi}}, \quad (11)$$

where Q is the Q-factor and is the signal-to-noise ratio at the receiver's decision circuit, as described in IEC 61280-2-8. It is computed from $OSNR$ and the transmitter extinction ratio, E_r, as follows:

$$Q = OSNR\frac{1-\frac{1}{E_r}}{1+\frac{1}{E_r}} \quad (12)$$

(3) At the specified BER, calculate transmitter and dispersion penalty:

Transmitter and dispersion penalty = $OSNR_{\text{impaired}} - OSNR_{\text{reference}}$ (13)

6.4 Calculate total transmitter power penalty

(1) Repeat step (1) of 6.3 to obtain $OSNR_{\text{impaired}}$.

(2) Repeat step (2) of 6.3 with $1/E_r = 0$ to obtain $OSNR_{\text{reference}}$.

(3) At the specified BER, calculate transmitter and dispersion penalty:

Total transmitter power penalty = $OSNR_{\text{impaired}} - OSNR_{\text{reference}}$. (14)

7 An example measurement and calculation of power penalties

Figure 3 shows an example measurement of the three power penalties described above. Some observations are as follows.

a) There is no limit to the fibre length that can be analyzed.

b) Dispersion penalty will have the lowest value because it only includes the effect of chromatic dispersion.

c) The transmitter and dispersion penalty will be next highest because it includes an additional penalty due to the non-rectangular transmitter modulation form.

d) The total transmitter power penalty is highest because it also includes an additional penalty due to the finite extinction ratio of the transmitter.

e) Only dispersion penalty approaches zero at zero fibre length.

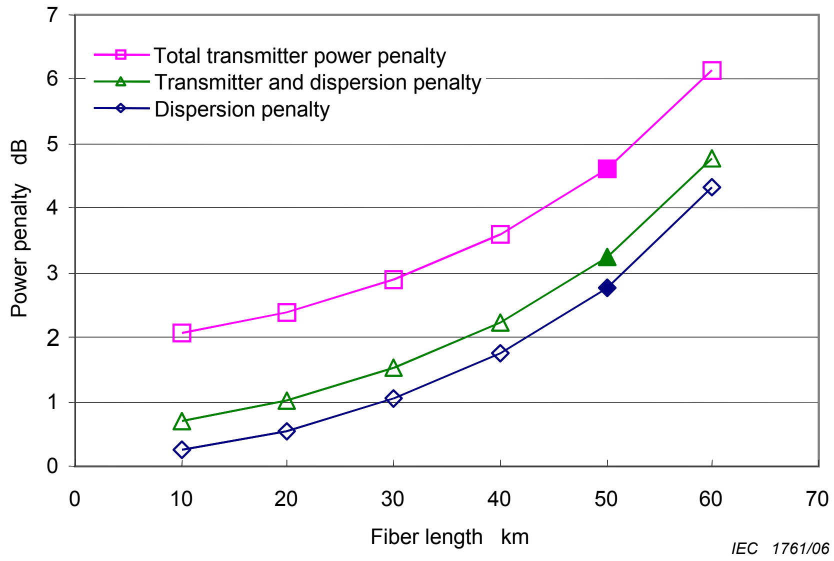

Figure 3 – An example measurement of the three power penalties

8 A comparison of dispersion penalty measurements from *BER* and TRC measurements

In order to validate the calculation of dispersion penalty from TRC data, a comparison was made to measurements with a *BER* test set, as in Clause 4. An electro-absorption modulated DFB at 10 Gbit/s at a wavelength of 1 550 nm was used for the test. The fibre was compliant with ITU-T G.652. The optical reference receiver had an electrical frequency response as described in ITU-T G.691 for STM-64 operation.

The result, shown in Figure 4, indicates agreement within 0,2 dB for penalties up to 2,0 dB. One significant contribution to measurement uncertainty is the characteristics of the reference receiver, which can have a large impact on dispersion penalty. G.691 allows a frequency response with a wide tolerance band. For the calculation from TRC data, an ideal response is assumed.

