IEC 61280-2-8

Edition 2.0 2021-03
REDLINE VERSION

INTERNATIONAL STANDARD

colour inside

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

IEC 61280-2-8:2021-03 RLV(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 33.180.10 ISBN 978-2-8322-9530-4

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FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES – ~~DIGITAL SYSTEMS –~~

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IEC 61280-2-8 has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics. It is an International Standard.

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

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

a) correction of errors in Formula (8) in 5.5.2 and in a related formula in 5.5.3;
b) correction of errors in the references to clauses, subclauses, figures, procedures, and in the Bibliography;
c) alignment of the terms and definitions in 3.1 with those in IEC 61281-1.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
86C/1708/FDIS	86C/1711/RVD

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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

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FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES – ~~DIGITAL SYSTEMS –~~

Part 2-8: Digital systems – Determination of low BER using Q-factor measurements

1 Scope

This part of IEC 61280 specifies two main methods for the determination of low BER values by making accelerated measurements. These include the variable decision threshold method (Clause 5) and the variable optical threshold method (Clause 6). In addition, a third method, the sinusoidal interference method, is described in Annex B.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
amplified spontaneous emission
ASE
~~impairment generated in optical amplifiers~~
optical power associated to spontaneously emitted photon amplified by an active medium in an optical amplifier

3.1.2
bit error ratio
BER
P_e
~~the number bits in error as a ratio of the total number of bits~~
number of errored bits divided by the total number of bits, over some stipulated period of time

3.1.3
intersymbol interference
ISI
~~mutual interference between symbols in a data stream, usually caused by non-linear effects and bandwidth limitations of the transmission path~~
overlap of adjacent pulses as caused by the limited bandwidth characteristics of the optical devices in a fibre optic link

3.1.4
Q-factor
Q
ratio of the difference between the mean voltage of the 1 and 0 rails, ~~and~~ to the sum of their standard deviation values

3.2 Abbreviated terms

AC	alternating current
CW	continuous wave (normally referring to a sinusoidal wave form)
DC	direct current
DSO	digital sampling oscilloscope
DUT	device under test
PRBS	pseudo-random binary sequence
SNR	signal-to-noise ratio

4 Measurement of low bit-error ratios

4.1 General considerations

Fibre optic communication systems and subsystems are inherently capable of providing exceptionally good error performance, even at very high bit rates. The mean bit error ratio (BER) may typically lie in the region 10^{-12} to 10^{-20}, depending on the nature of the system. While this type of performance is well in excess of practical performance requirements for digital signals, it gives the advantage of concatenating many links over long distances without the need to employ error correction techniques.

The measurement of such low error ratios presents special problems in terms of the time taken to measure a sufficiently large number of errors to obtain a statistically significant result. Table 1 presents the mean time required to accumulate 15 errors. This number of errors can be regarded as statistically significant, offering a confidence level of 75 % with a variability of 50 %.

Table 1 – Mean time for the accumulation of 15 errors as a function of BER and bit rate

~~BER / Bits/s~~	~~10^{-6}~~	~~10^{-7}~~	~~10^{-8}~~	~~10^{-9}~~	~~10^{-10}~~	~~10^{-11}~~	~~10^{-12}~~	~~10^{-13}~~	~~10^{-14}~~	~~10^{-15}~~
~~1,0M~~	~~1,5 s~~	~~15 s~~	~~2,5 min~~	~~25 min~~	~~4,2 h~~	~~1,7d~~	~~17 d~~	~~170 d~~	~~4,7 years~~	~~47 years~~
~~2,0M~~	~~750 ms~~	~~7,5 s~~	~~75 s~~	~~750 s~~	~~2,1 h~~	~~21 h~~	~~8,8 d~~	~~88 d~~	~~2,4 years~~	~~24 years~~
~~10M~~	~~150 ms~~	~~1,5 s~~	~~15 s~~	~~2,5 min~~	~~25 min~~	~~4,2 h~~	~~1,7 d~~	~~17 d~~	~~170 d~~	~~4,7 years~~
~~50M~~	~~30 ms~~	~~300 ms~~	~~3,0 s~~	~~30 s~~	~~5,0 min~~	~~50 min~~	~~8,3 h~~	~~3,5 d~~	~~35 d~~	~~350 d~~
~~100M~~	~~15 ms~~	~~150 ms~~	~~1,5 s~~	~~15 s~~	~~2,5 min~~	~~25 min~~	~~4,2 h~~	~~1,7 d~~	~~17 d~~	~~170 d~~
~~500M~~	~~3 ms~~	~~30 ms~~	~~300 ms~~	~~3,0 s~~	~~30 s~~	~~5,0 min~~	~~50 min~~	~~8,3 h~~	~~3,5 d~~	~~35 d~~
~~1,0G~~	~~1,5 ms~~	~~15 ms~~	~~150 ms~~	~~1,5 s~~	~~15 s~~	~~2,5 min~~	~~25 min~~	~~4,2 h~~	~~1,7 d~~	~~17 d~~
~~10G~~	~~150 µs~~	~~1,5 ms~~	~~15 ms~~	~~150 ms~~	~~1,5 s~~	~~15 s~~	~~2,5 min~~	~~25 min~~	~~4,2 h~~	~~1,7 d~~
~~40G~~	~~38 µs~~	~~380 µs~~	~~3,8 ms~~	~~38 ms~~	~~380 ms~~	~~3,8 s~~	~~38 s~~	~~6,3 min~~	~~63 min~~	~~10,4 h~~
~~100G~~	~~15 µs~~	~~150 µs~~	~~1,5 ms~~	~~15ms~~	~~150 ms~~	~~1,5 s~~	~~15 s~~	~~2,5 min~~	~~25 min~~	~~4,2 h~~

Bit rate	Mean times for the accumulation of 15 errors										
	BER										
	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}
1,0 Mbit/s	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7d	17 d	170 d	4,7 years	47 years
2,0 Mbit/s	75 ms	750 ms	7,5 s	75 s	750 s	2,1 h	21 h	8,8 d	88 d	2,4 years	24 years
10 Mbit/s	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 d	17 d	170 d	4,7 years
50 Mbit/s	3,0 ms	30 ms	300 ms	3,0 s	30 s	5,0 min	50 min	8,3 h	3,5 d	35 d	350 d
100 Mbit/s	1,5 ms	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 d	17 d	170 d
500 Mbit/s	300 µs	3 ms	30 ms	300 ms	3,0 s	30 s	5,0 min	50 min	8,3 h	3,5 d	35 d
1,0 Gbit/s	150 µs	1,5 ms	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 d	17 d
10 Gbit/s	15 µs	150 µs	1,5 ms	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 d
40 Gbit/s	3,8 µs	38 µs	380 µs	3,8 ms	38 ms	380 ms	3,8 s	38 s	6,3 min	63 min	10,4 h
100 Gbit/s	1,5 µs	15 µs	150 µs	1,5 ms	15ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h

The times given in Table 1 show that the direct measurement of the low BER values expected from fibre optic systems is not practical during installation and maintenance operations. One way of overcoming this difficulty is to artificially impair the signal-to-noise ratio at the receiver in a controlled manner, thus significantly increasing the BER and reducing the measurement time. The error performance is measured for various levels of impairment, and the results are then extrapolated to a level of zero impairment using computational or graphical methods according to theoretical or empirical regression algorithms.

The difficulty presented by the use of any regression technique for the determination of the error performance is that the theoretical BER value is related to the level of impairment via the inverse complementary error function (erfc). This means that very small changes in the impairment lead to very large changes in BER; for example, in the region of a BER value of 10^{-15}, a change of approximately 1 dB in the level of impairment results in a change of three orders of magnitude in the BER. A further difficulty is that a method based on extrapolation is unlikely to reveal a levelling off of the BER at only about 3 orders of magnitude below the lowest measured value.

It should also be noted that, in the case of digitally regenerated sections, the results obtained apply only to the regenerated section whose receiver is under test. Errors generated in upstream regenerated sections may generate an error plateau which may have to be taken into account in the error performance evaluation of the regenerator section under test.

As noted above, two main methods for the determination of low BER values by making accelerated measurements are described. These are the variable decision threshold method (Clause 5) and the variable optical threshold method (Clause 6). In addition, a third method, the sinusoidal interference method, is described in Annex B.

It should be noted that these methods are applicable to the determination of the error performance in respect of amplitude-based impairments. Jitter may also affect the error performance of a system, and its effect requires other methods of determination. If the error performance is dominated by jitter impairments, the amplitude-based methods described in this document will lead to BER values which are lower than the actual value.

The variable decision threshold method is the procedure which can most accurately measure the Q-factor and the BER for optical systems with unknown or unpredictable noise statistics. A key limitation, however, to the use of the variable threshold method to measure Q-factor and BER is the need to have access to the receiver electronics in order to manipulate the decision threshold. For systems where such access is not available, it may be useful to utilize the alternative variable optical threshold method. Both methods are capable of being automated in respect of measurement and computation of the results

4.2 Background to Q-factor

The Q-factor is the signal-to-noise ratio (SNR) at the decision circuit and is typically expressed as [1][1]:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \tag{1}$$

where

μ_1 and μ_0 are the mean voltage levels of the "1" and "0" rails, respectively;

σ_1 and σ_0 are the standard deviation values of the noise distribution on the "1" and "0" rails, respectively.

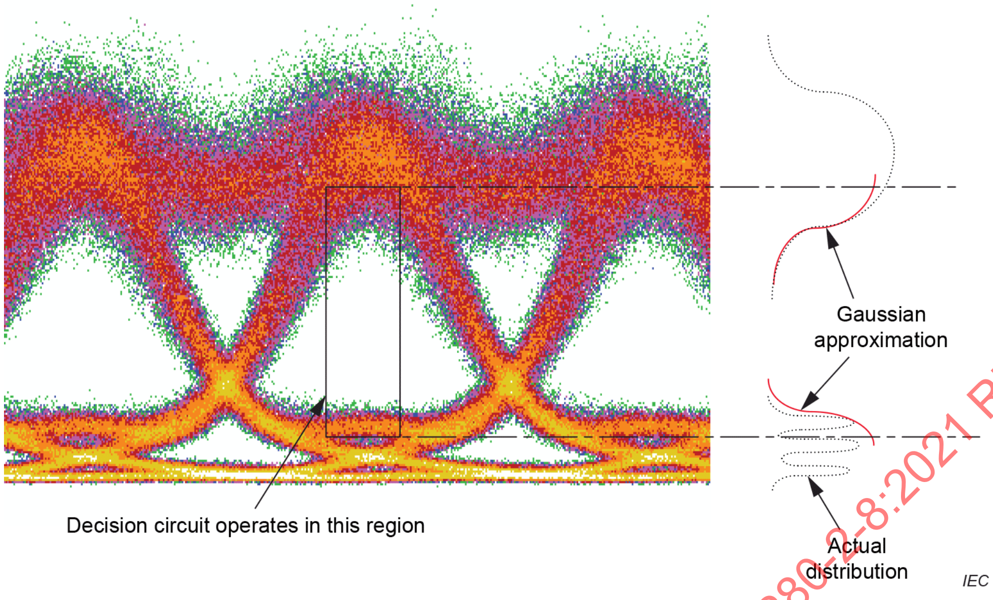
An accurate estimation of a system's transmission performance, or Q-factor, ~~must~~ shall take into consideration the effects of all sources of performance degradation, both fundamental and those due to real-world imperfections. Two important sources are amplified spontaneous emission (ASE) noise and intersymbol interference (ISI). Additive noise originates primarily from ASE of optical amplifiers. ISI arises from many effects, such as chromatic dispersion, fibre non-linearities, multi-path interference, polarization-mode dispersion and use of electronics with finite bandwidth. There may be other effects as well; for example, a poor impedance match can cause impairments such as long fall times or ringing on a waveform.

One possible method to measure Q-factor is the voltage histogram method in which a digital sampling oscilloscope is used to measure voltage histograms at the centre of a binary eye to estimate the waveform's Q-factor [2]. In this method, a pattern generator is used as a stimulus and the oscilloscope is used to measure the received eye opening and the standard deviation of the noise present in both voltage rails. As a rough approximation, the edge of visibility of the noise represents the 3σ points of an assumed Gaussian distribution. The advantage of using an oscilloscope to measure the eye is that it can be done rapidly on real traffic with a minimum of equipment.

The oscilloscope method for measuring the Q-factor has several shortcomings. When used to measure the eye of high-speed data (of the order of several Gbit/s), the oscilloscope's limited digital sampling rate (often in the order of a few hundred kilohertz) allows only a small minority of the high-speed data stream to be used in the Q-factor measurement. Longer observation times could reduce the impact of the slow sampling. A more fundamental shortcoming is that the Q estimates derived from the voltage histograms at the eye centre are often inaccurate. Various patterning effects and added noise from the front-end electronics of the oscilloscope can often obscure the real variance of the noise.

Figure 1 shows a sample eye diagram made on an operating system. It can be seen in this figure that the vertical histograms through the centre of the eye show patterning effects (less obvious is the noise added by the front-end electronics of the oscilloscope). It is difficult to predict the relationship between the Q measured this way and the actual BER measured with a test set.

1 Figures in square brackets refer to the Bibliography.



NOTE The data for measuring the Q-factor are obtained from the tail of the Gaussian distributions.

Figure 1 – Sample eye diagram showing patterning effects

Figure 2 shows another possible way of measuring Q-factor using an oscilloscope. The idea is to use the centre of the eye to estimate the eye opening and use the area between eye centres to estimate the noise. Pattern effect contributions to the width of the histogram would then be reduced. A drawback to this method is that it relies on measurements made on a portion of the eye that the receiver does not really ever use.

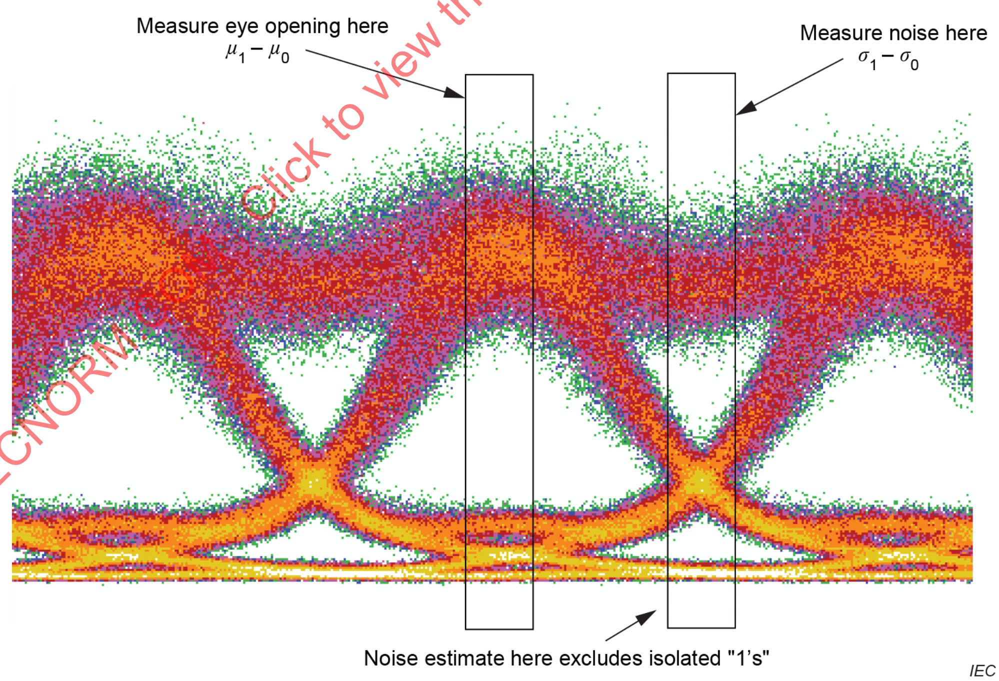


Figure 2 – More accurate measurement technique using a DSO that samples noise statistics between eye centres

It is tempting to conclude that the estimates for σ_1 and σ_0 would tend to be overestimated and that the resulting Q measurements would always form a lower bound to the actual Q for either of these oscilloscope-based methods. That is not necessarily the case. It is possible that the histogram distributions can be distorted in other ways, for example, skewed in such a way that the mean values overestimate the eye opening – and the resulting Q will actually not be a lower bound. There is, unfortunately, no easily characterized relationship between oscilloscope-derived Q measurements and BER performance.

5 Variable decision threshold method

5.1 Overview

This method of estimating the Q-factor relies on using a receiver front-end with a variable decision threshold. Some means of measuring the BER of the system is required. Typically, the measurement is performed with an error test set using a pseudo-random binary sequence (PRBS), but there are alternate techniques which allow operation with live traffic. The measurement relies on the fact that for a data eye with Gaussian statistics, the BER may be calculated analytically as follows:

$$BER(V_{\text{th}}) = \frac{1}{2}\left(erfc\left(\frac{|V_{\text{th}} - \mu_1|}{\sigma_1}\right) + erfc\left(\frac{|V_{\text{th}} - \mu_0|}{\sigma_0}\right)\right) \quad (2)$$

where

μ_1, μ_0 and σ_1, σ_0 are the mean and standard deviation of the "1" and "0" data rails;

V_{th} is the decision threshold level;

$erfc(.)$ is the complementary error function given by

$$erfc(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\beta^2/2} d\beta \cong \frac{1}{x\sqrt{2\pi}} e^{-x^2/2} \quad (3)$$

$$P_{\text{e}}(V_{\text{th}}) = \frac{1}{2}\left(\text{erfc}\left(\frac{|V_{\text{th}} - \mu_1|}{\sigma_1}\right) + \text{erfc}\left(\frac{|V_{\text{th}} - \mu_0|}{\sigma_0}\right)\right) \quad (2)$$

where

P_{e}	is the BER;
V_{th}	is the decision threshold level;
μ_1, μ_0 and σ_1, σ_0	are the mean and standard deviation of the "1" and "0" data rails;
erfc(.)	is the complementary error function given by

$$\text{erfc}(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} \text{e}^{-\beta^2/2} d\beta \cong \frac{1}{x\sqrt{2\pi}} \text{e}^{-x^2/2} \quad (3)$$

The approximation is nearly exact for $x > 3$.

The BER, given in Formula (2), is the sum of two terms. The first term is the conditional probability of deciding that a "0" has been received when a "1" has been sent, and the second term is the probability of deciding that a "1" has been received when a "0" has been sent.

In order to implement this technique, the BER is measured as a function of the threshold voltage (see Figure 3). Formula (2) is then used to convert the data into a plot of the Q-factor versus threshold, where the Q-factor is the argument of the complementary error function of either term in Formula (2). To make the conversion, the approximation is made that the BER is dominated by only one of the terms in Formula (2) according to whether the threshold is closer to the "1's" or the "0's" rail of the eye diagram.

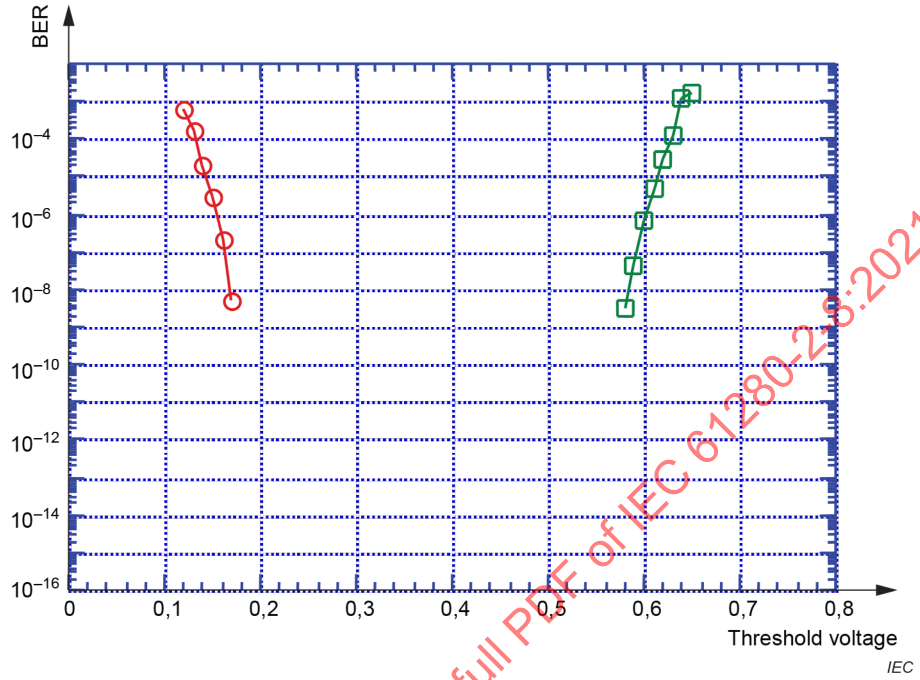


Figure 3 – Bit error ratio as a function of decision threshold level

Figure 4 shows the results of converting the data in Figure 3 into a plot of Q-factor versus threshold. The optimum Q-factor value as well as the optimum threshold setting needed to achieve this Q-factor are obtained from the intersection of the two best-fit lines through the data. This technique is described in detail in [3].