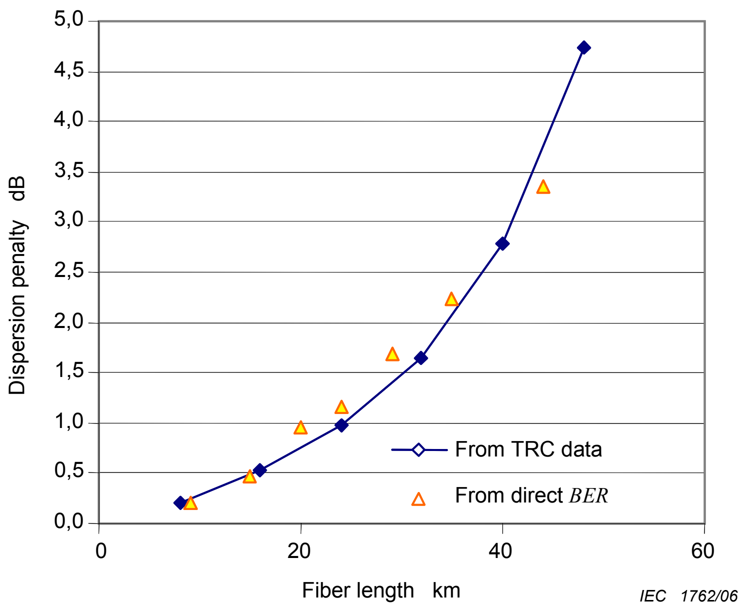

Figure 4 – Comparison of dispersion penalty results for measurements with a *BER* test set and for calculation from TRC data

Annex A
(informative)

Data analysis of bit error ratio versus received power in digital systems

A.1 Introduction

This annex provides analysis procedures for bit error ratio (BER) versus SNR or received power measurements for fibre optic systems. Detailed procedures are given for determining receiver sensitivity at a specified BER and for power penalty at a specified BER.

A.1.1 Intent

To determine parameters such as receiver sensitivity at a specified BER and power penalty at a specified BER, it is preferable to fit an equation to the BER versus received power data, rather than relying on individual data points. The advantages include better accuracy and repeatability, with fewer data points. By transforming the BER data, the data can be caused to follow a straight line for easy fitting and analysis.

A.1.2 Background

If SNR is the signal-to-noise ratio (average signal power to rms noise power), then the BER is given by

$$BER = \frac{erfc\left(SNR / \sqrt{2}\right)}{2} = \frac{1}{\sqrt{2\pi}} \int_{SNR}^{\infty} \exp\left(-\frac{t^2}{2}\right) dt \ . \qquad \text{(A.1)}$$

This expression assumes

a) a Gaussian distribution of receiver noise,

b) the noise contributions are identical for a received '1' or '0', and

c) the threshold level in the decision circuit is set at half the average signal power level of a '0' signal plus a '1' signal at the instant of sampling,

d) the average signal power is half of the difference between the average power of the ‘1’ bits and the ‘0’ bits.

Equation (1) is plotted in Figure A.1.

The transformation procedure linearizes Equation (A.1) and thus the depiction of the BER data. Two procedures to transform the BER data for analysis are given in Clause 2 of this annex. The general procedure can also be applied to non-Gaussian distributions (for example, Laplace or Cauchy) as long as an expression is obtained for the BER as a function of the signal-to-noise ratio.

NOTE As described above, the procedures in this technical report rely upon having an expression for the BER as a function of the SNR. The Gaussian distribution is often an accurate description of the behaviour of fibre optic systems. However, in some cases the system may not follow the expected behaviour. In some systems a BER "floor" may exist, perhaps due to excessive reflections or dispersion in the optical link. In these cases, it will generally not be possible to perform a fit to the data.