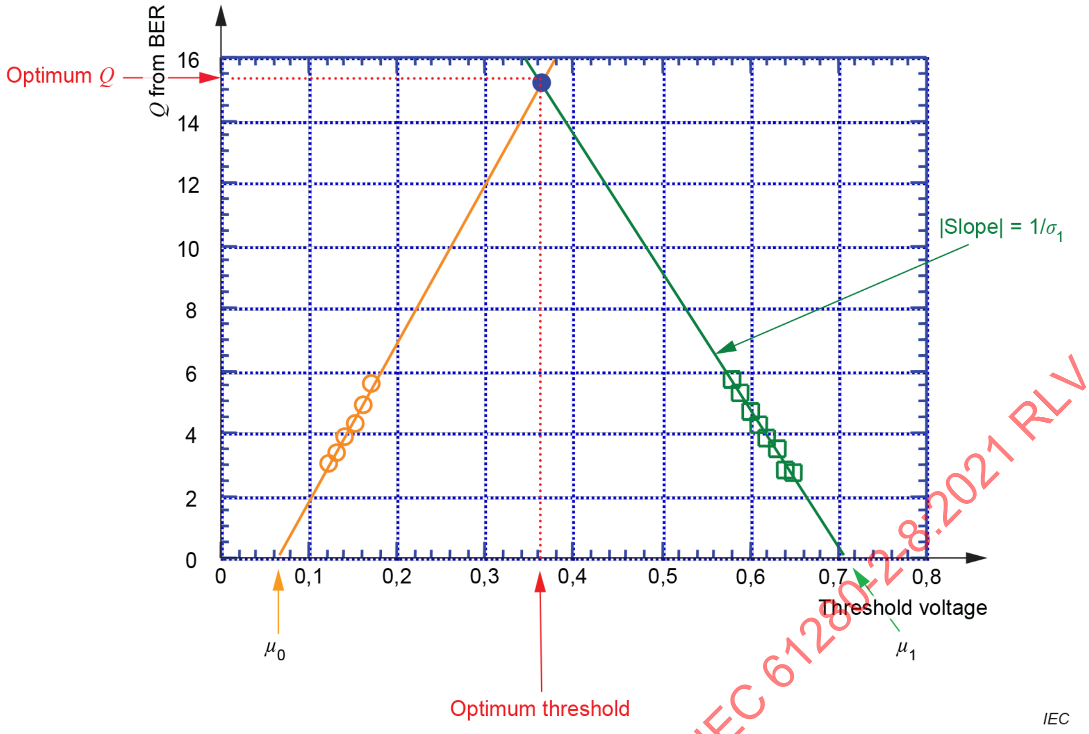


Figure 4 – Plot of Q-factor as a function of threshold voltage

The optimum threshold as well as the optimal Q can be obtained analytically by making use of the following approximation [4] for the inverse error function:

$$\left[\log\left\{\frac{1}{2}erfc(x)\right\}\right]^{-1} \approx 1,192 - 0,6681x - 0,0162x^2 \qquad (4)$$

where x is the log(BER).

NOTE Equation (4) is accurate to ±0,2 % over the range of BER from 10^{-5} to 10^{-10}.

$$\left[\log\left\{\frac{1}{2}\mathrm{erfc}(x)\right\}\right]^{-1} \approx 1,192 - 0,6681x - 0,0162x^2 \qquad (4)$$

where

x is $\log(P_e)$.

NOTE 1 Formula (4) is accurate to ±0,2 % over the range of P_e from 10^{-5} to 10^{-10}.

After evaluating the inverse error function, the data are plotted against the decision threshold level, V_{th}. As shown in Figure 4, a straight line is fitted to each set of data by linear regression. The equivalent variance and mean for the Q calculation are given by the slope and intercept respectively.

The minimum BER can be shown to occur at an optimal threshold, $V_{th\text{-}optimal}$, when the two terms in the argument in Formula (2) are equal, that is

$$\frac{\left(\mu_1 - V_{\text{th-optimal}}\right)}{\sigma_1} = \frac{\left(V_{\text{th-optimal}} - \mu_0\right)}{\sigma_0} = Q_{\text{opt}} \tag{5}$$

An explicit expression for $V_{\text{th-optimal}}$ in terms of $\mu_{1,0}$ and $\sigma_{1,0}$ can be derived from Formula (5) to be:

$$V_{\text{th-optimal}} = \frac{\sigma_0 \mu_1 + \sigma_1 \mu_0}{\sigma_0 + \sigma_1} \tag{6}$$

The value of Q_{opt} is obtained from Formula (1). The residual BER at the optimal threshold can be obtained from Formula (2) and is approximately

$$P_{\text{e-optimal}} \cong \frac{e^{-\left(Q_{\text{opt}}^2/2\right)}}{Q_{\text{opt}}\sqrt{2\pi}} \tag{7}$$

NOTE 2 This approximation is nearly exact for $Q_{\text{opt}} > 3$.

It should be noted that even though the variable threshold method makes use of Gaussian statistics, it provides accurate results for systems that have non-Gaussian noise statistics as well, for example, the non-Gaussian statistics that occur in a typical optically amplified system [5] [6]. This can be understood by examining Figure 1. The decision circuit of a receiver operates only on the interior region of the eye. This means that the only part of the vertical histogram that it uses is the "tail" that extends into the eye. The variable decision threshold method amounts to constructing a Gaussian approximation to the tail of the real distribution in the centre region of the eye where it affects the receiver operation directly. As the example in Figure 1 shows, this Gaussian approximation will not reproduce the actual histogram distribution at all, but it does not need to, for purposes of Q estimation.

Another way to view the variable decision threshold technique is to imagine replacing the real data eye with a fictitious eye having Gaussian statistics. The two eye diagrams have the same BER versus decision threshold voltage behaviour, so it is reasonable to assign them the same equivalent Q value, even though the details of the full eye diagram may be very different. ~~Of course, it does need to be kept in mind that~~ However, this analysis will not work for systems dominated by noise sources whose "tails" are not easily approximated to be Gaussian in shape; as, for example, would occur in a system dominated by cross-talk or modal noise. In taking these measurements, an inability to fit the data of Q-factor versus threshold to a straight line would provide a good indication of the presence of such noise sources.

Experimentally, it has been found that the Q values measured using the variable decision threshold method have a statistically valid level of correlation with the actual BER measurements.

5.2 Apparatus

An error performance analyser consisting of a pattern generator and a bit error ~~rate~~ ratio detector.

5.3 Sampling and specimens

The device under test (DUT) is a fibre optic digital system, consisting of an electro-optical transmitter at one end and an opto-electronic receiver at the other end. In between the transmitter and the receiver can be an optical network with links via optical fibres (for example, a DWDM network).

5.4 Procedure

Data for the Q measurement are collected at both the top "1" and bottom "0" regions of the eye as BER (over the range 10^{-5} to 10^{-10}) versus decision threshold. The equivalent mean (μ) and variance (σ) of the "1's" and "0's" are determined by fitting this data to a Gaussian characteristic.

The Q-factor is then calculated using Formula (1).

a) Connect the pattern generator and error detector to the system under test in accordance with Figure 5.

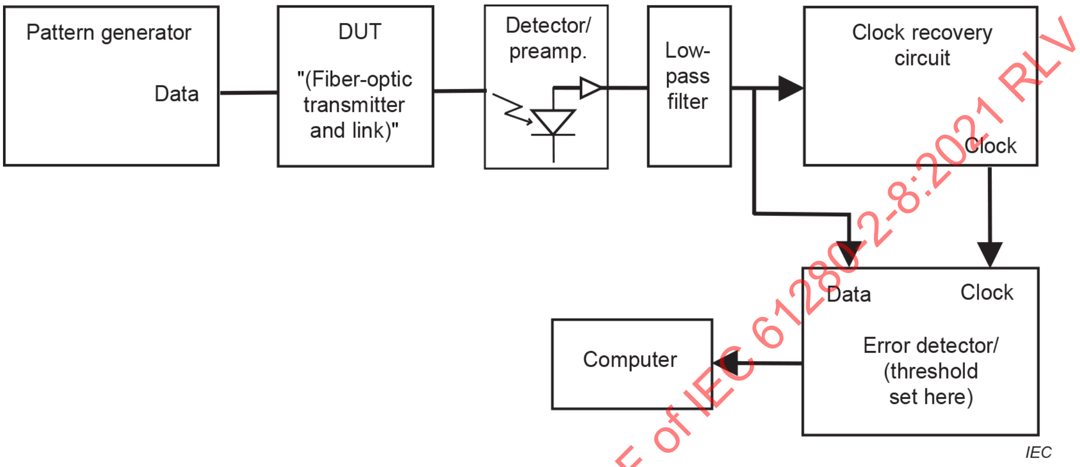


Figure 5 – Set-up for the variable decision threshold method

b) Set the clock source to the desired frequency.

c) Set up the pattern generator's pattern, data and clock amplitude, offset, polarity and termination as required.

d) Set up the error detector's pattern, data polarity and termination as required.

e) Set the decision threshold voltage and data input delay to achieve a sampling point that is approximately in the centre of the data eye as shown in Figure 6. This is the initial sampling point.

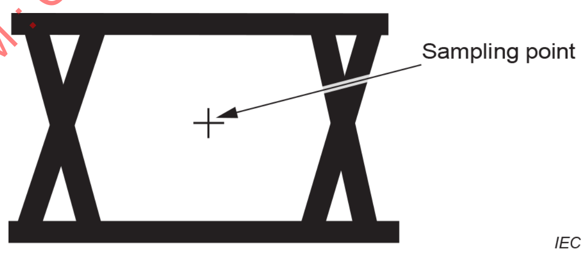


Figure 6 – Set-up of initial threshold level (approximately at the centre of the eye)

f) Enable the error detector's gating function and set it to gate by errors, for a minimum of 10, 100 or 1 000 errors.

g) Adjust the error detector's decision threshold voltage in a positive direction until the measured BER increases to a value greater than 1×10^{-10}. Note the decision threshold voltage (V_{b1}) and the BER.

h) Increase the decision threshold voltage until the BER rises above 10^{-5} and note the decision threshold voltage (V_{a1}) and the BER.

i) Note the difference between the two threshold values V_{a1} and V_{b1} and choose a step size (V_{step1}) that provides a reasonable number (greater than 5) of measurement points between these two decision threshold extremes. Starting from the threshold value V_{a1}, decrease the threshold value by the step size, V_{step1}. At each step, run a gating measurement on the error detector. Record the measured BER value and the corresponding decision threshold voltage.

j) The gating measurement from the error detector accumulates data and error information until the minimum number of errors – as specified in 5.5 f) – have been recorded. Selecting a larger minimum number of errors provides a statistically more accurate BER but at the expense of measurement time, particularly when measuring the low BER values. For a statistically significant result, the number of errors counted should not be less than 15.

k) Continue until the measured BER falls below 10^{-10}. This set of decision threshold voltage versus BER is the "1" data set.

l) Adjust decision threshold voltage back to the initial sampling point value and then continue in a negative direction until the BER increases again to greater than 10^{-10}. Note down the threshold value (V_{b0}) and the BER.

m) Decrease the decision threshold voltage until the BER rises above 10^{-5} and note the decision threshold voltage (V_{a0}) and the BER.

n) Note the difference between the two threshold values V_{a0} and V_{b0} and choose a step size (V_{step0}) that provides reasonable number (greater than 5) of measurement points between these two decision threshold extremes. Starting from the threshold value V_{a0}, increase the threshold value by the step size, V_{step0}. At each step, run a gating measurement on the error detector. Record the measured BER and the corresponding decision threshold voltage.

o) Continue until the measured BER falls below 1×10^{-10}. This set of decision threshold voltage versus BER is the "0" data set.

5.5 Calculations and interpretation of results

5.5.1 Sets of data

The procedure in 4.7 5.4 provides two sets (for the "0" and "1" rails) of data in the form:

$$\begin{bmatrix} D_1, BER_1 \\ D_2, BER_2 \\ . \\ . \\ D_n, BER_n \end{bmatrix}$$

where

D_i is the decision threshold voltage for "i"-th reading (for i =1, 2…,n);

BER$_i$ is the bit error rate for "i"-th reading (for i = 1, 2…,n);

n is the total number of data pairs.

$$\begin{bmatrix} D_1, P_{e\,1} \\ D_2, P_{e\,2} \\ . \\ . \\ D_n, P_{e\,n} \end{bmatrix}$$

where

D_i is the decision threshold voltage for "i"-th reading (for i = 1, 2…,n);

$P_{e\,i}$ is the bit error ratio for "i"-th reading (for i = 1, 2…,n);

n is the total number of data pairs.

~~NOTE~~ The total number of data pairs for the "0" and "1" rails need not be equal.

As an example, the voltage and BER values shown in Table 2 were obtained in a real-life experiment.

Table 2 – BER as a function of threshold voltage

~~"1" rail~~		~~"0" rail~~	
~~Threshold voltage V~~	~~BER~~	~~Threshold voltage V~~	~~BER~~
~~−1,75~~	~~5,18E-05~~	~~−4,37~~	~~8,76E-05~~
~~−1,80~~	~~2,09E-05~~	~~−4,34~~	~~1,90E-05~~
~~−1,85~~	~~7,33E-06~~	~~−4,31~~	~~5,18E-06~~
~~−1,90~~	~~2,77E-06~~	~~−4,28~~	~~1,06E-06~~
~~−1,95~~	~~9,61E-07~~	~~−4,25~~	~~2,12E-07~~
~~−2,00~~	~~1,96E-07~~	~~−4,22~~	~~3,45E-08~~
~~−2,05~~	~~6,30E-08~~	~~−4,19~~	~~3,52E-09~~
~~−2,10~~	~~1,95E-08~~	~~−4,16~~	~~2,77E-10~~
~~−2,15~~	~~3,45E-09~~		
~~−2,20~~	~~1,39E-09~~		

"1" rail		"0" rail	
Threshold voltage V	BER	Threshold voltage V	BER
−1,75	$5,18 \times 10^{-5}$	−4,37	$8,76 \times 10^{-5}$
−1,80	$2,09 \times 10^{-5}$	−4,34	$1,90 \times 10^{-5}$
−1,85	$7,33 \times 10^{-6}$	−4,31	$5,18 \times 10^{-6}$
−1,90	$2,77 \times 10^{-6}$	−4,28	$1,06 \times 10^{-6}$
−1,95	$9,61 \times 10^{-7}$	−4,25	$2,12 \times 10^{-7}$
−2,00	$1,96 \times 10^{-7}$	−4,22	$3,45 \times 10^{-8}$
−2,05	$6,30 \times 10^{-8}$	−4,19	$3,52 \times 10^{-9}$
−2,10	$1,95 \times 10^{-8}$	−4,16	$2,77 \times 10^{-10}$
−2,15	$3,45 \times 10^{-9}$		
−2,20	$1,39 \times 10^{-9}$		

5.5.2 Convert BER using inverse error function

Each BER value is then converted through an inverse error function, using the following approximation given in Formula (4).

$$f_i = \left[\log \left\{ \frac{1}{2} erfc(x_i) \right\} \right]_n^{-1} = 1,192 - 0,6681\{x_i\} - 0,0162\{x_i\}^2 \qquad (8)$$

~~where $x_i = \log_{10}(\mathrm{BER}_i)$.~~

$$f_i = \left[\log\left\{\frac{1}{2}\mathrm{erfc}(x_i)\right\}\right]^{-1} = 1{,}192 - 0{,}668\,1\{x_i\} - 0{,}016\,2\{x_i\}^2 \qquad (8)$$

where

x_i = $\log_{10}(P_{\mathrm{e}\,i})$.

This will produce two sets of data (for the "1" and "0") of the form:

$$\begin{bmatrix} D_1, f_1 \\ D_2, f_2 \\ . \\ . \\ D_n, f_n \end{bmatrix}$$

which should approximately fit a straight line.

Using the values given in Table 2, we get the sets of data shown in Table 4.

Table 3 – f_i as a function of D_i

"1" rail		"0" rail	
D_i V	f_i	D_i V	f_i
−1,75	3,757 8	−4,37	3,636 0
−1,80	3,963 8	−4,34	3,984 7
−1,85	4,195 6	−4,31	4,270 6
−1,90	4,404 3	−4,28	4,605 2
−1,95	4,625 7	−4,25	4,929 3
−2,00	4,944 9	−4,22	5,275 7
−2,05	5,162 9	−4,19	5,682 3
−2,10	5,379 9	− 4,16	6,097 5
−2,15	5,685 8		
−2,20	5,839 0		

5.5.3 Linear regression

Using the above data, a linear regression technique is used to fit, in turn, each set of data to a straight line with an equation of the form:

$$Y = A + BX$$

~~where~~

~~Y = $erf_e(BER)$ (inverse error function of BER),~~

~~X = D (decision threshold voltage)~~

$$Y = A + BX$$

where

$Y = \left[\frac{1}{2}\mathrm{erfc}(P_e)\right]^{-1}$ (*[F]$^{-1}$ inverse error function of F);

X = D (decision threshold voltage).

With n points of data per set, then, for both the top ("1") and bottom ("0") data sets, the following calculations should be performed [67]:

$$B = \frac{\sum XY - \frac{(\sum X)(\sum Y)}{n}}{\sum X^2 - \frac{(\sum X)^2}{n}} \qquad R^2 = \frac{\left(\sum XY - \frac{(\sum X)(\sum Y)}{n}\right)^2}{\left(\sum X^2 - \frac{(\sum X)^2}{n}\right)\left(\sum Y^2 - \frac{(\sum Y)^2}{n}\right)} \quad (9)$$

$$A = \frac{\sum Y}{n} - B\frac{\sum X}{n}$$

where

R^2 is the coefficient of determination (a measure of how well the data fits a straight line);

$\sum$ is the sum of values from 1 to n.

Using the values given in Table 3, we get the values shown in Table 4.

Table 4 – Values of linear regression constants

"1" rail			"0" rail		
A	***B***	***R***	***A***	***B***	***R***
−4,612 5	−4,763 8	0,998 9	53,989	11,530 7	0,998 4

5.5.4 Standard deviation and mean

$\sigma = \left|-\frac{1}{B}\right|$ (standard deviation of "1" or "0" noise region),

$\mu = \frac{-A}{B}$ (mean of "1" or "0" noise region).

Calculate μ_1, σ_1 from the "1" set of data and μ_0, σ_0 from the "0" set of data.

Using the example in Table 4, we get the values shown in Table 5.

Table 5 – Mean and standard deviation

"1" rail		"0" rail	
μ_1	σ_1	μ_0	σ_0
−0,968 2	0,209 9	−4,682 2	0,086 724 9

5.5.5 Optimum decision threshold

$$Q_{opt} = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \quad (10)$$

And thus, the optimum decision threshold is equal to

$$\frac{\sigma_0\mu_1 + \sigma_1\mu_0}{\sigma_1 + \sigma_0} \quad (11)$$

For the example given in Table 5, using the value derived for Q_{opt} of 12,52, the optimal decision threshold is −3,596 V.

5.5.6 BER optimum decision threshold

Also, the predicted residual BER at the optimum decision threshold is given by

$$P_e = \frac{e^{-\left(\frac{Q^2}{2}\right)}}{Q_{opt}\sqrt{2\pi}} \quad (12)$$

Assuming the value of 12,52 for Q_{opt} in our example data, the residual BER is calculated to be less than 1×10^{-18}.

5.5.7 BER non-optimum decision threshold

The BER value at decision threshold voltages other than the optimum can be calculated from the following formula:

$$P_e(D) = \frac{1}{2}\left\{\frac{e^{-\frac{\left(\frac{|\mu_1 - D|}{\sigma_1}\right)^2}{2}}}{\left(\frac{|\mu_1 - D|}{\sigma_1}\right)\sqrt{2\pi}} + \frac{e^{-\frac{\left(\frac{|\mu_0 - D|}{\sigma_0}\right)^2}{2}}}{\left(\frac{|\mu_0 - D|}{\sigma_0}\right)\sqrt{2\pi}}\right\} \quad (13)$$

5.5.8 Error bound

~~Using the formula in Annex A (equation A.5), one can derive the error bound on the derived value of Q-optimum.~~

An error bound for the value of Q is derived in Annex A. Using Formula (A.5), one can calculate the error bound for the value of Q_{opt}.

For the example shown, the absolute error bound on Q is ±0,5.

5.6 Test documentation

Report the following information for each test:

a) test date;
b) this document number and its year of publication;
c) specimen/sample (that is, optical transmission system being tested) identification;
d) two sets of data: one above the optimal threshold and the other below;
e) ~~Each data set should contain~~ at least 5 readings of threshold versus BER for each data set (for BER values varying from 10^{-5} to 10^{-10});
f) ~~Report~~ optimal Q as well as the optimal decision threshold;
g) ~~Report~~ possible error range in the value of Q.

5.7 Specification information

The following details shall be specified:

a) IEC document number;
b) any special test requirements;
c) failure or acceptance criteria.

6 Variable optical threshold method

6.1 Overview

This method consists of the optical addition of an interfering pre-set bias light to the received optical signal in order to increase the measured BER. Measurements taken at several values of bias light are extrapolated to zero bias, to evaluate the BER value for normal operation. This method is applicable to DC-coupled receivers only. The effect of adding a pre-set bias is shown in Figure 7.

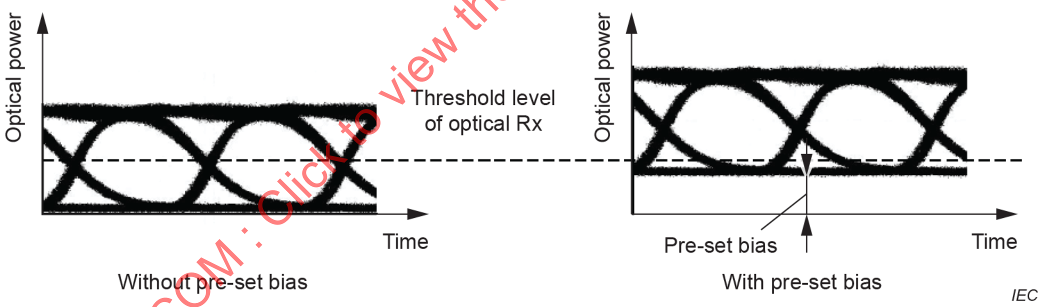


Figure 7 – Effect of optical bias

The method can be used to evaluate the error performance of an optical link or active device as shown in Figure ~~1~~ 8. Alternatively, the error performance of a complete system can be evaluated using the set-up shown in Figure ~~2~~ 9. The advantage of this method is that no internal access to equipment is required and that any internal error monitoring facility of the system under test can be utilized. If this is not available, conventional error-measuring equipment can be connected to the data input and output terminations of the system.

6.2 Apparatus

Common to all methods is the conventional error measurement equipment: a pattern generator and an error detector.

a) Conventional error measuring test equipment consisting of a pattern generator and separate error detector suitable for remote use. This is not required for system evaluation with self-contained error-monitoring facility.
b) A pre-set light source, stable to 0,1 dB over 1 h, of a wavelength similar to the system under test.

c) An optical attenuator stable to 0,1 dB over 1 h. An additional attenuator with equivalent stability may be required in the case of high signal levels at the receiver, for example, when testing a transmitter receiver pair.

d) An optical splitter/combiner with split ratios typically between 50:50 and 10:90, and with fibre compatible with that of the system and the pre-set bias light source.

6.3 Items under test

The item under test may be a digital fibre optic system consisting of a digital transmitter and a DC-coupled digital receiver which are connected via an optical link consisting of fibre or cable and may also include passive or active components. If a transmitter/receiver pair alone is to be tested, they should be connected via a fixed or variable optical attenuator.

The item under test may also be a self-contained transmission system comprising transmit and receive terminals connected via an optical link which itself may contain active devices such as regenerators and/or optical amplifiers. Such system may include internal error monitoring facilities.

6.4 Procedure for basic optical link

Refer to Figure 8.

a) Operate the transmitter and receiver, adjusting the received signal with the optical attenuator. It may be necessary to monitor the input power of the optical signal at the receiver.

b) Adjust the pre-set bias light until a predetermined high value of BER, such as 10^{-4}, is reached.

c) Decrease the bias a step at a time, and at each step record the BER measured by the error detector. Measure at least 5 data pairs, with the BER values to 2 significant figures.

d) Repeat ~~3~~ c).

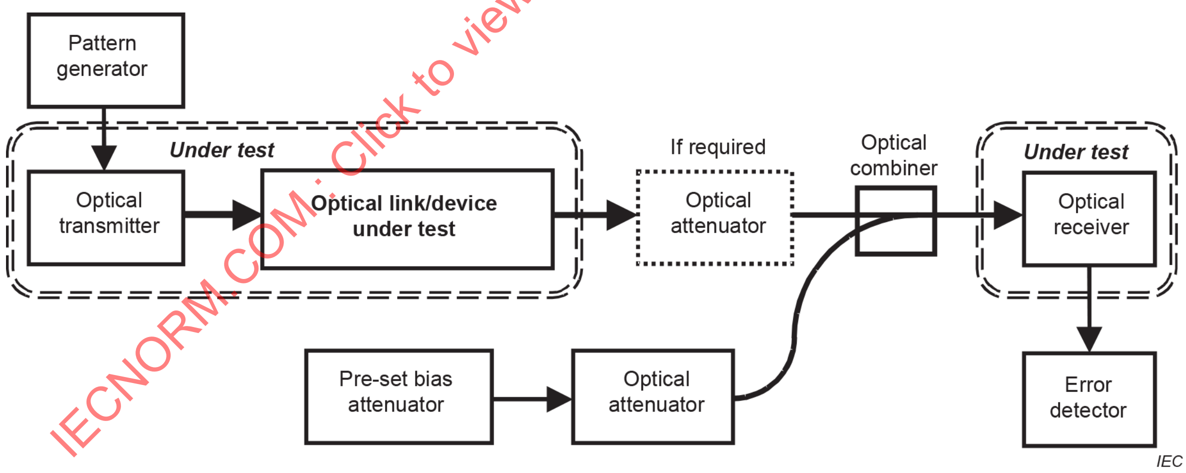


Figure 8 – Set-up for optical link or device test

6.5 Procedure for self-contained system

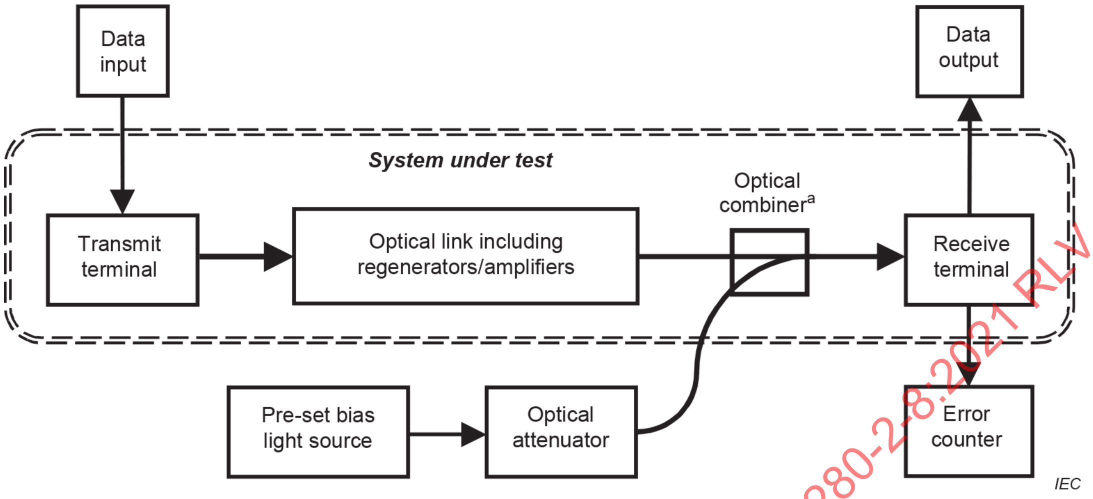
Refer to Figure 9.

a) Set up the system for normal operation. If no optical combiner is incorporated, insert such a device at the input terminal of the receiver. If the system does not contain error monitoring facilities, connect a pattern generator to a data input of the transmit terminal and the corresponding error detector to the appropriate data output terminal.

b) Adjust the pre-set bias light until a predetermined high value of BER, such as 10^{-4}, is reached.

c) Decrease the bias a step at a time, and at each step record the BER measured by the error detector. Measure at least 5 data pairs, with the BER values to 2 significant figures.

d) Repeat ~~3~~ c).



[a] To be inserted if system is not equipped with an optical combiner.

Figure 9 – Set-up for system test

6.6 Evaluation of results

The injection of an optical bias signal is, in essence, similar to a variation in the detection threshold. Thus, the mathematical model for the evaluation of the results is substantially the same as that used for the variable threshold method. To a first-order approximation, therefore, the relationship between the amplitude of the optical bias signal and the resulting value of BER can be represented by the equation:

$$Y = A + BX \quad (14)$$

where

Y = $\log_{10}(P_e)$ and is the log BER;

X is the bias amplitude.

An example of a set of results is given in Table 6.

Table 6 – Example of optical bias test

Bias µW	BER	Log BER
6,00	$1,0 \times 10^{-4}$	−4,00
5,75	$2,7 \times 10^{-5}$	−4,57
5,50	$7,0 \times 10^{-6}$	−5,15
5,25	$1,4 \times 10^{-6}$	−5,85
5,00	$3,0 \times 10^{-7}$	−6,52
4,75	$5,0 \times 10^{-8}$	−7,30
4,50	$1,0 \times 10^{-8}$	−8,00

In order to achieve a precision to two significant digits for the BER values, it is necessary to accumulate sufficient errors, approximately 100, to achieve consistency. The time taken to measure errors ~~must~~ shall, however, not compromise the stability of the amplitude of the optical bias, since small variations in this amplitude can have a large effect on the subsequent extrapolation procedure.

Using the results given in Table 6 and applying the linear regression techniques described in ~~2.5.3~~ 5.5.3, the basic value of BER can be determined by extrapolation as shown in Figure ~~9~~ 10.

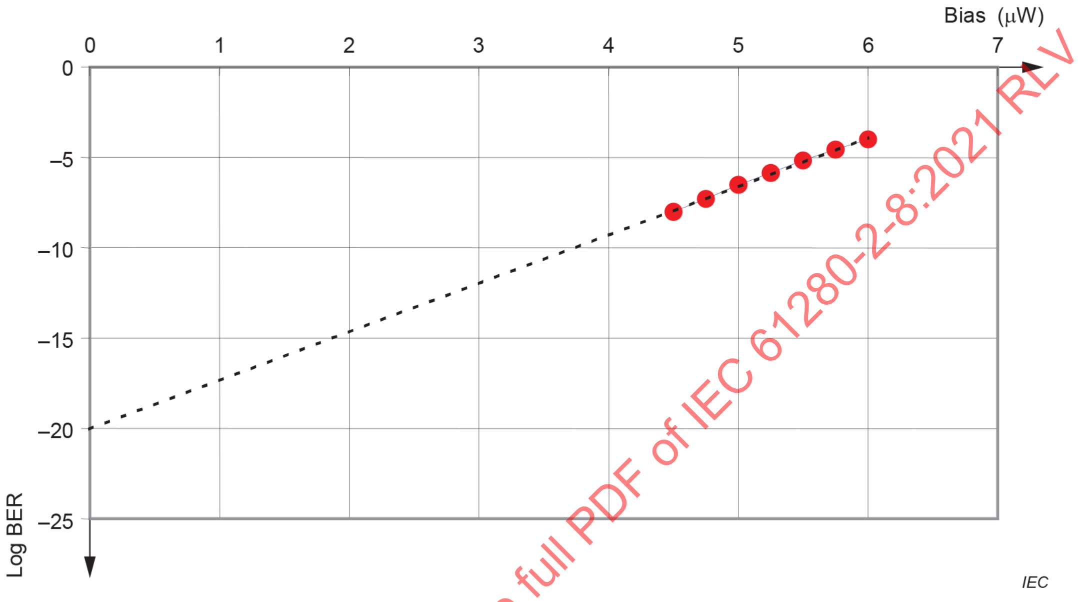


Figure 10 – Extrapolation of log BER as a function of bias

For the results given in Table 6, the BER value, as shown by the extrapolation in Figure ~~9~~ 10, is predicted to be 10^{-20}.

Annex A
(normative)

Calculation of error bound in the value of Q

Let us assume that the linear regression fit (of form $Y = A + BX$) gives rise to two straight line fits for the "0" and "1" rails as follows:

$$\begin{aligned} Y_0 &= A_0 + B_0 X \quad \text{(for the "0" rail)} \\ Y_1 &= A_1 + B_1 X \quad \text{(for the "1" rail)} \end{aligned} \tag{A.1}$$

As shown in Figure 4, the two lines intersect at the point X_{optimal}, the optimal decision threshold. At this value of X, both Y_0 and Y_1 are equal, that is

$$\begin{aligned} A_0 + B_0 X_{\text{optimal}} &= A_1 + B_1 X_{\text{optimal}} \quad \text{or} \\ X_{\text{optimal}} &= \frac{A_1 - A_0}{B_0 - B_1} \end{aligned} \tag{A.2}$$

The value of Y at the optimal threshold is Q, that is

$$\begin{aligned} Q &= A_1 + B_1 X_{\text{optimal}} \\ &= \frac{A_1 B_0 - A_0 B_1}{B_0 - B_1} \end{aligned} \tag{A.3}$$

The derivatives of Q with respect to each of the variables A_0, A_1, B_0 and B_1 are

$$\begin{aligned} \frac{\partial Q}{\partial A_0} &= \alpha, \quad \frac{\partial Q}{\partial A_1} = \beta \\ \frac{\partial Q}{\partial B_0} &= -\alpha\gamma, \quad \frac{\partial Q}{\partial B_1} = -\beta\gamma \end{aligned} \tag{A.4}$$

where $\alpha = -\frac{B_1}{B_0 - B_1}$, $\beta = \frac{B_0}{B_0 - B_1}$ and $\gamma = \frac{A_0 - A_1}{B_0 - B_1}$

The maximum error in Q, given by ΔQ_{max}, can be bounded by

$$\begin{aligned} \Delta Q_{\text{max}}^2 &= \left(\frac{\partial Q}{\partial A_0}\right)^2 \sigma_{A_0}^2 + \left(\frac{\partial Q}{\partial A_1}\right)^2 \sigma_{A_1}^2 + \left(\frac{\partial Q}{\partial B_0}\right)^2 \sigma_{B_0}^2 + \left(\frac{\partial Q}{\partial B_1}\right)^2 \sigma_{B_1}^2 \\ &= \alpha^2 \left(\gamma^2 \sigma_{B_0}^2 + \sigma_{A_0}^2\right) + \beta^2 \left(\gamma^2 \sigma_{B_1}^2 + \sigma_{A_1}^2\right) \end{aligned} \tag{A.5}$$

where

$\sigma_{A_0}^2$ and $\sigma_{A_1}^2$ are the uncertainties in the Y-intercepts for the "0" and "1" rails, respectively;

$\sigma_{B_0}^2$ and $\sigma_{B_1}^2$ are the uncertainties in the slopes of the "0" and "1" rails.

It is assumed that the factors A_0, A_1, B_0 and B_1 are uncorrelated. Formula (A.5) gives the absolute maximum spread in the value of Q.

These variances are given in [~~7~~8] to be:

$$\sigma_A^2 \cong \frac{S^2 \sum X^2}{\Delta} \quad \text{and} \quad \sigma_B^2 \cong \frac{N \cdot S^2}{\Delta} \tag{A.6}$$

where

N is the number of data points.

$$\Delta = N \sum X^2 - \left(\sum X\right)^2 \text{ and}$$

$$S^2 = \frac{1}{N-2} \sum (Y - A - BX)^2$$

Annex B
(informative)

Sinusoidal interference method

B.1 ~~Introduction~~ Overview

This method, optically or electrically, adds an interfering sinusoidal signal to the digital signal at a point before the receiver decision circuit in order to increase the measured BER. The measurements, taken at several values of reducing sinusoidal amplitude, are extrapolated to zero amplitude, thereby giving the system BER.

The sinusoidal signal can be injected into the receiver optically, by adding it to the optical data input. This method is usually the only procedure available for testing at the system or link level since access to the decision circuit is normally not available in operational equipment. To add the sinusoidal signal electrically requires electrical access to the decision circuitry of the receiver which would be more suitable for testing at the component or subsystem level.

Both methods should yield similar results since they rely on an extrapolation to the point where the impairment has been removed.

The optical method requires an AC-coupled receiver, while the electrical method is applicable to an AC- or DC-coupled receiver.

B.2 Apparatus

Common to all methods is the conventional error measurement equipment: a pattern generator and an error detector.

a) A sinewave generator capable of producing a frequency within the passband of the system under test, and of generating stable output levels between 1 mV and 1 V, with at least 3 digits' amplitude resolution. A typical frequency synthesizer meets these requirements.
b) An analogue laser transmitter, with adjustable CW output power, stable to 0,1 dB over 1 h, of a wavelength similar to the system under test and capable of being modulated at a frequency well within the passband of the receiver under test. This serves as an "interfering laser".
c) An optical splitter/combiner with split ratios typically between 50:50 and 10:90, and with fibre compatible with that of the system and the interfering laser.
d) An analogue optical receiver capable of detecting frequencies within the passband of the system under test, used to confirm proper operation of the interfering laser.

B.3 Sampling and specimens

The specimen is a fibre optic digital system consisting of a digital transmitter and a digital receiver. In between them is either a fibre link consisting of fibre or cable and possibly passive or active components (if an operational link is to be tested) or a variable optical attenuator (if the transmitter/receiver pair alone is to be tested).

B.4 Procedure

B.4.1 Optical sinusoidal interference method

Refer to Figure B.1.

a) Place the combiner with one input port connected to either the fibre link or attenuator. Connect the output port to the receiver and the other input port to the interfering laser, which is modulated by the sinewave generator. Connect the receiver to the error detector.

b) Adjust the transmitter and receiver to the desired operating conditions. Adjust the data pattern and, if the attenuator is used, the received power. The receiver input power level ~~is to~~ shall be held constant for the duration of the measurement procedure.

c) Choose the frequency of the sinewave generator to be well within the passband of the receiver and not harmonically related to the bit-rate. It should be significantly different (such as 1 Mbit/s) from the bit-rate so that no slow beat phenomena are possible.

d) Turn on the interfering laser and adjust its output level so that its power as seen at the output of the combiner is similar to the power seen there due to the laser transmitter of the data link under test. Apply modulation to the interfering laser and adjust the modulation depth until a BER value of approximately 10^{-4} is reached. (It is assumed that the BER is immeasurably low before the interfering signal is added.) Ensure that the interfering laser output is not distorted by monitoring it with the analogue optical receiver. It may be necessary to choose a combiner with a different coupling ratio or to adjust the signal level of the interfering laser in order to achieve the above.

e) Decrease the modulation depth of the interfering laser a step at a time by adjusting the output level of the sinewave generator, and at each step record the BER value measured by the error detector.

f) Measure at least 5 data pairs, with the BER values measured to 2 significant figures.

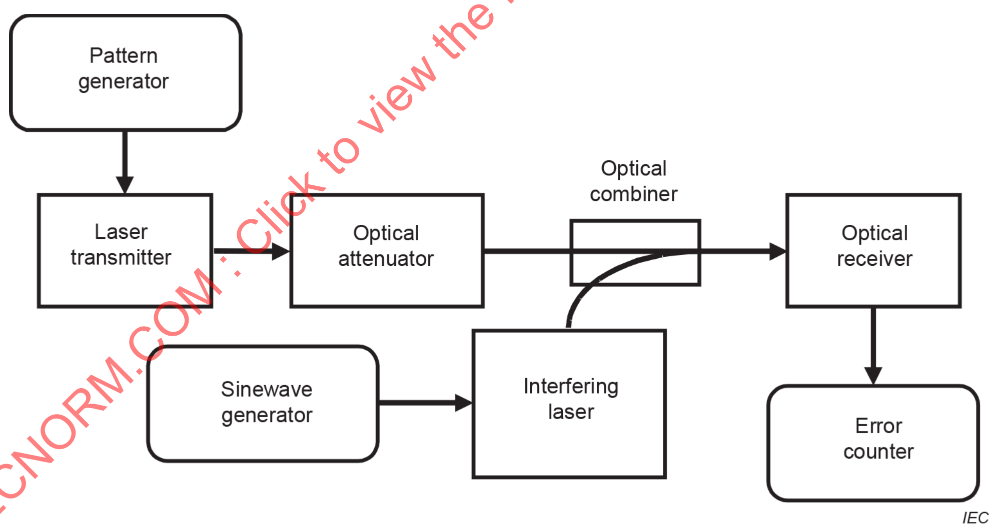


Figure B.1 – Set-up for the sinusoidal interference method by optical injection

Table B.1 is an example.