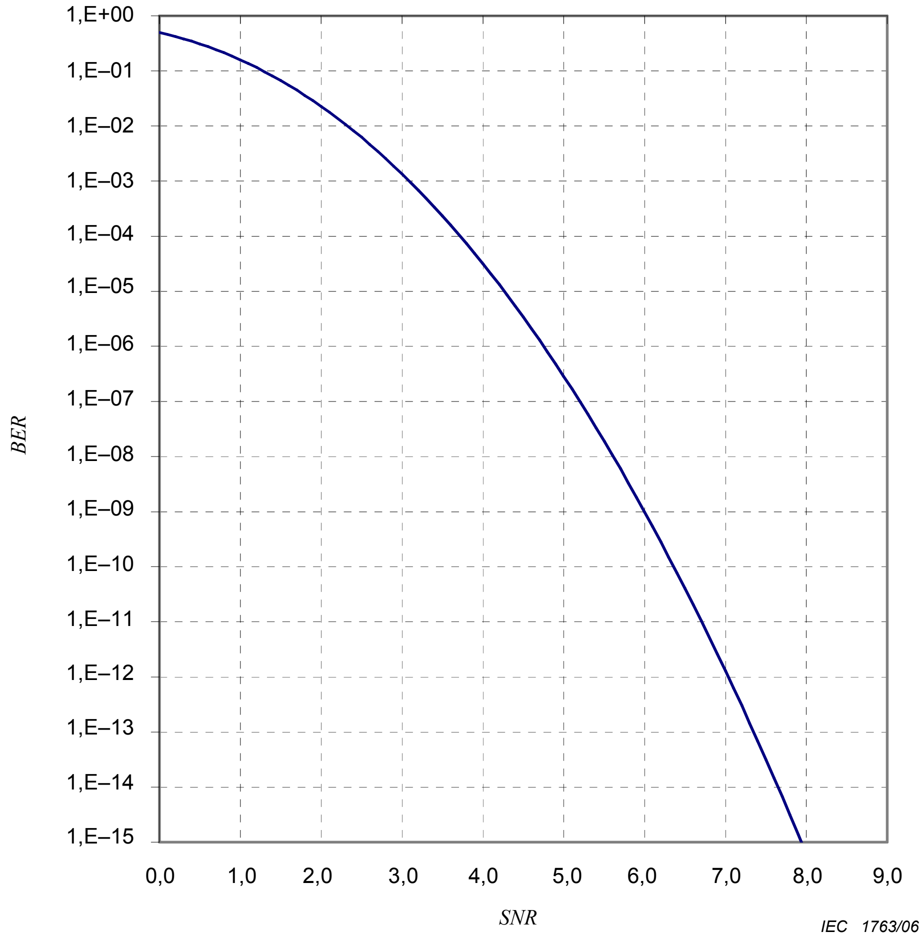

Figure A.1 – Plot of Equation (A.1) with *SNR* plotted linearly

Generally speaking, the curve-fit to the data should not be used to extrapolate beyond the highest and lowest *BER* data points, because 'nonlinearities', such as *BER* floors, may occur beyond the measured region. Extrapolations should be done only when there is a reasonable certainty that nonlinearities are not present.

A.2 Procedure

A.2.1 Exact method

(1) For each *BER* data point solve Equation (1) for the value of *SNR*. The value of *SNR* for the range of interest can be determined by using a look-up table for Equation (A.1) as given in Table A.1, with linear interpolation between values. Alternatively, numerical methods can be used.