Table B.1 – Results for sinusoidal injection

Sinewave amplitude A (mV)	BER
100	$5,0 \times 10^{-5}$
95	$1,1 \times 10^{-5}$
90	$6,3 \times 10^{-6}$
85	$9,8 \times 10^{-7}$
80	$2,3 \times 10^{-7}$
75	$4,6 \times 10^{-8}$

In order to achieve a precision to two significant digits for the BER values, it is necessary to accumulate sufficient errors, approximately 100, to achieve consistency. The time taken to measure errors ~~must~~ shall, however, not compromise the stability of the amplitude of the interference signal, since small variations in the amplitude of the interfering signal can have a large effect on the subsequent extrapolation procedure.

B.4.2 Electrical sinusoidal interference method

Refer to Figure B.2.

a) AC-couple the sinewave generator to the decision threshold input of the comparator in the receiver under test. If the comparator has differential data inputs, a large series resistor can be used to isolate the comparator data signal from the sinewave generator. If isolation is difficult to achieve, use the threshold modification method of Clause ~~2~~ 5.

b) Adjust the transmitter and receiver to the desired operating conditions. Adjust the data pattern and, if the attenuator is used, the received power to be constant for the duration of the measurement procedure.

c) Choose the frequency of the sinewave generator to be well within the passband of the receiver and not harmonically related to the bit-rate. It should be significantly different (such as 1 Mbit/s) from the bit-rate so that no slow-beat phenomena are possible. The frequency should also be well above the range of any AGC or threshold-tracking loop in the receiver.

d) Adjust the amplitude of the sinewave generator until a BER value of approximately 10^{-4} is reached.

e) Decrease the amplitude of the interference one step at a time, by decreasing the output of the sinewave generator. At each step, record the BER using the error detector. The resulting data should be similar to those given in ~~3.4.1~~ 5.4.

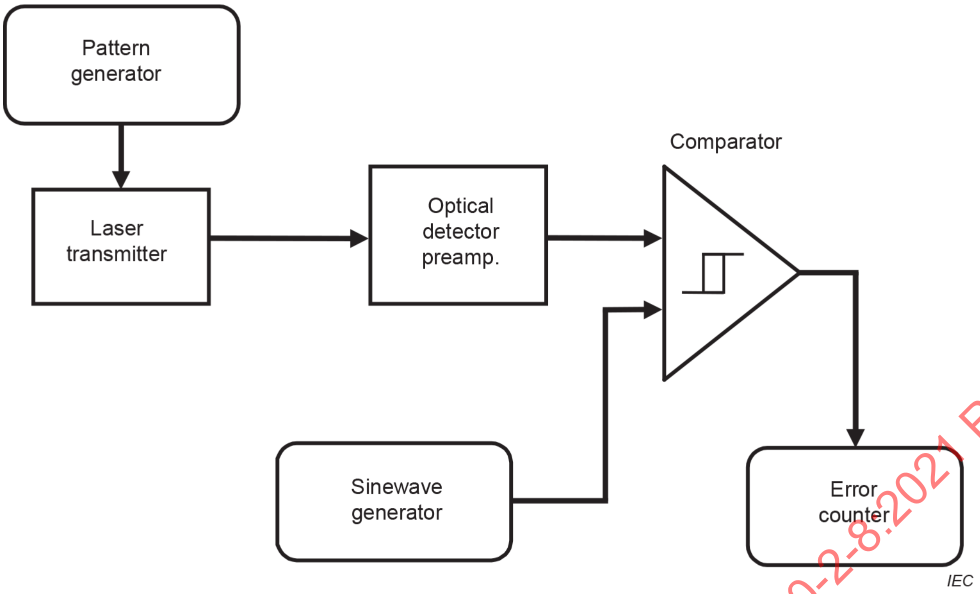


Figure B.2 – Set-up for the sinusoidal interference method by electrical injection

B.5 Calculations and interpretation of results

B.5.1 Mathematical analysis

These calculations apply for both the optical and electrical options of B.4.1 and B.4.2. Denote the data pairs as given in Table B.1 as (A_i, ~~BER$_i$~~ $P_{e\ i}$). Transform the BER values using the function:

$$\psi\left(P_{e\ i}\right)=\frac{-c_2+\sqrt{c_2^2-4c_1\left(c_3+x_i\right)}}{2c_1} \quad \text{(B.1)}$$

where

x_i = ln(2 $P_{e\ i}$);

c_1 = 0,492 6;

c_2 = 0,294 8;

c_3 = 0,792 1.

B.5.2 Extrapolation

Fit a straight line to the values $\psi(P_{e\ i})$ versus A_i. Extrapolate it to the ordinate where A_0 = 0, as shown in the example of Figure B.3, which yields the value $\psi(P_{e0}) = Q$. The curve is not a very good fit for BER values greater than 10^{-4} because of the ~~erfc~~ approximation used for the complementary error function (erfc) in the equation. Therefore, data with BER values higher than 10^{-4} should not be used.

Calculate the system BER as

$$P_e=\frac{1}{2}\,\text{erfc}\left(\frac{Q}{\sqrt{2}}\right)\cong\frac{1}{Q}\,e^{-Q^2/2}\cdot\frac{1-Q^{-2}+3Q^{-4}}{\sqrt{2\pi}} \quad \text{(B.2)}$$

This is the estimated value of BER at which the system under test is operating. The above approximation to erfc(.) is sufficiently accurate for all error ~~rates~~ ratios of interest.

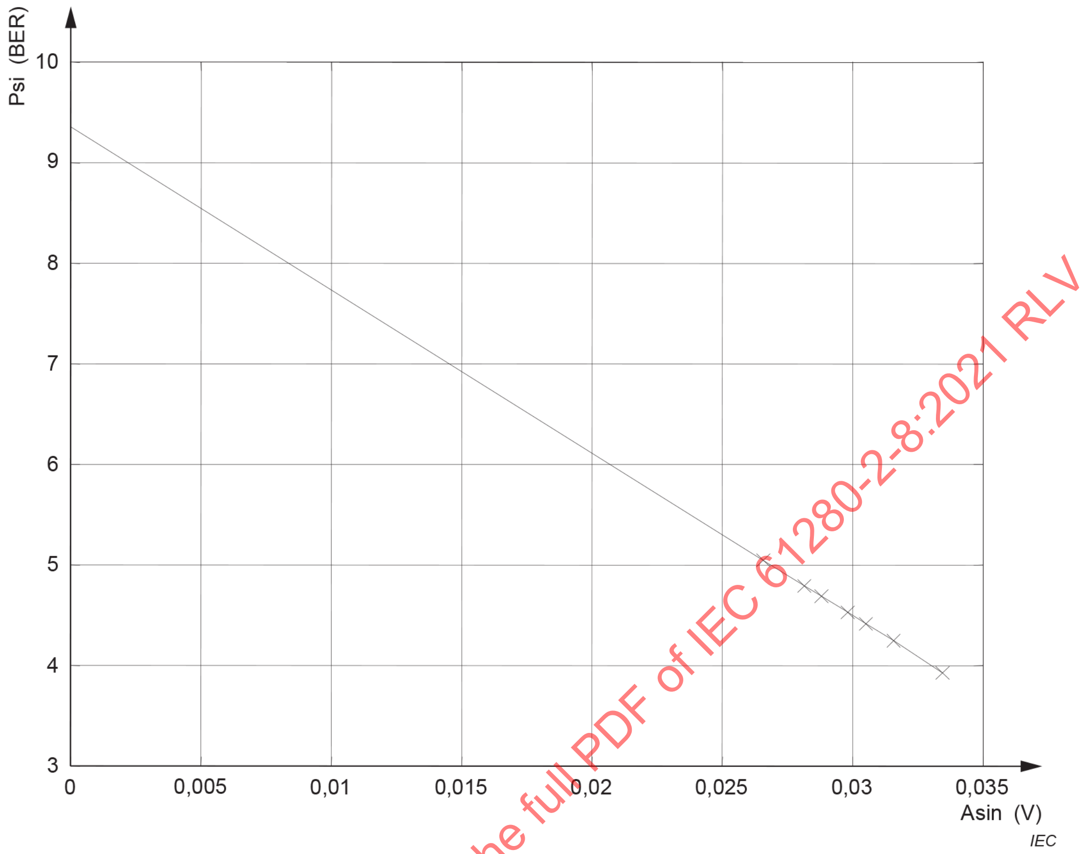


Figure B.3 – BER result from the sinusoidal interference method (data points and extrapolated line)

B.5.3 Expected results

Figure B.4 is an example of the results to be expected using the above extrapolation techniques. The BER of a 50 Mbit/s, single-mode data link was measured by 3 techniques:

- conventional BER measurement down to 10^{-10};
- extrapolation using the optical interference method of B.4.1;
- extrapolation using the electrical interference method of B.4.2.

The solid line is an error function fit to the measured data using best estimates for the noise of the receiver, which is independent of received power and the noise from the transmitter, which is proportional to received power.

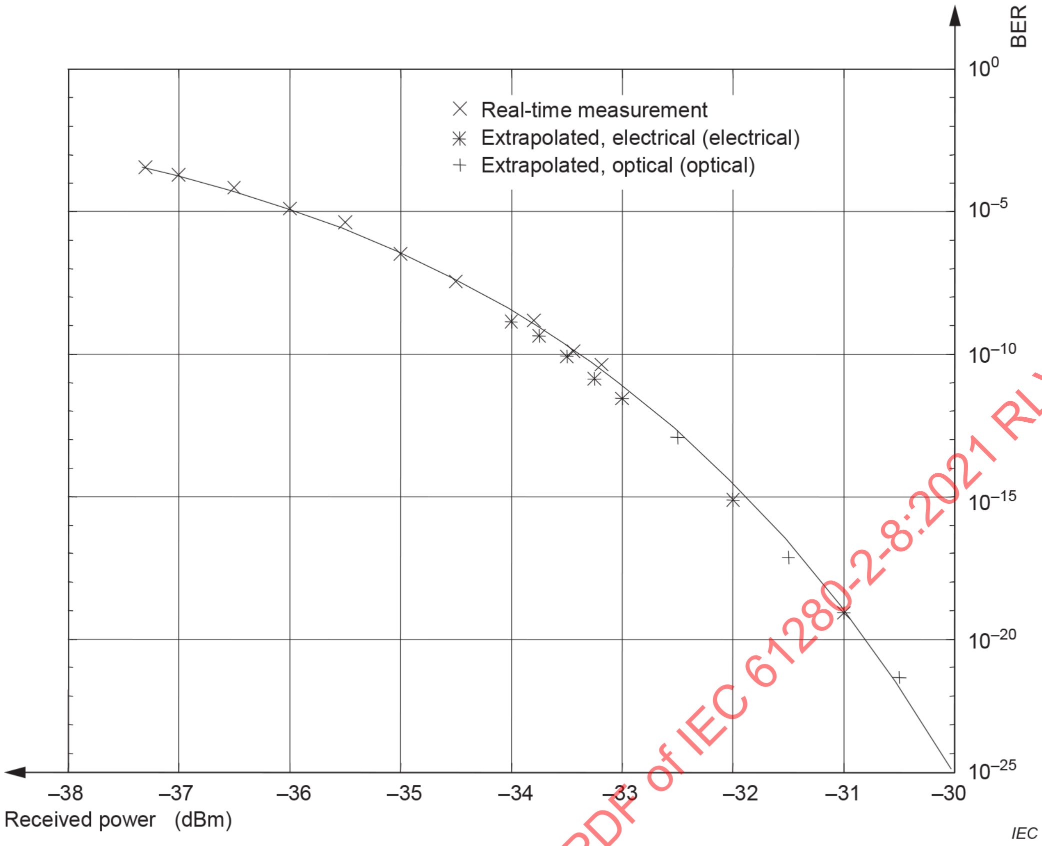


Figure B.4 – BER versus optical power for three methods

B.6 Documentation

The following information shall be reported with each test:

a) date of test;
b) this document number and its year of the publication;
c) specimen identification;
d) type of transmitter;
e) type of receiver.

B.7 Specification information

The following details shall be specified:

a) IEC number;
b) any special test requirements;
c) failure or acceptance criteria.

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IEC 61280-2-8

Edition 2.0 2021-03

INTERNATIONAL STANDARD

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

Procédures d'essai des sous-systèmes de télécommunications fibroniques – Partie 2-8: Systèmes numériques – Détermination de faibles valeurs de BER en utilisant des mesures du facteur Q

IEC 61280-2-8:2021-03(en-fr)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES –

Part 2-8: Digital systems –
Determination of low BER using Q-factor measurements

FOREWORD

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IEC 61280-2-8 has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics. It is an International Standard.

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

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

a) correction of errors in Formula (8) in 5.5.2 and in a related formula in 5.5.3;
b) correction of errors in the references to clauses, subclauses, figures, procedures, and in the Bibliography;
c) alignment of the terms and definitions in 3.1 with those in IEC 61281-1.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
86C/1708/FDIS	86C/1711/RVD

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES –

Part 2-8: Digital systems – Determination of low BER using Q-factor measurements

1 Scope

This part of IEC 61280 specifies two main methods for the determination of low BER values by making accelerated measurements. These include the variable decision threshold method (Clause 5) and the variable optical threshold method (Clause 6). In addition, a third method, the sinusoidal interference method, is described in Annex B.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
amplified spontaneous emission
ASE
optical power associated to spontaneously emitted photon amplified by an active medium in an optical amplifier

3.1.2
bit error ratio
BER
P_e
number of errored bits divided by the total number of bits, over some stipulated period of time

3.1.3
intersymbol interference
ISI
overlap of adjacent pulses as caused by the limited bandwidth characteristics of the optical devices in a fibre optic link

3.1.4
Q-factor
Q
ratio of the difference between the mean voltage of the 1 and 0 rails, to the sum of their standard deviation values

3.2 Abbreviated terms

AC	alternating current
CW	continuous wave (normally referring to a sinusoidal wave form)
DC	direct current
DSO	digital sampling oscilloscope
DUT	device under test
PRBS	pseudo-random binary sequence
SNR	signal-to-noise ratio

4 Measurement of low bit-error ratios

4.1 General considerations

Fibre optic communication systems and subsystems are inherently capable of providing exceptionally good error performance, even at very high bit rates. The mean bit error ratio (BER) may typically lie in the region 10^{-12} to 10^{-20}, depending on the nature of the system. While this type of performance is well in excess of practical performance requirements for digital signals, it gives the advantage of concatenating many links over long distances without the need to employ error correction techniques.

The measurement of such low error ratios presents special problems in terms of the time taken to measure a sufficiently large number of errors to obtain a statistically significant result. Table 1 presents the mean time required to accumulate 15 errors. This number of errors can be regarded as statistically significant, offering a confidence level of 75 % with a variability of 50 %.

Table 1 – Mean time for the accumulation of 15 errors as a function of BER and bit rate

Bit rate	Mean times for the accumulation of 15 errors										
	BER										
	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}
1,0 Mbit/s	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7d	17 d	170 d	4,7 years	47 years
2,0 Mbit/s	75 ms	750 ms	7,5 s	75 s	750 s	2,1 h	21 h	8,8 d	88 d	2,4 years	24 years
10 Mbit/s	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 d	17 d	170 d	4,7 years
50 Mbit/s	3,0 ms	30 ms	300 ms	3,0 s	30 s	5,0 min	50 min	8,3 h	3,5 d	35 d	350 d
100 Mbit/s	1,5 ms	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 d	17 d	170 d
500 Mbit/s	300 µs	3 ms	30 ms	300 ms	3,0 s	30 s	5,0 min	50 min	8,3 h	3,5 d	35 d
1,0 Gbit/s	150 µs	1,5 ms	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 d	17 d
10 Gbit/s	15 µs	150 µs	1,5 ms	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 d
40 Gbit/s	3,8 µs	38 µs	380 µs	3,8 ms	38 ms	380 ms	3,8 s	38 s	6,3 min	63 min	10,4 h
100 Gbit/s	1,5 µs	15 µs	150 µs	1,5 ms	15ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h

The times given in Table 1 show that the direct measurement of the low BER values expected from fibre optic systems is not practical during installation and maintenance operations. One way of overcoming this difficulty is to artificially impair the signal-to-noise ratio at the receiver in a controlled manner, thus significantly increasing the BER and reducing the measurement time. The error performance is measured for various levels of impairment, and the results are then extrapolated to a level of zero impairment using computational or graphical methods according to theoretical or empirical regression algorithms.

The difficulty presented by the use of any regression technique for the determination of the error performance is that the theoretical BER value is related to the level of impairment via the inverse complementary error function (erfc). This means that very small changes in the impairment lead to very large changes in BER; for example, in the region of a BER value of 10^{-15}, a change of approximately 1 dB in the level of impairment results in a change of three orders of magnitude in the BER. A further difficulty is that a method based on extrapolation is unlikely to reveal a levelling off of the BER at only about 3 orders of magnitude below the lowest measured value.

It should also be noted that, in the case of digitally regenerated sections, the results obtained apply only to the regenerated section whose receiver is under test. Errors generated in upstream regenerated sections may generate an error plateau which may have to be taken into account in the error performance evaluation of the regenerator section under test.

As noted above, two main methods for the determination of low BER values by making accelerated measurements are described. These are the variable decision threshold method (Clause 5) and the variable optical threshold method (Clause 6). In addition, a third method, the sinusoidal interference method, is described in Annex B.

It should be noted that these methods are applicable to the determination of the error performance in respect of amplitude-based impairments. Jitter may also affect the error performance of a system, and its effect requires other methods of determination. If the error performance is dominated by jitter impairments, the amplitude-based methods described in this document will lead to BER values which are lower than the actual value.

The variable decision threshold method is the procedure which can most accurately measure the Q-factor and the BER for optical systems with unknown or unpredictable noise statistics. A key limitation, however, to the use of the variable threshold method to measure Q-factor and BER is the need to have access to the receiver electronics in order to manipulate the decision threshold. For systems where such access is not available, it may be useful to utilize the alternative variable optical threshold method. Both methods are capable of being automated in respect of measurement and computation of the results

4.2 Background to Q-factor

The Q-factor is the signal-to-noise ratio (SNR) at the decision circuit and is typically expressed as [1][1]:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \quad (1)$$

where

μ_1 and μ_0 are the mean voltage levels of the "1" and "0" rails, respectively;

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

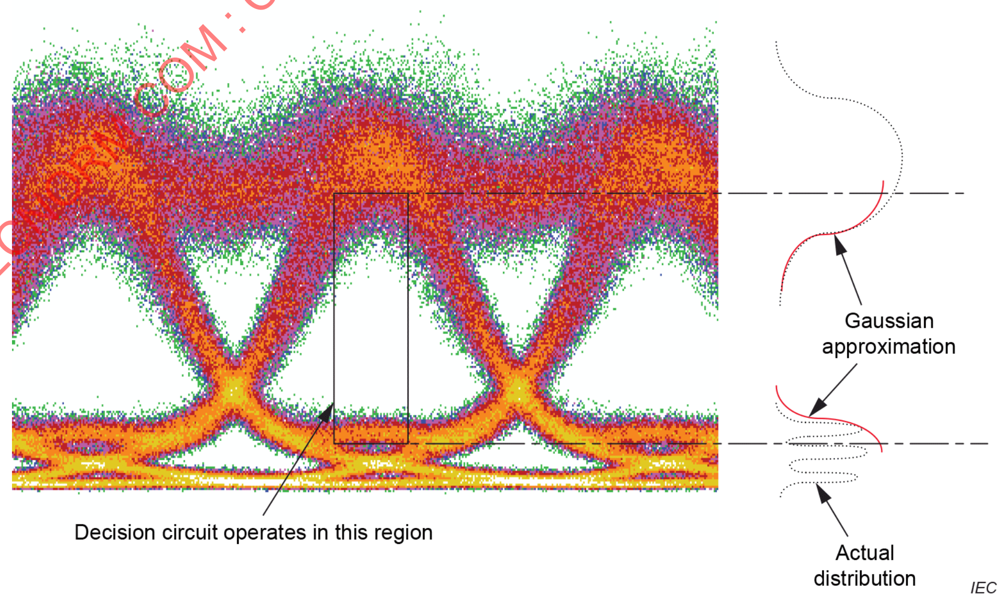
σ_1 and σ_0 are the standard deviation values of the noise distribution on the "1" and "0" rails, respectively.