Table A.1 – Values for *BER* versus *SNR*

SNR	BER	SNR	BER	SNR	BER
0,0	5,000E-01	2,8	2,555E-03	5,6	1,072E-08
0,1	4,602E-01	2,9	1,866E-03	5,7	5,990E-09
0,2	4,207E-01	3,0	1,350E-03	5,8	3,316E-09
0,3	3,821E-01	3,1	9,676E-04	5,9	1,818E-09
0,4	3,446E-01	3,2	6,871E-04	6,0	9,866E-10
0,5	3,085E-01	3,3	4,834E-04	6,1	5,303E-10
0,6	2,743E-01	3,4	3,369E-04	6,2	2,823E-10
0,7	2,420E-01	3,5	2,326E-04	6,3	1,488E-10
0,8	2,119E-01	3,6	1,591E-04	6,4	7,769E-11
0,9	1,841E-01	3,7	1,078E-04	6,5	4,016E-11
1,0	1,587E-01	3,8	7,235E-05	6,6	2,056E-11
1,1	1,357E-01	3,9	4,810E-05	6,7	1,042E-11
1,2	1,151E-01	4,0	3,167E-05	6,8	5,231E-12
1,3	9,680E-02	4,1	2,066E-05	6,9	2,600E-12
1,4	8,076E-02	4,2	1,335E-05	7,0	1,280E-12
1,5	6,681E-02	4,3	8,540E-06	7,1	6,238E-13
1,6	5,480E-02	4,4	5,413E-06	7,2	3,011E-13
1,7	4,457E-02	4,5	3,398E-06	7,3	1,439E-13
1,8	3,593E-02	4,6	2,112E-06	7,4	6,809E-14
1,9	2,872E-02	4,7	1,301E-06	7,5	3,191E-14
2,0	2,275E-02	4,8	7,933E-07	7,6	1,481E-14
2,1	1,786E-02	4,9	4,792E-07	7,7	6,803E-15
2,2	1,390E-02	5,0	2,867E-07	7,8	3,095E-15
2,3	1,072E-02	5,1	1,698E-07	7,9	1,395E-15
2,4	8,198E-03	5,2	9,964E-08	8,0	6,221E-16
2,5	6,210E-03	5,3	5,790E-08	8,1	2,748E-16
2,6	4,661E-03	5,4	3,332E-08	8,2	1,202E-16
2,7	3,467E-03	5,5	1,899E-08	8,3	5,206E-17

(2) For each value of *SNR*, compute

$$SNR_{dB} = 10\log_{10}(SNR) \tag{A.2}$$

and

$$Y = 10^{(A + B\,SNR_{\mathrm{dB}})}, \tag{A.3}$$

so that Equation (A.3) appears as a straight line when plotted on semi-logarithmic graph paper as in Figure A.2. The constants, *A* and *B* are chosen so that Equation (A.3) intersects the *BER* curve at 10^{-3} and 10^{-12}, the desired range for plotting *BER*. Knowing that the line passes through the points (4,900, 10^{-3}) and (8,472, 10^{-12}) gives *A* = 9,344 and *B* = –2,519. Numerical methods may also be used.

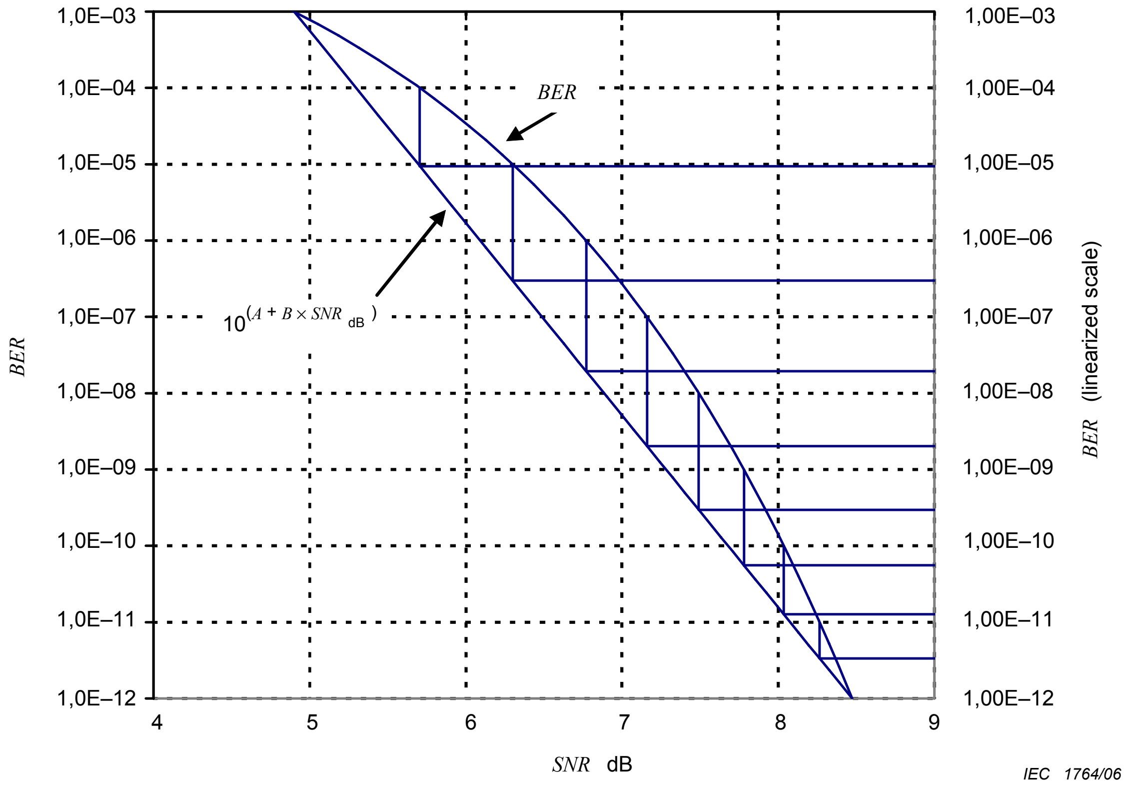

Figure A.2 – Graphical illustration of method to transform y-axis

(3) Plot the data points Y on a logarithmic y-axis versus SNR, (in dB) on a linear x-axis. Figure A.2 graphically illustrates where each decade (for example, 10^{-3}, 10^{-4}, etc.) of BER data is plotted on the logarithmic axis. Using the resulting modified y-axis on the right of Figure A.2 allows the BER data to be read from the graph. The Y data is of no direct further interest.

(4) Fit the exponential equation to the data points by solving for c and m using the least-squares method, using:

$$m = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sum X^2 - \frac{\left(\sum X\right)^2}{N}}, \qquad \text{(A.4)}$$

and

$$c = \frac{\sum Y - m \sum X}{N}, \qquad \text{(A.5)}$$

where $X = SNR$ and Σ denotes a sum over all N data points.

(5) Determine the fitted SNR at a given BER.

i) Find the value of Y_0 for the desired BER_0 as in Step 1. (For the example of a BER of 10^{-10}, Y_0 equals 1,261e-11.)

ii) Solve for the fitted SNR by evaluating:

$$SNR_0 = \frac{\log_{10} Y_0 - c}{m} \tag{A.6}$$

A.2.2 Log-log approximate procedure

(1) For each BER data point, calculate the $BER_{\log}$ value as

$$BER_{\log} = 1 - \frac{\log(-\log BER)}{\log(-\log BER_T)} \tag{A.7}$$

where BER_T is the bit error ratio requirement (for example, 10^{-10}).

The transformation results in an excellent linearization of the function over the BER range of interest (10^{-3} to 10^{-12}). A BER data value of 0.1 will be transformed to a $BER_{\log}$ value of 1, and a BER data value of 10^{-10} will be transformed to a $BER_{\log}$ value of 0, for a BER_T of 10^{-10}.

(2) Fit the data to the straight line

$$BER_{\log} = m P_R + c \tag{A.8}$$

using the least-squares method. Equations (A.4) and (A.5) may be used to evaluate *m* and *c*, where Y = $BER_{\log}$.

(3) Determine the receiver sensitivity at the target BER_T.

$$sensitivity = \frac{-c}{m} \tag{A.9}$$

An alternative approach is to use the approximation function:

$$BER_{\log} = \ln(-\ln(BER)) = m * P_r + c \tag{A.10}$$

Then calculate m and c with a standard least-square method.
The sensitivity for an arbitrary bit error rate can now be calculated with the formula

$$Sensitivity = (\ln(-\ln(BER_T)) - c) / m \tag{A.11}$$

A.2.3 Example

The following BER versus received power, P_R, data has been obtained for a fibre optic system. Using the exact procedure of A.2.1, SNR_{dB} and Y are calculated using Equations (A.2) and (A.3).

Table A.2 – Experimental data for exact linearization

P_R dBm	*BER*	*SNR* dB	*Y*
–38,0	5,00E-5	5,9002	3,020-6
–37,5	6,25E-6	6,4035	1,629-7
–37,0	5,17E-7	6,8887	9,764-9
–36,5	4,50E-8	7,2802	1,008E-9
–36,0	2,25E-9	7,6824	9,772E-11
–35,7	2,42E-10	7,9408	2,183E-11

The coefficients for the fitted line are calculated as m = –2,206 and c = –89,479 using Equations (A.4) and (A.5).