An accurate estimation of a system's transmission performance, or Q-factor, shall take into consideration the effects of all sources of performance degradation, both fundamental and those due to real-world imperfections. Two important sources are amplified spontaneous emission (ASE) noise and intersymbol interference (ISI). Additive noise originates primarily from ASE of optical amplifiers. ISI arises from many effects, such as chromatic dispersion, fibre non-linearities, multi-path interference, polarization-mode dispersion and use of electronics with finite bandwidth. There may be other effects as well; for example, a poor impedance match can cause impairments such as long fall times or ringing on a waveform.

One possible method to measure Q-factor is the voltage histogram method in which a digital sampling oscilloscope is used to measure voltage histograms at the centre of a binary eye to estimate the waveform's Q-factor [2]. In this method, a pattern generator is used as a stimulus and the oscilloscope is used to measure the received eye opening and the standard deviation of the noise present in both voltage rails. As a rough approximation, the edge of visibility of the noise represents the 3σ points of an assumed Gaussian distribution. The advantage of using an oscilloscope to measure the eye is that it can be done rapidly on real traffic with a minimum of equipment.

The oscilloscope method for measuring the Q-factor has several shortcomings. When used to measure the eye of high-speed data (of the order of several Gbit/s), the oscilloscope's limited digital sampling rate (often in the order of a few hundred kilohertz) allows only a small minority of the high-speed data stream to be used in the Q-factor measurement. Longer observation times could reduce the impact of the slow sampling. A more fundamental shortcoming is that the Q estimates derived from the voltage histograms at the eye centre are often inaccurate. Various patterning effects and added noise from the front-end electronics of the oscilloscope can often obscure the real variance of the noise.

Figure 1 shows a sample eye diagram made on an operating system. It can be seen in this figure that the vertical histograms through the centre of the eye show patterning effects (less obvious is the noise added by the front-end electronics of the oscilloscope). It is difficult to predict the relationship between the Q measured this way and the actual BER measured with a test set.



NOTE The data for measuring the Q-factor are obtained from the tail of the Gaussian distributions.

Figure 1 – Sample eye diagram showing patterning effects

Figure 2 shows another possible way of measuring Q-factor using an oscilloscope. The idea is to use the centre of the eye to estimate the eye opening and use the area between eye centres to estimate the noise. Pattern effect contributions to the width of the histogram would then be reduced. A drawback to this method is that it relies on measurements made on a portion of the eye that the receiver does not really ever use.

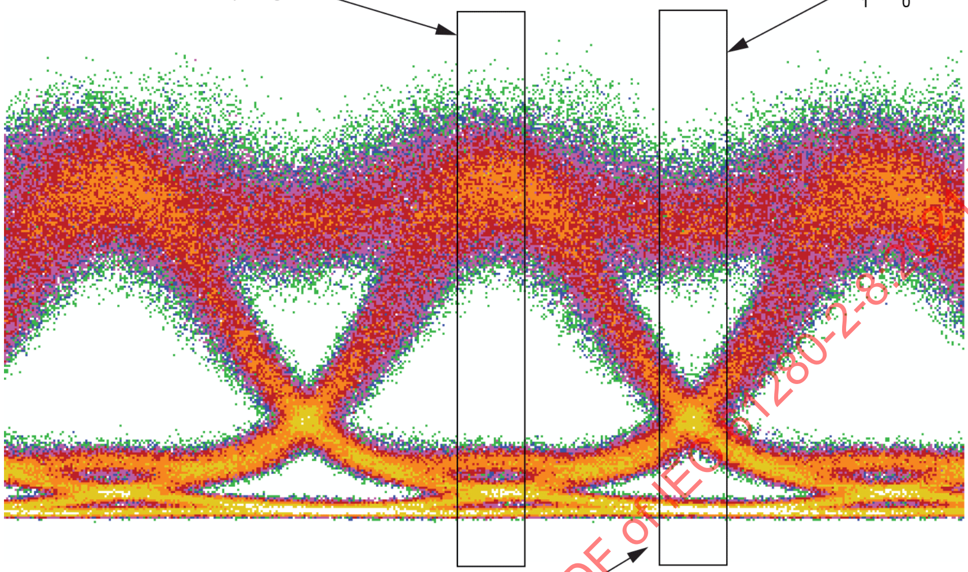


Figure 2 – More accurate measurement technique using a DSO that samples noise statistics between eye centres

It is tempting to conclude that the estimates for σ_1 and σ_0 would tend to be overestimated and that the resulting Q measurements would always form a lower bound to the actual Q for either of these oscilloscope-based methods. That is not necessarily the case. It is possible that the histogram distributions can be distorted in other ways, for example, skewed in such a way that the mean values overestimate the eye opening – and the resulting Q will actually not be a lower bound. There is, unfortunately, no easily characterized relationship between oscilloscope-derived Q measurements and BER performance.

5 Variable decision threshold method

5.1 Overview

This method of estimating the Q-factor relies on using a receiver front-end with a variable decision threshold. Some means of measuring the BER of the system is required. Typically, the measurement is performed with an error test set using a pseudo-random binary sequence (PRBS), but there are alternate techniques which allow operation with live traffic. The measurement relies on the fact that for a data eye with Gaussian statistics, the BER may be calculated analytically as follows:

$$P_e(V_{th}) = \frac{1}{2}\left(\operatorname{erfc}\left(\frac{|V_{th} - \mu_1|}{\sigma_1}\right) + \operatorname{erfc}\left(\frac{|V_{th} - \mu_0|}{\sigma_0}\right)\right) \quad (2)$$

where

P_e	is the BER;
V_{th}	is the decision threshold level;
μ_1, μ_0 and σ_1, σ_0	are the mean and standard deviation of the "1" and "0" data rails;
erfc(.)	is the complementary error function given by

$$\mathrm{erfc}(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \mathrm{e}^{-\beta^2/2} d\beta \cong \frac{1}{x\sqrt{2\pi}} \mathrm{e}^{-x^2/2} \qquad (3)$$

The approximation is nearly exact for $x > 3$.

The BER, given in Formula (2), is the sum of two terms. The first term is the conditional probability of deciding that a "0" has been received when a "1" has been sent, and the second term is the probability of deciding that a "1" has been received when a "0" has been sent.

In order to implement this technique, the BER is measured as a function of the threshold voltage (see Figure 3). Formula (2) is then used to convert the data into a plot of the Q-factor versus threshold, where the Q-factor is the argument of the complementary error function of either term in Formula (2). To make the conversion, the approximation is made that the BER is dominated by only one of the terms in Formula (2) according to whether the threshold is closer to the "1's" or the "0's" rail of the eye diagram.

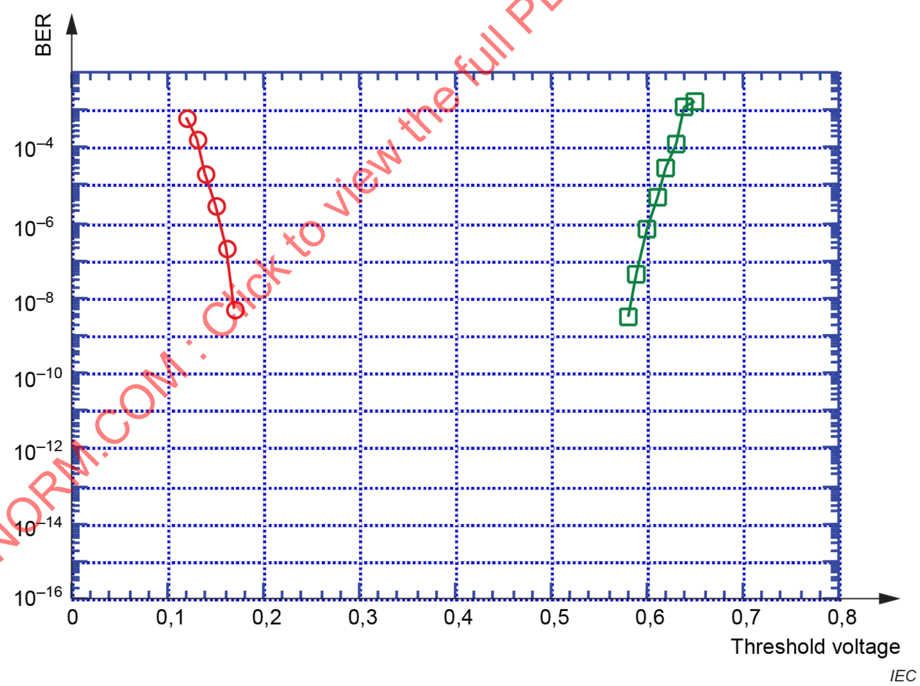


Figure 3 – Bit error ratio as a function of decision threshold level

Figure 4 shows the results of converting the data in Figure 3 into a plot of Q-factor versus threshold. The optimum Q-factor value as well as the optimum threshold setting needed to achieve this Q-factor are obtained from the intersection of the two best-fit lines through the data. This technique is described in detail in [3].

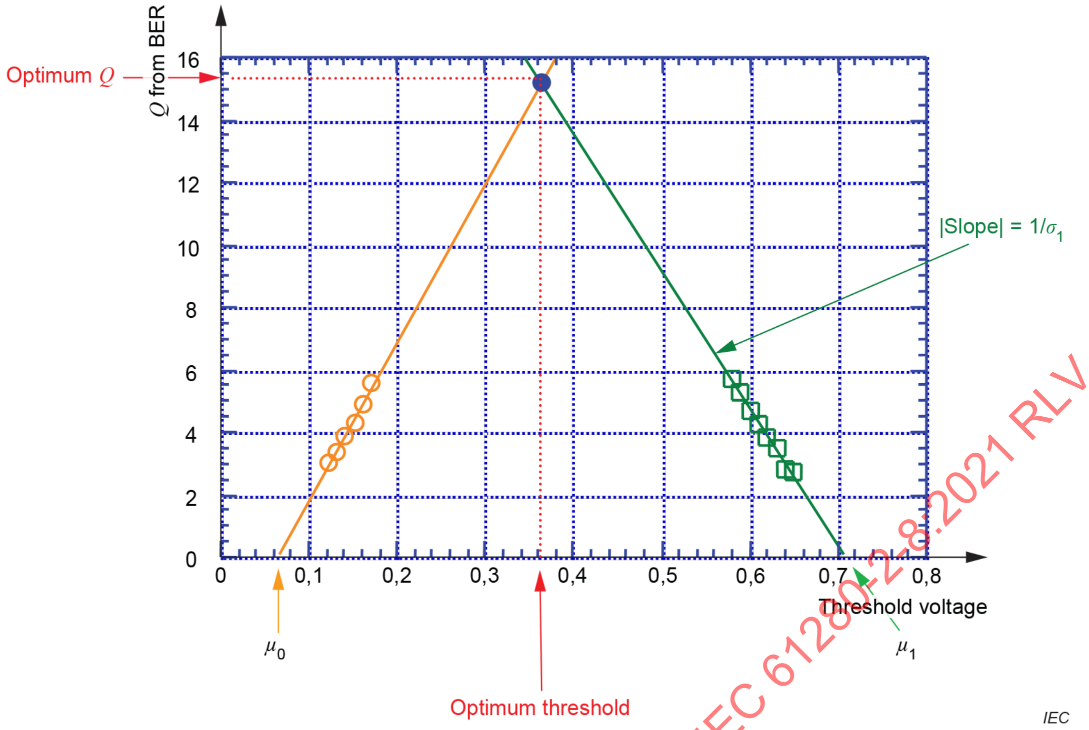


Figure 4 – Plot of Q-factor as a function of threshold voltage

The optimum threshold as well as the optimal Q can be obtained analytically by making use of the following approximation [4] for the inverse error function:

$$\left[\log\left\{\frac{1}{2}\mathrm{erfc}(x)\right\}\right]^{-1} \approx 1{,}192 - 0{,}6681x - 0{,}0162x^2 \quad (4)$$

where

x is $\log(P_e)$.

NOTE 1 Formula (4) is accurate to ±0,2 % over the range of P_e from 10^{-5} to 10^{-10}.

After evaluating the inverse error function, the data are plotted against the decision threshold level, V_{th}. As shown in Figure 4, a straight line is fitted to each set of data by linear regression. The equivalent variance and mean for the Q calculation are given by the slope and intercept respectively.

The minimum BER can be shown to occur at an optimal threshold, $V_{th\text{-optimal}}$, when the two terms in the argument in Formula (2) are equal, that is

$$\frac{\left(\mu_1 - V_{th-optimal}\right)}{\sigma_1} = \frac{\left(V_{th-optimal} - \mu_0\right)}{\sigma_0} = Q_{opt} \quad (5)$$

An explicit expression for $V_{th\text{-optimal}}$ in terms of $\mu_{1,0}$ and $\sigma_{1,0}$ can be derived from Formula (5) to be:

$$V_{th-optimal} = \frac{\sigma_0\mu_1 + \sigma_1\mu_0}{\sigma_0 + \sigma_1} \quad (6)$$

The value of Q_{opt} is obtained from Formula (1). The residual BER at the optimal threshold can be obtained from Formula (2) and is approximately

$$P_{\text{e-optimal}} \cong \frac{e^{-\left(Q_{opt}^2/2\right)}}{Q_{opt}\sqrt{2\pi}} \quad (7)$$

NOTE 2 This approximation is nearly exact for $Q_{opt} > 3$.

It should be noted that even though the variable threshold method makes use of Gaussian statistics, it provides accurate results for systems that have non-Gaussian noise statistics as well, for example, the non-Gaussian statistics that occur in a typical optically amplified system [5] [6]. This can be understood by examining Figure 1. The decision circuit of a receiver operates only on the interior region of the eye. This means that the only part of the vertical histogram that it uses is the "tail" that extends into the eye. The variable decision threshold method amounts to constructing a Gaussian approximation to the tail of the real distribution in the centre region of the eye where it affects the receiver operation directly. As the example in Figure 1 shows, this Gaussian approximation will not reproduce the actual histogram distribution at all, but it does not need to, for purposes of Q estimation.

Another way to view the variable decision threshold technique is to imagine replacing the real data eye with a fictitious eye having Gaussian statistics. The two eye diagrams have the same BER versus decision threshold voltage behaviour, so it is reasonable to assign them the same equivalent Q value, even though the details of the full eye diagram may be very different. However, this analysis will not work for systems dominated by noise sources whose "tails" are not easily approximated to be Gaussian in shape, as, for example, would occur in a system dominated by cross-talk or modal noise. In taking these measurements, an inability to fit the data of Q-factor versus threshold to a straight line would provide a good indication of the presence of such noise sources.

Experimentally, it has been found that the Q values measured using the variable decision threshold method have a statistically valid level of correlation with the actual BER measurements.

5.2 Apparatus

An error performance analyser consisting of a pattern generator and a bit error ratio detector.

5.3 Sampling and specimens

The device under test (DUT) is a fibre optic digital system, consisting of an electro-optical transmitter at one end and an opto-electronic receiver at the other end. In between the transmitter and the receiver can be an optical network with links via optical fibres (for example, a DWDM network).

5.4 Procedure

Data for the Q measurement are collected at both the top "1" and bottom "0" regions of the eye as BER (over the range 10^{-5} to 10^{-10}) versus decision threshold. The equivalent mean (μ) and variance (σ) of the "1's" and "0's" are determined by fitting this data to a Gaussian characteristic.

The Q-factor is then calculated using Formula (1).

a) Connect the pattern generator and error detector to the system under test in accordance with Figure 5.

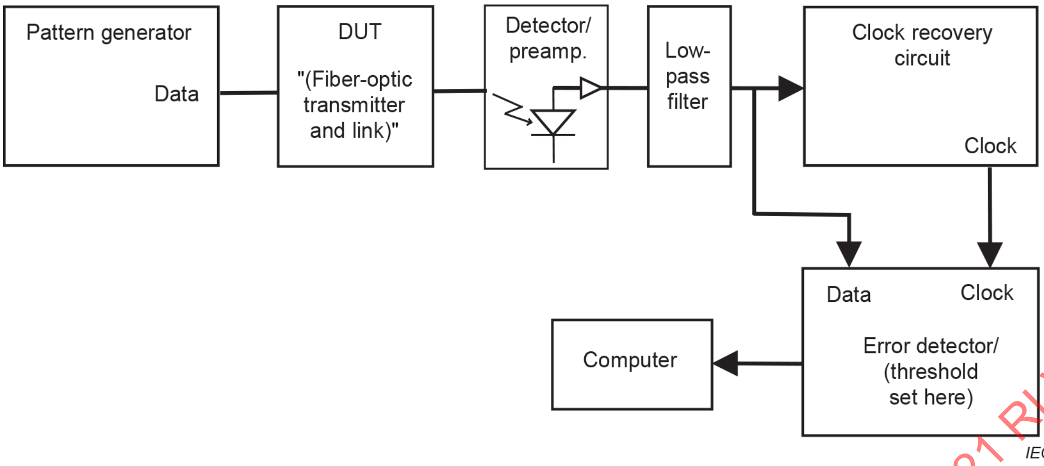


Figure 5 – Set-up for the variable decision threshold method

b) Set the clock source to the desired frequency.

c) Set up the pattern generator's pattern, data and clock amplitude, offset, polarity and termination as required.

d) Set up the error detector's pattern, data polarity and termination as required.

e) Set the decision threshold voltage and data input delay to achieve a sampling point that is approximately in the centre of the data eye as shown in Figure 6. This is the initial sampling point.

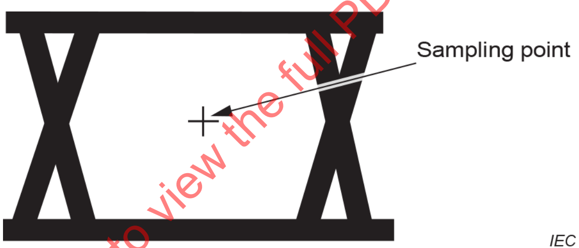


Figure 6 – Set-up of initial threshold level (approximately at the centre of the eye)

f) Enable the error detector's gating function and set it to gate by errors, for a minimum of 10, 100 or 1 000 errors.

g) Adjust the error detector's decision threshold voltage in a positive direction until the measured BER increases to a value greater than 1 × 10^{-10}. Note the decision threshold voltage (V_{b1}) and the BER.

h) Increase the decision threshold voltage until the BER rises above 10^{-5} and note the decision threshold voltage (V_{a1}) and the BER.

i) Note the difference between the two threshold values V_{a1} and V_{b1} and choose a step size (V_{step1}) that provides a reasonable number (greater than 5) of measurement points between these two decision threshold extremes. Starting from the threshold value V_{a1}, decrease the threshold value by the step size, V_{step1}. At each step, run a gating measurement on the error detector. Record the measured BER value and the corresponding decision threshold voltage.

j) The gating measurement from the error detector accumulates data and error information until the minimum number of errors – as specified in f) – have been recorded. Selecting a larger minimum number of errors provides a statistically more accurate BER but at the expense of measurement time, particularly when measuring the low BER values. For a statistically significant result, the number of errors counted should not be less than 15.

k) Continue until the measured BER falls below 10^{-10}. This set of decision threshold voltage versus BER is the "1" data set.

l) Adjust decision threshold voltage back to the initial sampling point value and then continue in a negative direction until the BER increases again to greater than 10^{-10}. Note down the threshold value (V_{b0}) and the BER.

m) Decrease the decision threshold voltage until the BER rises above 10^{-5} and note the decision threshold voltage (V_{a0}) and the BER.

n) Note the difference between the two threshold values V_{a0} and V_{b0} and choose a step size (V_{step0}) that provides reasonable number (greater than 5) of measurement points between these two decision threshold extremes. Starting from the threshold value V_{a0}, increase the threshold value by the step size, V_{step0}. At each step, run a gating measurement on the error detector. Record the measured BER and the corresponding decision threshold voltage.

o) Continue until the measured BER falls below 1×10^{-10}. This set of decision threshold voltage versus BER is the "0" data set.

5.5 Calculations and interpretation of results

5.5.1 Sets of data

The procedure in 5.4 provides two sets (for the "0" and "1" rails) of data in the form:

$$\begin{bmatrix} D_1, P_{e\,1} \\ D_2, P_{e\,2} \\ . \\ . \\ D_n, P_{e\,n} \end{bmatrix}$$

where

D_i is the decision threshold voltage for "i"-th reading (for i = 1, 2…,n);

$P_{e\,i}$ is the bit error ratio for "i"-th reading (for i = 1, 2…,n);

n is the total number of data pairs.