Figure A.3 shows a plot of *BER* versus the received power using the modified y-axis. In making the plot, the *Y* values are actually plotted on a normal log scale. However, with the modified y-axis displayed, the *BER* values can be read directly from the graph. The fitted line is also plotted. The calculated receiver sensitivity at 10^{-10} *BER* according to Equation (A.6) is 35,62 dBm.

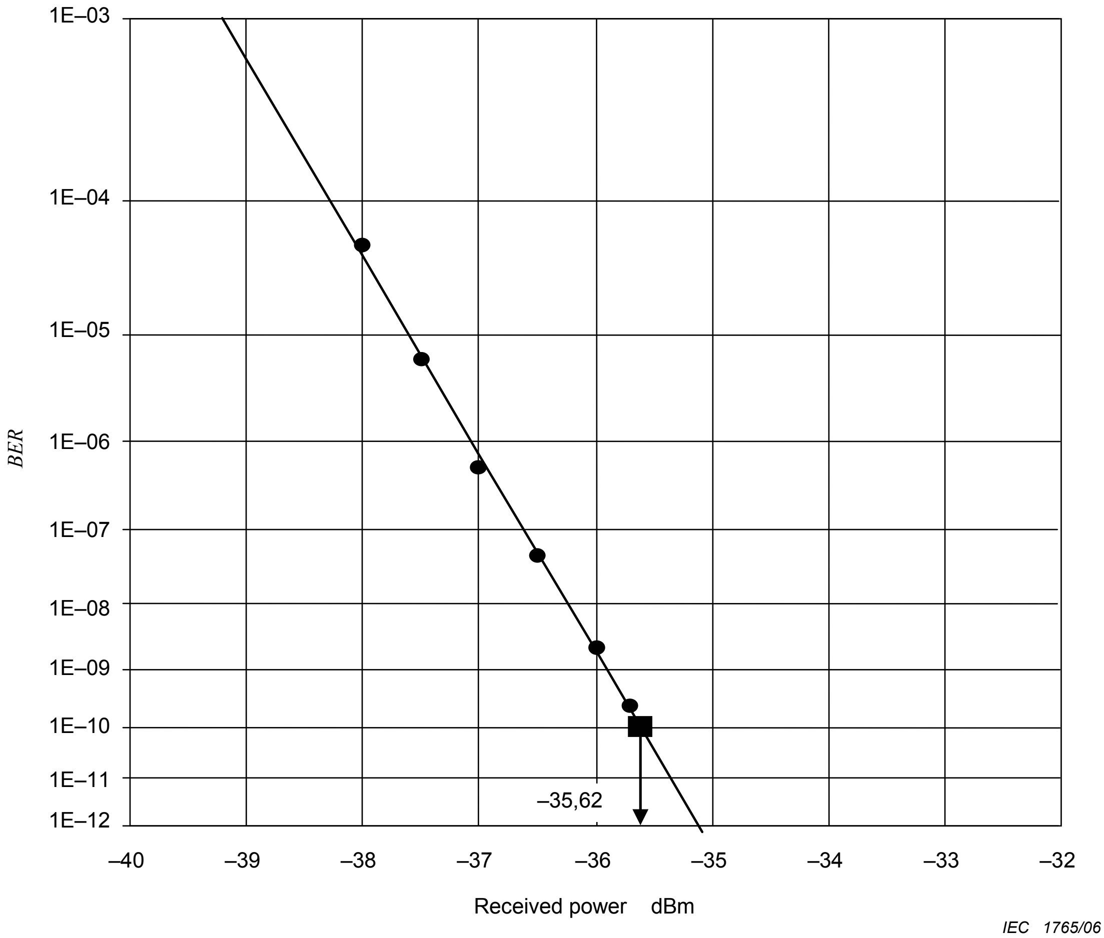

Figure A.3 – Example plot and analysis using the exact procedure.

The same data are analysed using the log-log procedure of A.2.2. The BER_{log} values are calculated using equation (A.7).