The total number of data pairs for the "0" and "1" rails need not be equal.

As an example, the voltage and BER values shown in Table 2 were obtained in a real-life experiment.

Table 2 – BER as a function of threshold voltage

"1" rail		"0" rail	
Threshold voltage V	**BER**	**Threshold voltage** V	**BER**
−1,75	$5{,}18 \times 10^{-5}$	−4,37	$8{,}76 \times 10^{-5}$
−1,80	$2{,}09 \times 10^{-5}$	−4,34	$1{,}90 \times 10^{-5}$
−1,85	$7{,}33 \times 10^{-6}$	−4,31	$5{,}18 \times 10^{-6}$
−1,90	$2{,}77 \times 10^{-6}$	−4,28	$1{,}06 \times 10^{-6}$
−1,95	$9{,}61 \times 10^{-7}$	−4,25	$2{,}12 \times 10^{-7}$
−2,00	$1{,}96 \times 10^{-7}$	−4,22	$3{,}45 \times 10^{-8}$
−2,05	$6{,}30 \times 10^{-8}$	−4,19	$3{,}52 \times 10^{-9}$
−2,10	$1{,}95 \times 10^{-8}$	−4,16	$2{,}77 \times 10^{-10}$
−2,15	$3{,}45 \times 10^{-9}$		
−2,20	$1{,}39 \times 10^{-9}$		

5.5.2 Convert BER using inverse error function

Each BER value is then converted through an inverse error function, using the following approximation given in Formula (4).

$$f_i = \left[\log \left\{ \frac{1}{2} \operatorname{erfc}(x_i) \right\} \right]^{-1} = 1{,}192 - 0{,}668\,1 \{x_i\} - 0{,}016\,2 \{x_i\}^2 \tag{8}$$

where

x_i = $\log_{10} (P_{e\ i})$.

This will produce two sets of data (for the "1" and "0") of the form:

$$\begin{bmatrix} D_1, f_1 \\ D_2, f_2 \\ . \\ . \\ D_n, f_n \end{bmatrix}$$

which should approximately fit a straight line.

Using the values given in Table 2, we get the sets of data shown in Table 4.

Table 3 – f_i as a function of D_i

"1" rail		"0" rail	
D_i V	f_i	D_i V	f_i
−1,75	3,757 8	−4,37	3,636 0
−1,80	3,963 8	−4,34	3,984 7
−1,85	4,195 6	−4,31	4,270 6
−1,90	4,404 3	−4,28	4,605 2
−1,95	4,625 7	−4,25	4,929 3
−2,00	4,944 9	−4,22	5,275 7
−2,05	5,162 9	−4,19	5,682 3
−2,10	5,379 9	− 4,16	6,097 5
−2,15	5,685 8		
−2,20	5,839 0		

5.5.3 Linear regression

Using the above data, a linear regression technique is used to fit, in turn, each set of data to a straight line with an equation of the form:

$$Y = A + BX$$

where

Y = $\left[\frac{1}{2}\text{erfc}(P_e)\right]^{-1}$ (*$[F]^{-1}$ inverse error function of F);

X = D (decision threshold voltage).

With n points of data per set, then, for both the top ("1") and bottom ("0") data sets, the following calculations should be performed [7]:

$$B = \frac{\sum XY - \frac{\left(\sum X\right)\left(\sum Y\right)}{n}}{\sum X^2 - \frac{\left(\sum X\right)^2}{n}} \qquad R^2 = \frac{\left(\sum XY - \frac{\left(\sum X\right)\left(\sum Y\right)}{n}\right)^2}{\left(\sum X^2 - \frac{\left(\sum X\right)^2}{n}\right)\left(\sum Y^2 - \frac{\left(\sum Y\right)^2}{n}\right)} \qquad (9)$$

$$A = \frac{\sum Y}{n} - B\frac{\sum X}{n}$$

where

R^2 is the coefficient of determination (a measure of how well the data fits a straight line);

$\sum$ is the sum of values from 1 to n.

Using the values given in Table 3, we get the values shown in Table 4.

Table 4 – Values of linear regression constants

"1" rail			"0" rail		
A	***B***	***R***	***A***	***B***	***R***
−4,612 5	−4,763 8	0,998 9	53,989	11,530 7	0,998 4

5.5.4 Standard deviation and mean

$\sigma = \left| -\frac{1}{B} \right|$ (standard deviation of "1" or "0" noise region),

$\mu = \frac{-A}{B}$ (mean of "1" or "0" noise region).

Calculate μ_1, σ_1 from the "1" set of data and μ_0, σ_0 from the "0" set of data.

Using the example in Table 4, we get the values shown in Table 5.

Table 5 – Mean and standard deviation

"1" rail		"0" rail	
μ_1	σ_1	μ_0	σ_0
–0,968 2	0,209 9	–4,682 2	0,086 724 9

5.5.5 Optimum decision threshold

$$Q_{opt} = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \quad (10)$$

And thus, the optimum decision threshold is equal to

$$\frac{\sigma_0 \mu_1 + \sigma_1 \mu_0}{\sigma_1 + \sigma_0} \quad (11)$$

For the example given in Table 5, using the value derived for Q_{opt} of 12,52, the optimal decision threshold is −3,596 V.

5.5.6 BER optimum decision threshold

Also, the predicted residual BER at the optimum decision threshold is given by

$$P_e = \frac{e^{-\left(\frac{Q^2}{2}\right)}}{Q_{opt}\sqrt{2\pi}} \quad (12)$$

Assuming the value of 12,52 for Q_{opt} in our example data, the residual BER is calculated to be less than 1×10^{-18}.

5.5.7 BER non-optimum decision threshold

The BER value at decision threshold voltages other than the optimum can be calculated from the following formula:

$$P_e(D) = \frac{1}{2}\left\{ \frac{e^{-\frac{\left(\frac{|\mu_1 - D|}{\sigma_1}\right)^2}{2}}}{\left(\frac{|\mu_1 - D|}{\sigma_1}\right)\sqrt{2\pi}} + \frac{e^{-\frac{\left(\frac{|\mu_0 - D|}{\sigma_0}\right)^2}{2}}}{\left(\frac{|\mu_0 - D|}{\sigma_0}\right)\sqrt{2\pi}} \right\} \tag{13}$$

5.5.8 Error bound

An error bound for the value of Q is derived in Annex A. Using Formula (A.5), one can calculate the error bound for the value of Q_{opt}.

For the example shown, the absolute error bound on Q is ±0,5.

5.6 Test documentation

Report the following information for each test:

a) test date;

b) this document number and its year of publication;

c) specimen/sample (that is, optical transmission system being tested) identification;

d) two sets of data: one above the optimal threshold and the other below;

e) at least 5 readings of threshold versus BER for each data set (for BER values varying from 10^{-5} to 10^{-10});

f) optimal Q as well as the optimal decision threshold;

g) possible error range in the value of Q.

5.7 Specification information

The following details shall be specified:

a) IEC document number;

b) any special test requirements;

c) failure or acceptance criteria.

6 Variable optical threshold method

6.1 Overview

This method consists of the optical addition of an interfering pre-set bias light to the received optical signal in order to increase the measured BER. Measurements taken at several values of bias light are extrapolated to zero bias, to evaluate the BER value for normal operation. This method is applicable to DC-coupled receivers only. The effect of adding a pre-set bias is shown in Figure 7.

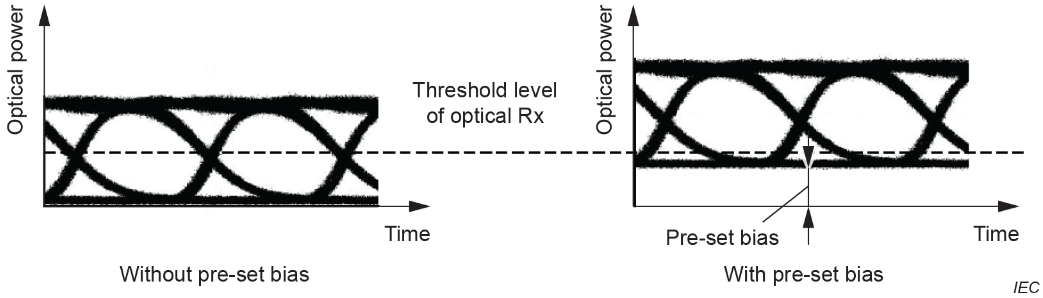


Figure 7 – Effect of optical bias

The method can be used to evaluate the error performance of an optical link or active device as shown in Figure 8. Alternatively, the error performance of a complete system can be evaluated using the set-up shown in Figure 9. The advantage of this method is that no internal access to equipment is required and that any internal error monitoring facility of the system under test can be utilized. If this is not available, conventional error-measuring equipment can be connected to the data input and output terminations of the system.

6.2 Apparatus

Common to all methods is the conventional error measurement equipment: a pattern generator and an error detector.

a) Conventional error measuring test equipment consisting of a pattern generator and separate error detector suitable for remote use. This is not required for system evaluation with self-contained error-monitoring facility.
b) A pre-set light source, stable to 0,1 dB over 1 h, of a wavelength similar to the system under test.
c) An optical attenuator stable to 0,1 dB over 1 h. An additional attenuator with equivalent stability may be required in the case of high signal levels at the receiver, for example, when testing a transmitter receiver pair.
d) An optical splitter/combiner with split ratios typically between 50:50 and 10:90, and with fibre compatible with that of the system and the pre-set bias light source.

6.3 Items under test

The item under test may be a digital fibre optic system consisting of a digital transmitter and a DC-coupled digital receiver which are connected via an optical link consisting of fibre or cable and may also include passive or active components. If a transmitter/receiver pair alone is to be tested, they should be connected via a fixed or variable optical attenuator.

The item under test may also be a self-contained transmission system comprising transmit and receive terminals connected via an optical link which itself may contain active devices such as regenerators and/or optical amplifiers. Such system may include internal error monitoring facilities.

6.4 Procedure for basic optical link

Refer to Figure 8.

a) Operate the transmitter and receiver, adjusting the received signal with the optical attenuator. It may be necessary to monitor the input power of the optical signal at the receiver.
b) Adjust the pre-set bias light until a predetermined high value of BER, such as 10^{-4}, is reached.
c) Decrease the bias a step at a time, and at each step record the BER measured by the error detector. Measure at least 5 data pairs, with the BER values to 2 significant figures.

d) Repeat c).

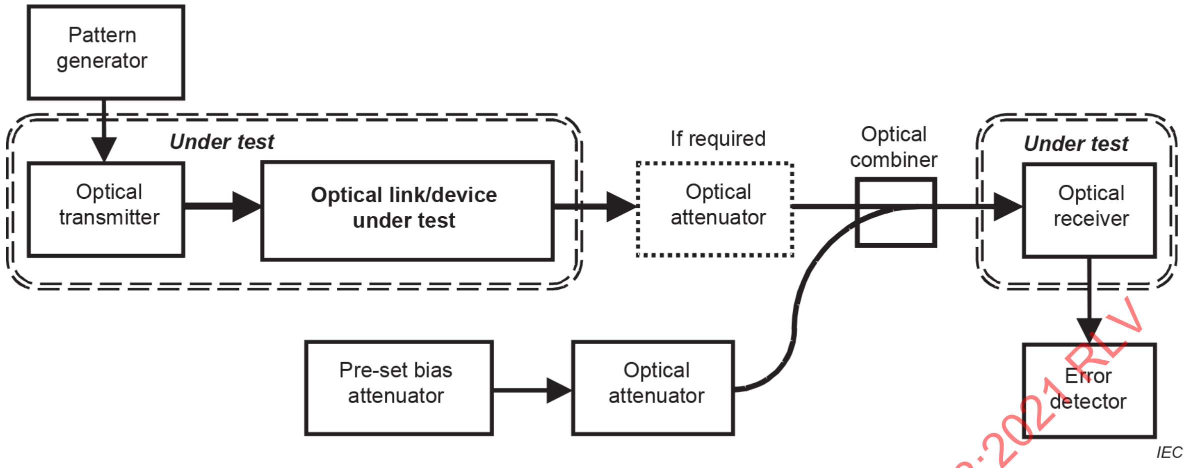


Figure 8 – Set-up for optical link or device test

6.5 Procedure for self-contained system

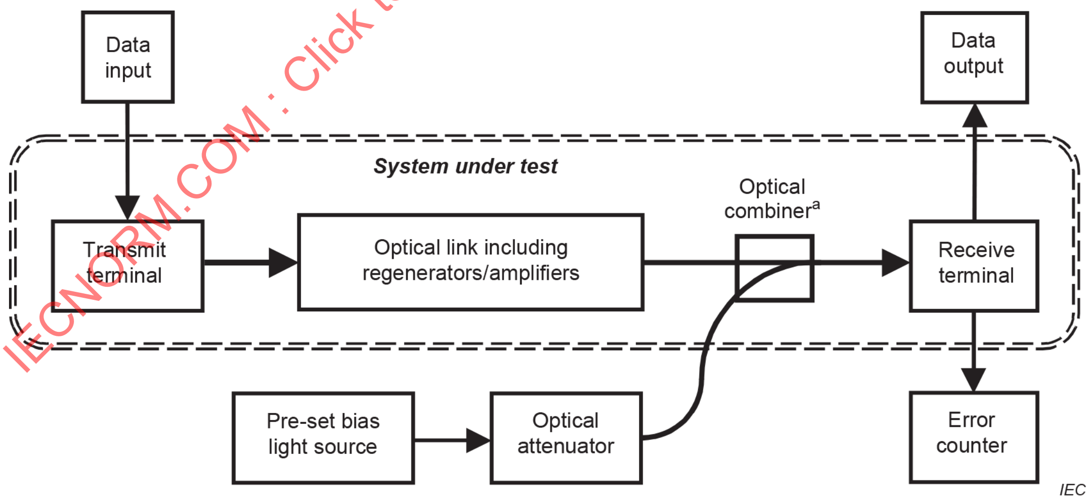
Refer to Figure 9.

a) Set up the system for normal operation. If no optical combiner is incorporated, insert such a device at the input terminal of the receiver. If the system does not contain error monitoring facilities, connect a pattern generator to a data input of the transmit terminal and the corresponding error detector to the appropriate data output terminal.

b) Adjust the pre-set bias light until a predetermined high value of BER, such as 10^{-4}, is reached.

c) Decrease the bias a step at a time, and at each step record the BER measured by the error detector. Measure at least 5 data pairs, with the BER values to 2 significant figures.

d) Repeat c).



[a] To be inserted if system is not equipped with an optical combiner.

Figure 9 – Set-up for system test

6.6 Evaluation of results

The injection of an optical bias signal is, in essence, similar to a variation in the detection threshold. Thus, the mathematical model for the evaluation of the results is substantially the same as that used for the variable threshold method. To a first-order approximation, therefore, the relationship between the amplitude of the optical bias signal and the resulting value of BER can be represented by the equation:

$$Y = A + BX \quad (14)$$

where

Y = $\log_{10}(P_e)$ and is the log BER;

X is the bias amplitude.

An example of a set of results is given in Table 6.

Table 6 – Example of optical bias test

Bias µW	BER	Log BER
6,00	$1,0 \times 10^{-4}$	−4,00
5,75	$2,7 \times 10^{-5}$	−4,57
5,50	$7,0 \times 10^{-6}$	−5,15
5,25	$1,4 \times 10^{-6}$	−5,85
5,00	$3,0 \times 10^{-7}$	−6,52
4,75	$5,0 \times 10^{-8}$	−7,30
4,50	$1,0 \times 10^{-8}$	−8,00

In order to achieve a precision to two significant digits for the BER values, it is necessary to accumulate sufficient errors, approximately 100, to achieve consistency. The time taken to measure errors shall, however, not compromise the stability of the amplitude of the optical bias, since small variations in this amplitude can have a large effect on the subsequent extrapolation procedure.

Using the results given in Table 6 and applying the linear regression techniques described in 5.5.3, the basic value of BER can be determined by extrapolation as shown in Figure 10.

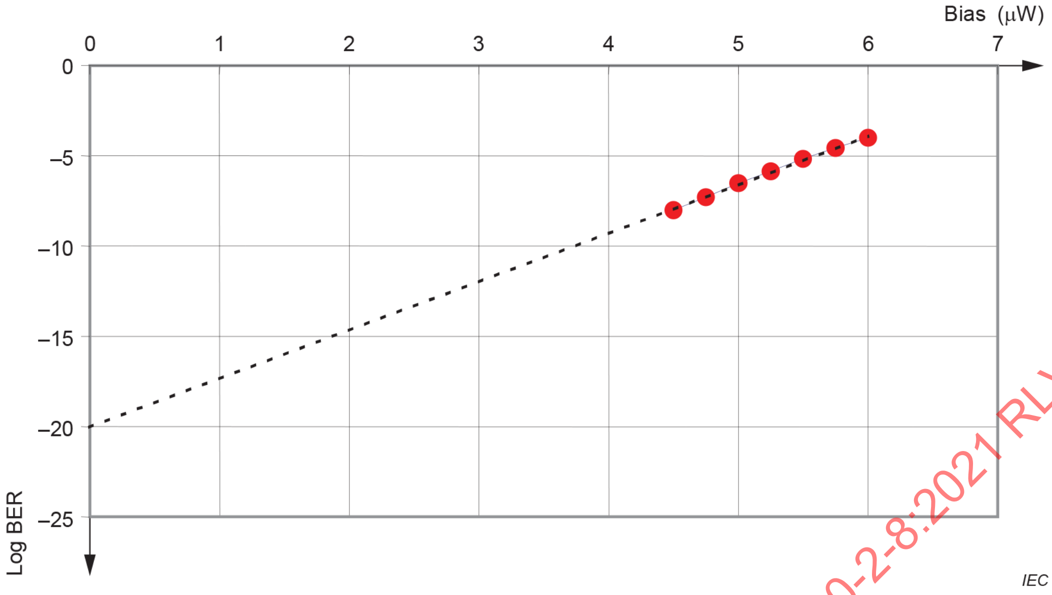


Figure 10 – Extrapolation of log BER as a function of bias

For the results given in Table 6, the BER value, as shown by the extrapolation in Figure 10, is predicted to be 10^{-20}.

Annex A
(normative)

Calculation of error bound in the value of Q

Let us assume that the linear regression fit (of form $Y = A + BX$) gives rise to two straight line fits for the "0" and "1" rails as follows:

$$\begin{aligned} Y_0 &= A_0 + B_0 X \quad \text{(for the "0" rail)} \\ Y_1 &= A_1 + B_1 X \quad \text{(for the "1" rail)} \end{aligned} \tag{A.1}$$

As shown in Figure 4, the two lines intersect at the point X_{optimal}, the optimal decision threshold. At this value of X, both Y_0 and Y_1 are equal, that is

$$\begin{aligned} A_0 + B_0 X_{\text{optimal}} &= A_1 + B_1 X_{\text{optimal}} \quad \text{or} \\ X_{\text{optimal}} &= \frac{A_1 - A_0}{B_0 - B_1} \end{aligned} \tag{A.2}$$

The value of Y at the optimal threshold is Q, that is

$$\begin{aligned} Q &= A_1 + B_1 X_{\text{optimal}} \\ &= \frac{A_1 B_0 - A_0 B_1}{B_0 - B_1} \end{aligned} \tag{A.3}$$

The derivatives of Q with respect to each of the variables A_0, A_1, B_0 and B_1 are

$$\begin{aligned} \frac{\partial Q}{\partial A_0} &= \alpha, \quad \frac{\partial Q}{\partial A_1} = \beta \\ \frac{\partial Q}{\partial B_0} &= -\alpha\gamma, \quad \frac{\partial Q}{\partial B_1} = -\beta\gamma \end{aligned} \tag{A.4}$$

where $\alpha = -\frac{B_1}{B_0 - B_1}$, $\beta = \frac{B_0}{B_0 - B_1}$ and $\gamma = \frac{A_0 - A_1}{B_0 - B_1}$

The maximum error in Q, given by ΔQ_{max}, can be bounded by

$$\begin{aligned} \Delta Q_{\text{max}}^2 &= \left(\frac{\partial Q}{\partial A_0}\right)^2 \sigma_{A_0}^2 + \left(\frac{\partial Q}{\partial A_1}\right)^2 \sigma_{A_1}^2 + \left(\frac{\partial Q}{\partial B_0}\right)^2 \sigma_{B_0}^2 + \left(\frac{\partial Q}{\partial B_1}\right)^2 \sigma_{B_1}^2 \\ &= \alpha^2\left(\gamma^2 \sigma_{B_0}^2 + \sigma_{A_0}^2\right) + \beta^2\left(\gamma^2 \sigma_{B_1}^2 + \sigma_{A_1}^2\right) \end{aligned} \tag{A.5}$$

where

$\sigma_{A_0}^2$ and $\sigma_{A_1}^2$ are the uncertainties in the Y-intercepts for the "0" and "1" rails, respectively;

$\sigma_{B_0}^2$ and $\sigma_{B_1}^2$ are the uncertainties in the slopes of the "0" and "1" rails.

It is assumed that the factors A_0, A_1, B_0 and B_1 are uncorrelated. Formula (A.5) gives the absolute maximum spread in the value of Q.

These variances are given in [8] to be:

$$\sigma_A^2 \cong \frac{S^2 \sum X^2}{\Delta} \quad \text{and} \quad \sigma_B^2 \cong \frac{N \cdot S^2}{\Delta} \tag{A.6}$$

where

N is the number of data points.

$$\Delta = N \sum X^2 - \left(\sum X\right)^2 \text{ and}$$

$$S^2 = \frac{1}{N-2} \sum (Y - A - BX)^2$$

Annex B
(informative)

Sinusoidal interference method

B.1 Overview

This method, optically or electrically, adds an interfering sinusoidal signal to the digital signal at a point before the receiver decision circuit in order to increase the measured BER. The measurements, taken at several values of reducing sinusoidal amplitude, are extrapolated to zero amplitude, thereby giving the system BER.

The sinusoidal signal can be injected into the receiver optically, by adding it to the optical data input. This method is usually the only procedure available for testing at the system or link level since access to the decision circuit is normally not available in operational equipment. To add the sinusoidal signal electrically requires electrical access to the decision circuitry of the receiver which would be more suitable for testing at the component or subsystem level.

Both methods should yield similar results since they rely on an extrapolation to the point where the impairment has been removed.

The optical method requires an AC-coupled receiver, while the electrical method is applicable to an AC- or DC-coupled receiver.

B.2 Apparatus

Common to all methods is the conventional error measurement equipment: a pattern generator and an error detector.

a) A sinewave generator capable of producing a frequency within the passband of the system under test, and of generating stable output levels between 1 mV and 1 V, with at least 3 digits' amplitude resolution. A typical frequency synthesizer meets these requirements.

b) An analogue laser transmitter, with adjustable CW output power, stable to 0,1 dB over 1 h, of a wavelength similar to the system under test and capable of being modulated at a frequency well within the passband of the receiver under test. This serves as an "interfering laser".

c) An optical splitter/combiner with split ratios typically between 50:50 and 10:90, and with fibre compatible with that of the system and the interfering laser.

d) An analogue optical receiver capable of detecting frequencies within the passband of the system under test, used to confirm proper operation of the interfering laser.

B.3 Sampling and specimens

The specimen is a fibre optic digital system consisting of a digital transmitter and a digital receiver. In between them is either a fibre link consisting of fibre or cable and possibly passive or active components (if an operational link is to be tested) or a variable optical attenuator (if the transmitter/receiver pair alone is to be tested).

B.4 Procedure

B.4.1 Optical sinusoidal interference method

Refer to Figure B.1.

a) Place the combiner with one input port connected to either the fibre link or attenuator. Connect the output port to the receiver and the other input port to the interfering laser, which is modulated by the sinewave generator. Connect the receiver to the error detector.

b) Adjust the transmitter and receiver to the desired operating conditions. Adjust the data pattern and, if the attenuator is used, the received power. The receiver input power level shall be held constant for the duration of the measurement procedure.

c) Choose the frequency of the sinewave generator to be well within the passband of the receiver and not harmonically related to the bit-rate. It should be significantly different (such as 1 Mbit/s) from the bit-rate so that no slow beat phenomena are possible.

d) Turn on the interfering laser and adjust its output level so that its power as seen at the output of the combiner is similar to the power seen there due to the laser transmitter of the data link under test. Apply modulation to the interfering laser and adjust the modulation depth until a BER value of approximately 10^{-4} is reached. (It is assumed that the BER is immeasurably low before the interfering signal is added.) Ensure that the interfering laser output is not distorted by monitoring it with the analogue optical receiver. It may be necessary to choose a combiner with a different coupling ratio or to adjust the signal level of the interfering laser in order to achieve the above.

e) Decrease the modulation depth of the interfering laser a step at a time by adjusting the output level of the sinewave generator, and at each step record the BER value measured by the error detector.

f) Measure at least 5 data pairs, with the BER values measured to 2 significant figures.

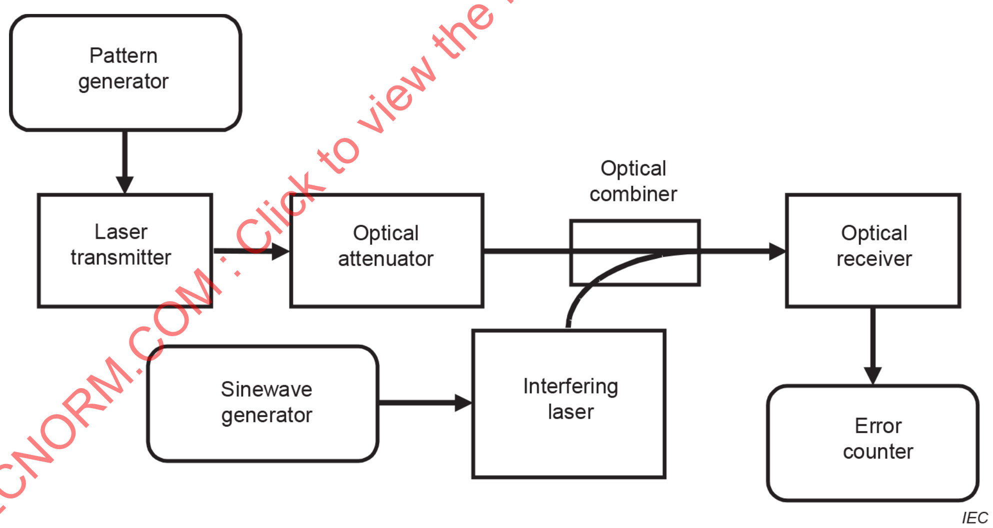


Figure B.1 – Set-up for the sinusoidal interference method by optical injection

Table B.1 is an example.

Table B.1 – Results for sinusoidal injection

Sinewave amplitude A (mV)	BER
100	$5,0 \times 10^{-5}$
95	$1,1 \times 10^{-5}$
90	$6,3 \times 10^{-6}$
85	$9,8 \times 10^{-7}$
80	$2,3 \times 10^{-7}$
75	$4,6 \times 10^{-8}$

In order to achieve a precision to two significant digits for the BER values, it is necessary to accumulate sufficient errors, approximately 100, to achieve consistency. The time taken to measure errors shall, however, not compromise the stability of the amplitude of the interference signal, since small variations in the amplitude of the interfering signal can have a large effect on the subsequent extrapolation procedure.

B.4.2 Electrical sinusoidal interference method

Refer to Figure B.2.

a) AC-couple the sinewave generator to the decision threshold input of the comparator in the receiver under test. If the comparator has differential data inputs, a large series resistor can be used to isolate the comparator data signal from the sinewave generator. If isolation is difficult to achieve, use the threshold modification method of Clause 5.

b) Adjust the transmitter and receiver to the desired operating conditions. Adjust the data pattern and, if the attenuator is used, the received power to be constant for the duration of the measurement procedure.

c) Choose the frequency of the sinewave generator to be well within the passband of the receiver and not harmonically related to the bit-rate. It should be significantly different (such as 1 Mbit/s) from the bit-rate so that no slow-beat phenomena are possible. The frequency should also be well above the range of any AGC or threshold-tracking loop in the receiver.

d) Adjust the amplitude of the sinewave generator until a BER value of approximately 10^{-4} is reached.

e) Decrease the amplitude of the interference one step at a time, by decreasing the output of the sinewave generator. At each step, record the BER using the error detector. The resulting data should be similar to those given in 5.4.

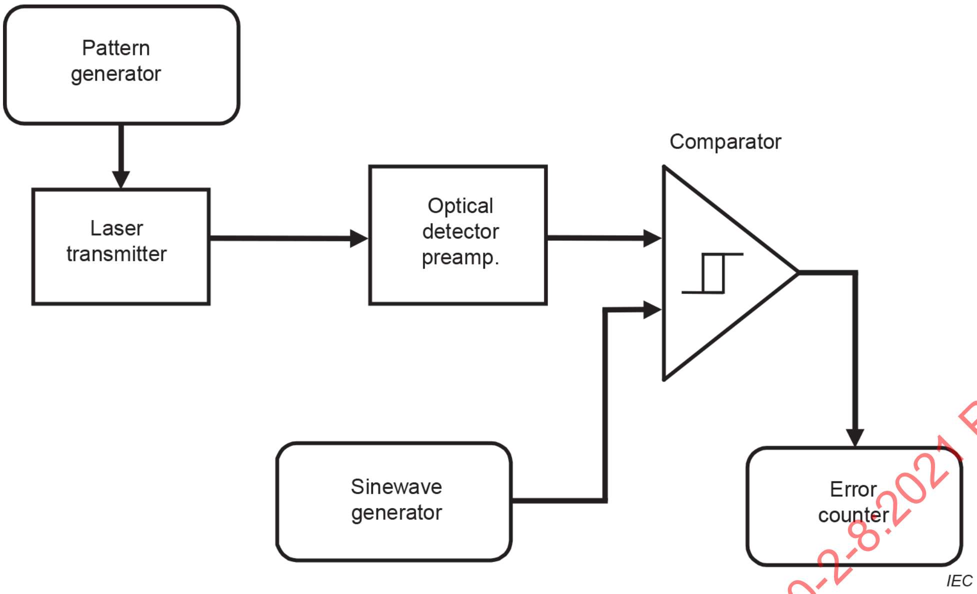


Figure B.2 – Set-up for the sinusoidal interference method by electrical injection

B.5 Calculations and interpretation of results

B.5.1 Mathematical analysis

These calculations apply for both the optical and electrical options of B.4.1 and B.4.2. Denote the data pairs as given in Table B.1 as $(A_i, P_{e\ i})$. Transform the BER values using the function:

$$\psi\left(P_{e\,i}\right)=\frac{-c_2+\sqrt{c_2^2-4c_1\left(c_3+x_i\right)}}{2c_1} \quad \text{(B.1)}$$

where

x_i = ln(2 $P_{e\ i}$);

c_1 = 0,492 6;

c_2 = 0,294 8;

c_3 = 0,792 1.

B.5.2 Extrapolation

Fit a straight line to the values $\psi(P_{e\ i})$ versus A_i. Extrapolate it to the ordinate where A_0 = 0, as shown in the example of Figure B.3, which yields the value $\psi(P_{e\,0})=Q$. The curve is not a very good fit for BER values greater than 10^{-4} because of the approximation used for the complementary error function (erfc) in the equation. Therefore, data with BER values higher than 10^{-4} should not be used.

Calculate the system BER as

$$P_e=\frac{1}{2}\,\text{erfc}\left(\frac{Q}{\sqrt{2}}\right)\cong\frac{1}{Q}\,e^{-Q^2/2}\cdot\frac{1-Q^{-2}+3Q^{-4}}{\sqrt{2\pi}} \quad \text{(B.2)}$$

This is the estimated value of BER at which the system under test is operating. The above approximation to erfc(.) is sufficiently accurate for all error ratios of interest.

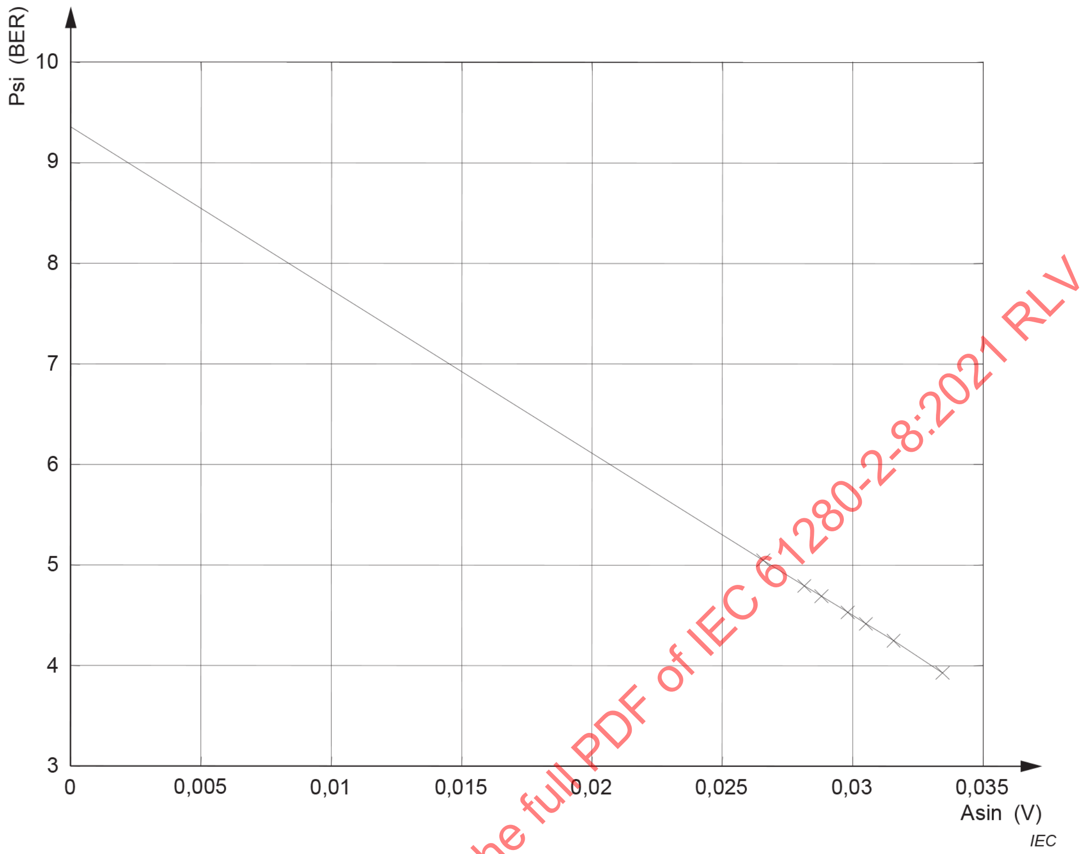


Figure B.3 – BER result from the sinusoidal interference method (data points and extrapolated line)

B.5.3 Expected results

Figure B.4 is an example of the results to be expected using the above extrapolation techniques. The BER of a 50 Mbit/s, single-mode data link was measured by 3 techniques:

- conventional BER measurement down to 10^{-10};
- extrapolation using the optical interference method of B.4.1;
- extrapolation using the electrical interference method of B.4.2.

The solid line is an error function fit to the measured data using best estimates for the noise of the receiver, which is independent of received power and the noise from the transmitter, which is proportional to received power.

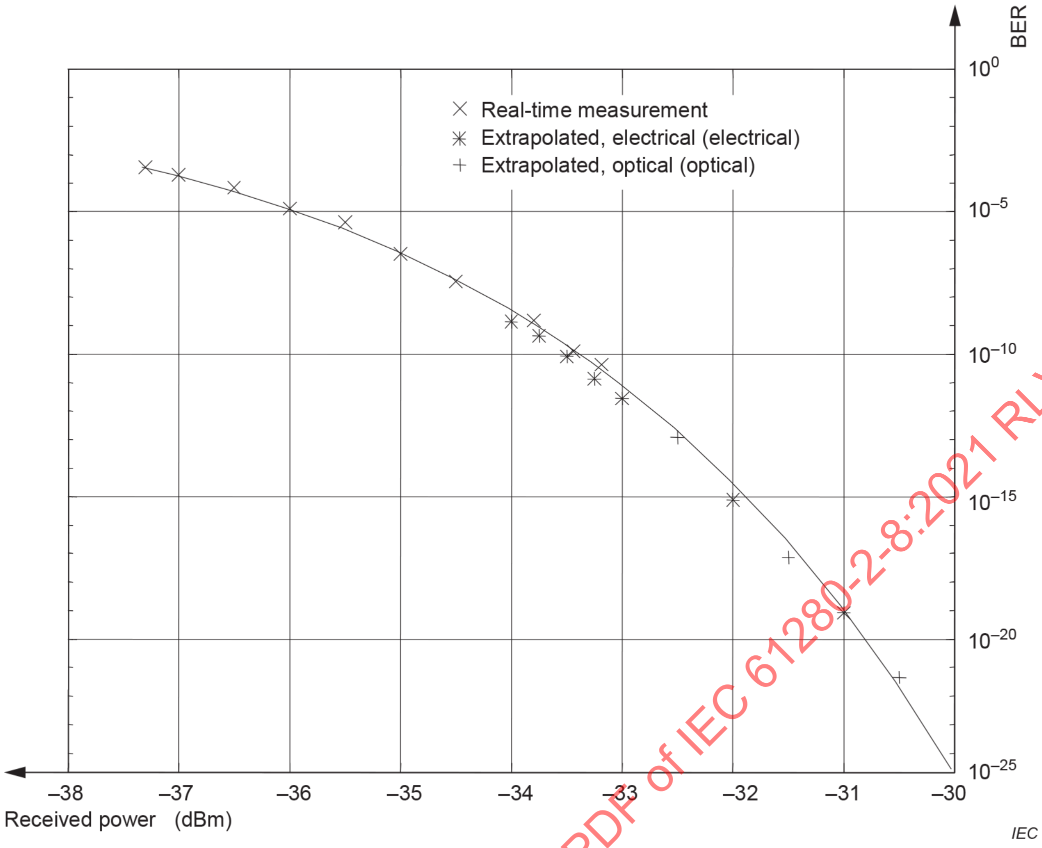


Figure B.4 – BER versus optical power for three methods

B.6 Documentation

The following information shall be reported with each test:

a) date of test;
b) this document number and its year of the publication;
c) specimen identification;
d) type of transmitter;
e) type of receiver.

B.7 Specification information

The following details shall be specified:

a) IEC number;
b) any special test requirements;
c) failure or acceptance criteria.

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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PROCÉDURES D'ESSAI DES SOUS-SYSTÈMES DE TÉLÉCOMMUNICATIONS FIBRONIQUES –

Partie 2-8: Systèmes numériques – Détermination de faibles valeurs de BER en utilisant des mesures du facteur Q

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L'IEC 61280-2-8 a été établie par le sous-comité 86C: Systèmes et dispositifs actifs à fibres optiques, du comité d'études 86 de l'IEC: Fibres optiques. Le présent document est une Norme internationale.

Cette deuxième édition annule et remplace la première édition parue en 2003. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

a) correction d'erreurs dans la Formule (8) en 5.5.2 et dans une formule associée en 5.5.3;
b) correction d'erreurs dans les références aux articles, paragraphes, figures et procédures, ainsi que dans la bibliographie;
c) alignement des termes et définitions en 3.1 sur ceux de l'IEC 61281-1.

Le texte de cette Norme internationale est issu des documents suivants:

FDIS	Rapport de vote
86C/1708/FDIS	86C/1711/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette approbation.

La langue utilisée pour l'élaboration de la présente Norme internationale est l'anglais.

Le présent document a été rédigé selon les Directives ISO/IEC, Partie 2, et élaboré conformément aux Directives ISO/IEC, Partie 1 et aux Directives ISO/IEC, Supplément IEC, disponibles à l'adresse: www.iec.ch/members_experts/refdocs. Les principaux types de documents élaborés par l'IEC sont décrits de manière plus détaillée à l'adresse: www.iec.ch/standardsdev/publications.

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- reconduit,
- supprimé,
- remplacé par une édition révisée, ou
- amendé.

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PROCÉDURES D'ESSAI DES SOUS-SYSTÈMES DE TÉLÉCOMMUNICATIONS FIBRONIQUES –

Partie 2-8: Systèmes numériques – Détermination de faibles valeurs de BER en utilisant des mesures du facteur Q

1 Domaine d'application

La présente partie de l'IEC 61280 spécifie deux méthodes principales permettant de déterminer de faibles valeurs de BER en réalisant des mesures accélérées. Ces méthodes utilisent soit un seuil de décision variable (Article 5), soit un seuil optique variable (Article 6). De plus, une troisième méthode fondée sur le brouillage sinusoïdal est décrite à l'Annexe B.