Table A.3 – Experimental data for log-log analysis

P_R dBm	BER	BER_{log}
–38,0	5,00E-05	3,664E-01
–37,5	6,25E-06	2,837E-01
–37,0	5,17E-07	2,016E-01
–36,5	4,50E-08	1,339E-01
–36,0	2,25E-09	6,309E-02
–35,7	2,42E-10	1,700E-02

Fitting the data to equation (A.8) yields: BER_{log}= –5,347 – 0,15019*P_R. Figure A.4 shows a plot of BER_{log} versus the received power and the fitted line. The receiver sensitivity at 10^{-10} BER calculated by equation (A.9) is –35,60 dBm. This agrees closely with the value obtained by the exact linearization method, above.

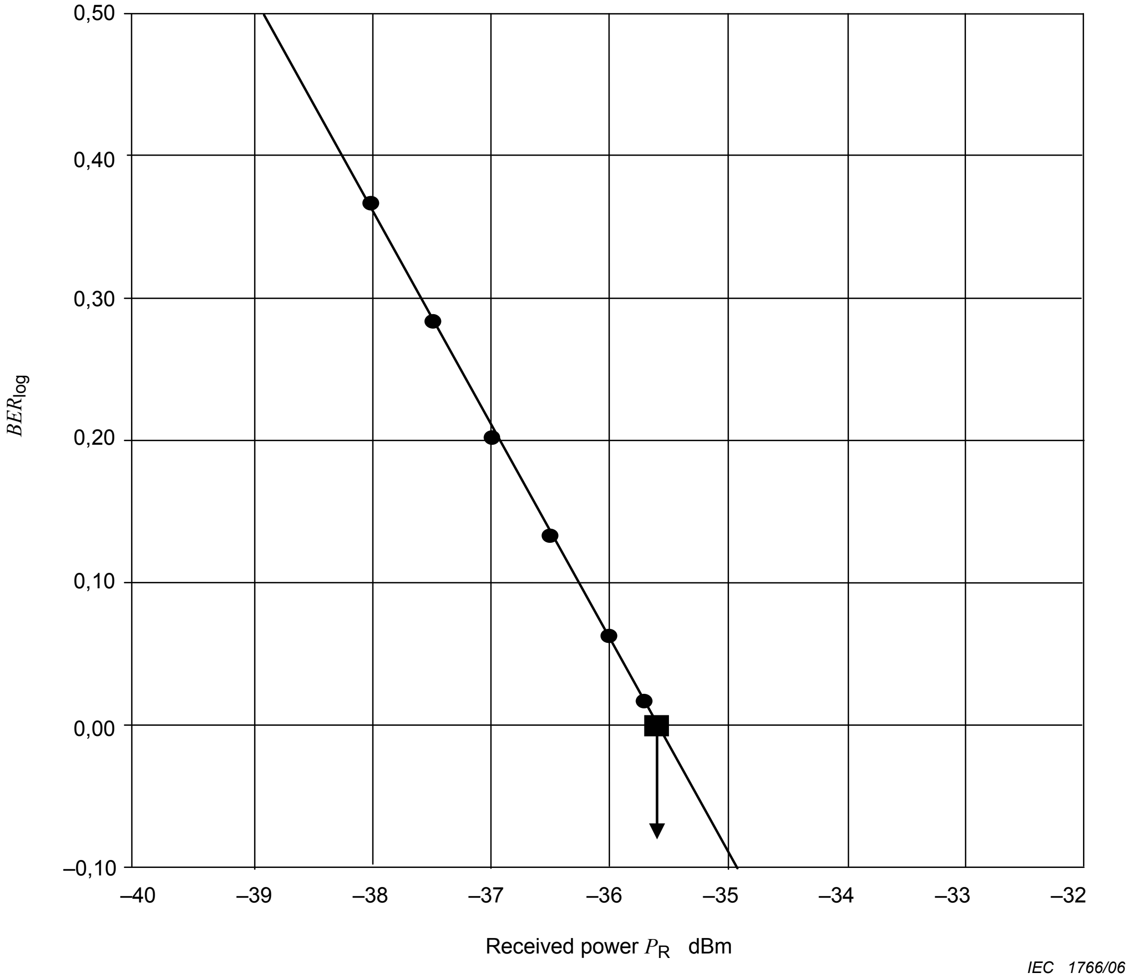

Figure A.4 – Example plot and analysis using the log-log procedure

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