2 Références normatives

Le présent document ne contient aucune référence normative.

3 Termes, définitions et termes abrégés

3.1 Termes et définitions

Pour les besoins du présent document, les termes et définitions suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

3.1.1
émission spontanée amplifiée
ASE
dans un amplificateur optique, puissance rayonnante optique associée à des photons émis spontanément et amplifiée par un milieu actif

Note 1 à l'article: L'abréviation "ASE" est dérivée du terme anglais développé correspondant "amplified spontaneous emission".

3.1.2
taux d'erreur sur les bits
BER
P_e
nombre de bits erronés divisé par le nombre total de bits, sur une période de temps spécifiée

Note 1 à l'article: L'abréviation "BER" est dérivée du terme anglais développé correspondant "bit error ratio".

3.1.3
brouillage intersymbole
ISI
chevauchement des impulsions adjacentes occasionné par des caractéristiques limitées de largeur de bande des dispositifs optiques dans une liaison fibronique

Note 1 à l'article: L’abréviation "ISI" est dérivée du terme anglais développé correspondant "intersymbol interference".

3.1.4
facteur Q
Q
rapport entre la différence entre la tension moyenne des rails 1 et 0, et la somme de leurs valeurs d’écart-type

3.2 Termes abrégés

CA	courant alternatif
CW	continuous wave (onde continue, ayant normalement une forme sinusoïdale)
CC	courant continu
DSO	digital sampling oscilloscope (oscilloscope à échantillonnage numérique)
DUT	device under test (dispositif en essai)
PRBS	pseudo-random binary sequence (séquence binaire pseudo-aléatoire)
SNR	signal-to-noise ratio (rapport signal/bruit)

4 Mesure de faibles valeurs du taux d’erreur sur les bits

4.1 Considérations générales

Les systèmes et sous-systèmes de télécommunications fibroniques sont, par nature, capables d’offrir d’excellentes performances en termes d’erreur, même à des débits binaires très élevés. Selon la nature du système, le taux d’erreur sur les bits (BER) moyen peut généralement être dans la région allant de 10^{-12} à 10^{-20}. Bien que ce type de performance soit nettement supérieur aux exigences de performances pratiques applicables aux signaux numériques, il présente l’avantage de concaténer de nombreuses liaisons sur de longues distances sans qu’il soit nécessaire de recourir à des techniques de correction d’erreurs.

La mesure de ces faibles taux d’erreur pose des problèmes particuliers en termes de temps nécessaire pour mesurer un nombre d’erreurs suffisamment élevé pour obtenir un résultat statistiquement significatif. Le Tableau 1 présente le temps moyen exigé pour accumuler 15 erreurs. Ce nombre d’erreurs peut être considéré comme statistiquement significatif, en offrant un niveau de confiance de 75 % avec une variabilité de 50 %.

Tableau 1 – Temps moyen pour l'accumulation de 15 erreurs en fonction du BER et du débit binaire

Débit binaire	Temps moyens pour l'accumulation de 15 erreurs										
	BER										
	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}
1,0 Mbit/s	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 j	17 j	170 j	4,7 ans	47 ans
2,0 Mbit/s	75 ms	750 ms	7,5 s	75 s	750 s	2,1 h	21 h	8,8 j	88 j	2,4 ans	24 ans
10 Mbit/s	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 j	17 j	170 j	4,7 ans
50 Mbit/s	3,0 ms	30 ms	300 ms	3,0 s	30 s	5,0 min	50 min	8,3 h	3,5 j	35 j	350 j
100 Mbit/s	1,5 ms	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 j	17 j	170 j
500 Mbit/s	300 µs	3 ms	30 ms	300 ms	3,0 s	30 s	5,0 min	50 min	8,3 h	3,5 j	35 j
1,0 Gbit/s	150 µs	1,5 ms	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 j	17 j
10 Gbit/s	15 µs	150 µs	1,5 ms	15 ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h	1,7 j
40 Gbit/s	3,8 µs	38 µs	380 µs	3,8 ms	38 ms	380 ms	3,8 s	38 s	6,3 min	63 min	10,4 h
100 Gbit/s	1,5 µs	15 µs	150 µs	1,5 ms	15ms	150 ms	1,5 s	15 s	2,5 min	25 min	4,2 h

Les temps indiqués dans le Tableau 1 montrent que la mesure directe des faibles valeurs de BER attendues pour des systèmes fibroniques n'est pas pratique au cours des opérations d'installation et de maintenance. Une façon de surmonter cette difficulté consiste à dégrader artificiellement et de manière contrôlée le rapport signal/bruit au niveau du récepteur, pour ainsi augmenter le BER de manière significative et réduire le temps de mesure. Les performances en termes d'erreur sont mesurées pour différents niveaux de dégradation, et les résultats sont ensuite extrapolés à un niveau de dégradation nulle en utilisant des méthodes informatiques ou graphiques reposant sur des algorithmes de régression théoriques ou empiriques.

La difficulté engendrée par l'utilisation d'une technique de régression pour déterminer les performances en termes d'erreur est que la valeur théorique du BER est liée au niveau de dégradation par la fonction d'erreur complémentaire (erfc) inverse. Ceci signifie que de très petites variations du niveau de dégradation entraînent de très grandes variations du BER. Par exemple, dans la région d'une valeur de BER de 10^{-15}, une variation d'environ 1 dB du niveau de dégradation entraîne une variation du BER de trois ordres de grandeur. Une autre difficulté est qu'il est peu probable qu'une méthode reposant sur une extrapolation révèle une stabilisation du BER à seulement 3 ordres de grandeur environ sous la plus basse valeur mesurée.

Il convient également de noter que, dans le cas de sections régénérées par voie numérique, les résultats obtenus s'appliquent uniquement à la section régénérée dont le récepteur est soumis à essai. Les erreurs générées dans des sections régénérées en amont peuvent produire un plateau d'erreur qui peut devoir être pris en compte pour évaluer les performances en termes d'erreur de la section de régénérateur en essai.

Comme cela a été indiqué ci-dessus, deux méthodes principales sont décrites pour déterminer de faibles valeurs de BER en réalisant des mesures accélérées. Ces méthodes utilisent soit un seuil de décision variable (Article 5), soit un seuil optique variable (Article 6). De plus, une troisième méthode fondée sur le brouillage sinusoïdal est décrite à l'Annexe B.

Il convient de noter que ces méthodes sont applicables à la détermination des performances en termes d'erreur en ce qui concerne les dégradations liées à l'amplitude. La gigue peut également affecter les performances d'un système en termes d'erreur, et son effet exige d'autres méthodes de détermination. Si les performances en termes d'erreur sont dominées par des dégradations dues à la gigue, les méthodes fondées sur l'amplitude décrites dans le présent document produiront des valeurs de BER inférieures à la valeur réelle.

La méthode à seuil de décision variable est la procédure qui permet de mesurer le facteur Q et le BER avec la plus grande exactitude pour les systèmes optiques dont les statistiques de bruit sont inconnues ou imprévisibles. Cependant, la principale limite à l'utilisation de la méthode à seuil variable pour mesurer le facteur Q et le BER est la nécessité d'avoir accès à l'électronique du récepteur afin de manipuler le seuil de décision. Pour les systèmes dans lesquels un tel accès est impossible, la méthode à seuil optique variable peut constituer une alternative utile. Pour les deux méthodes, il est possible d'automatiser la mesure et le calcul des résultats.

4.2 Informations sur le facteur Q

Le facteur Q est le rapport signal/bruit (SNR) au niveau du circuit de décision. Il est généralement exprimé sous la forme suivante [1][1]:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \qquad (1)$$

où

μ_1 et μ_0 sont les niveaux de tension moyens des rails "1" et "0", respectivement;

σ_1 et σ_0 sont les valeurs d'écart-type de la distribution de bruit sur les rails "1" et "0", respectivement.

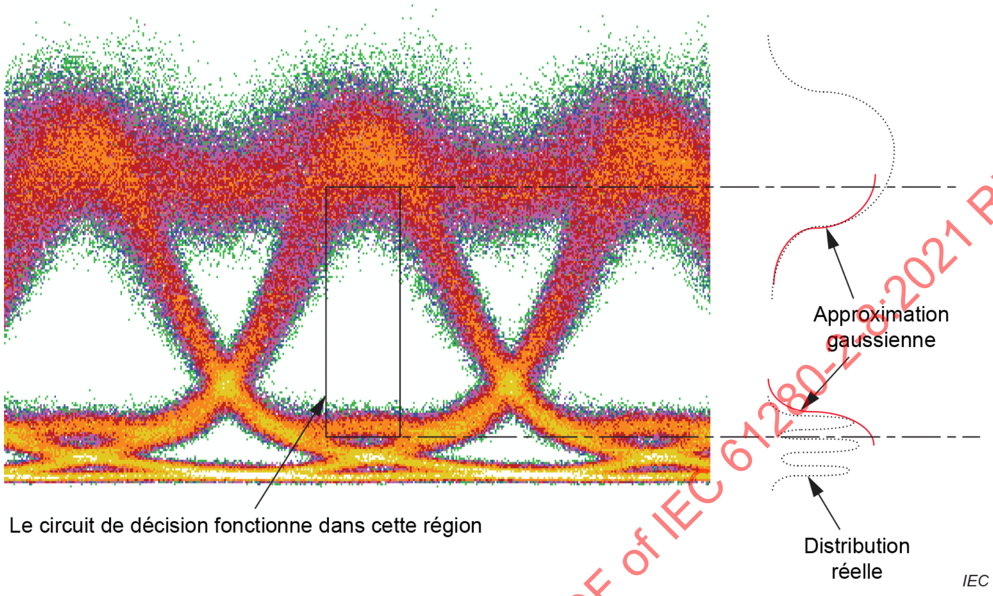
Une estimation précise de la performance de transmission d'un système, ou le facteur Q, doit tenir compte des effets de toutes les sources de dégradation de performance, dégradation à la fois fondamentale et due aux imperfections du monde réel. Deux sources importantes sont le bruit d'émission spontanée amplifiée (ASE) et le brouillage intersymbole (ISI). Le bruit additionnel est essentiellement généré par l'ASE des amplificateurs optiques. L'ISI résulte de nombreux effets, tels que la dispersion chromatique, les non-linéarités des fibres, le brouillage à trajets multiples, la dispersion modale de polarisation et l'utilisation d'électronique à largeur de bande finie. Il peut également y avoir d'autres effets, par exemple une mauvaise adaptation d'impédance peut occasionner des dégradations telles que des temps de décroissance longs ou une forme d'onde amortie.

Une méthode de mesure possible du facteur Q est la méthode des histogrammes de tension qui utilise un oscilloscope d'échantillonnage numérique pour mesurer des histogrammes de tension au centre d'un œil binaire pour estimer le facteur Q de la forme d'onde [2]. Dans cette méthode, un générateur de motifs d'impulsions sert de stimulus et l'oscilloscope est utilisé pour mesurer l'ouverture d'œil reçue et l'écart-type du bruit présent dans les deux rails de tension. A titre d'approximation grossière, le bord de visibilité du bruit représente les points 3σ d'une loi normale supposée. L'avantage d'utiliser un oscilloscope pour mesurer l'œil est sa rapidité sur un trafic réel avec un minimum de matériel.

La méthode de mesure du facteur Q à l'oscilloscope présente plusieurs inconvénients. Lorsque l'oscilloscope est utilisé pour mesurer l'œil de données à haut débit (de l'ordre de plusieurs Gbit/s), sa vitesse d'échantillonnage numérique limitée (souvent de l'ordre de quelques centaines de kilohertz) ne permet d'utiliser qu'une petite partie du flux de données à haut débit pour mesurer le facteur Q. Des temps d'observation plus longs peuvent réduire l'impact de l'échantillonnage lent. Un autre inconvénient plus important est que les estimations de Q découlant des histogrammes de tension au centre de l'œil sont souvent imprécises. Les différents effets de moirage et le bruit ajouté généré par l'électronique frontale de l'oscilloscope peuvent souvent masquer la variance réelle du bruit.

[1] Les chiffres entre crochets renvoient à la bibliographie.

La Figure 1 est un exemple de diagramme de l'œil d'un système en fonctionnement. Cette figure révèle que les histogrammes verticaux passant par le centre de l'œil présentent des effets de moirage (le bruit généré par l'électronique frontale de l'oscilloscope est moins évident). Il est difficile de prédire la relation entre le facteur Q mesuré de cette façon et le BER réel déterminé avec un banc de mesure.



NOTE Les données utilisées pour mesurer le facteur Q sont obtenues à partir de la queue des distributions gaussiennes.

Figure 1 – Exemple de diagramme de l'œil montrant des effets de moirage

La Figure 2 illustre une autre méthode possible pour mesurer le facteur Q en utilisant un oscilloscope. L'idée est d'utiliser le centre de l'œil pour estimer l'ouverture de l'œil et d'utiliser la zone entre les centres des yeux pour estimer le bruit. Les contributions de l'effet de moirage à la largeur de l'histogramme seraient alors réduites. Un inconvénient de cette méthode est qu'elle repose sur des mesures réalisées sur une partie de l'œil que le récepteur n'utilise jamais réellement.

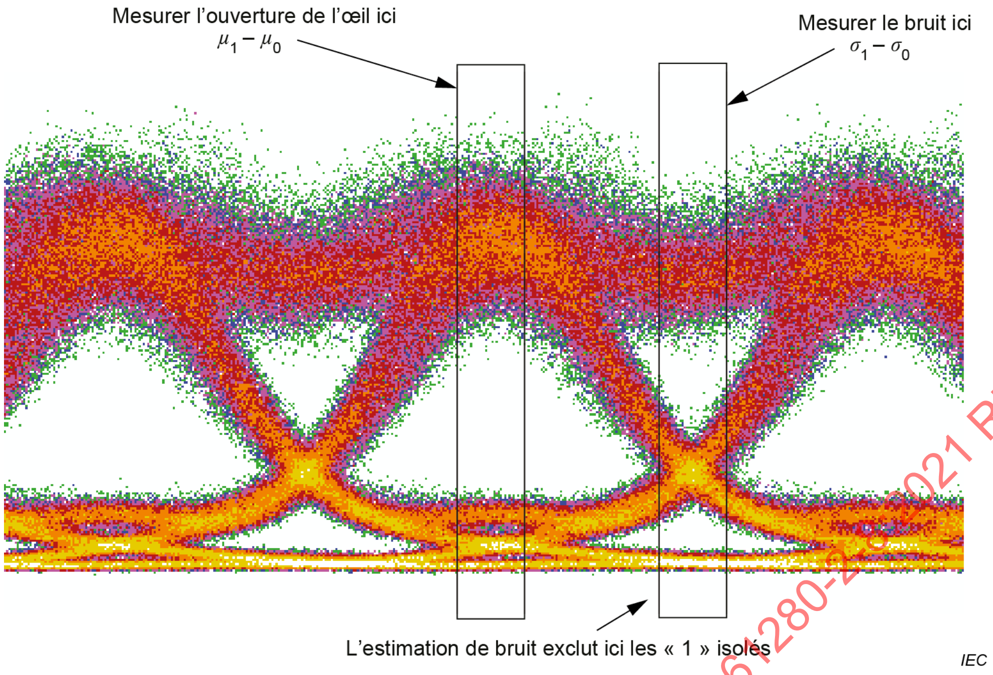


Figure 2 – Technique de mesure plus précise utilisant un oscilloscope d'échantillonnage numérique (DSO) qui échantillonne les statistiques de bruit entre les centres des yeux

Il est tentant de conclure que les valeurs de σ_1 et σ_0 tendent à être surestimées et que les mesures résultantes du facteur Q forment toujours une borne inférieure au facteur Q réel pour l'une ou l'autre de ces méthodes à base d'oscilloscope. Ce n'est pas forcément le cas. Il est possible que les distributions de l'histogramme soient déformées d'autres manières. Elles peuvent par exemple être asymétriques de telle sorte que les valeurs moyennes surestiment l'ouverture de l'œil et le facteur Q résultant n'est plus une borne inférieure. Malheureusement, il n'existe pas de relation facilement caractérisée entre les mesures de facteur Q réalisées au moyen d'un oscilloscope et les performances en termes de BER.

5 Méthode à seuil de décision variable

5.1 Vue d'ensemble

Cette méthode d'estimation du facteur Q s'appuie sur l'utilisation d'un récepteur frontal avec un seuil de décision variable. Des moyens de mesure du BER du système sont exigés. En général, la mesure est réalisée avec un banc de mesure d'erreurs utilisant une séquence binaire pseudo-aléatoire (PRBS), mais il existe des techniques alternatives qui permettent un fonctionnement avec un trafic actif. La mesure repose sur le fait que pour un œil de données avec des statistiques gaussiennes, le BER peut être calculé de manière analytique comme suit:

$$P_e(V_{th}) = \frac{1}{2}\left(\operatorname{erfc}\left(\frac{|V_{th} - \mu_1|}{\sigma_1}\right) + \operatorname{erfc}\left(\frac{|V_{th} - \mu_0|}{\sigma_0}\right)\right) \tag{2}$$

où

P_e est le BER;

V_{th} est le niveau du seuil de décision;

μ_1, μ_0 et σ_1, σ_0 sont la moyenne et l'écart-type des rails de données "1" et "0";

erfc(.) est la fonction d'erreur complémentaire donnée par:

$$\mathrm{erfc}(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \mathrm{e}^{-\beta^2/2} d\beta \cong \frac{1}{x\sqrt{2\pi}} \mathrm{e}^{-x^2/2} \quad (3)$$

L'approximation est pratiquement exacte pour $x > 3$.

Le BER, donné dans la Formule (2), est la somme de deux termes. Le premier terme est la probabilité conditionnelle de décider qu'un "0" a été reçu quand un "1" a été envoyé, et le deuxième terme est la probabilité de décider qu'un "1" a été reçu quand un "0" a été envoyé.

Pour mettre en œuvre cette technique, le BER est mesuré en fonction de la tension de seuil (voir Figure 3). La Formule (2) est ensuite utilisée pour convertir les données en un tracé du facteur Q en fonction du seuil, où le facteur Q est l'argument de la fonction d'erreur complémentaire de l'un des termes de la Formule (2). Pour effectuer la conversion, l'approximation selon laquelle le BER est dominé par un seul des termes dans la Formule (2), selon que le seuil est plus près du rail de "1" ou du rail de "0" du diagramme de l'œil, est considérée.

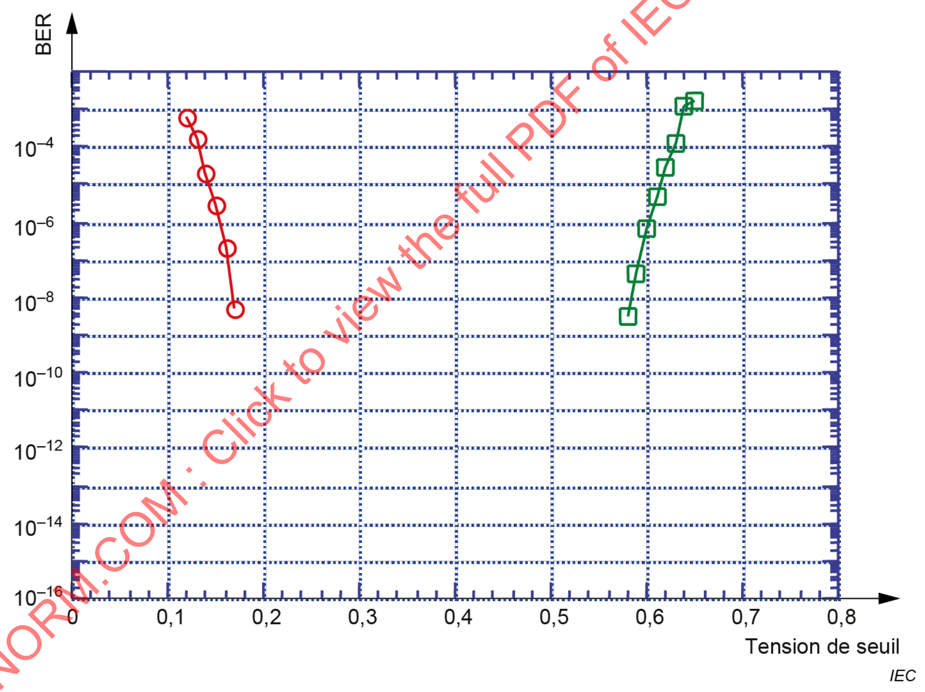


Figure 3 – Taux d'erreur sur les bits en fonction du niveau du seuil de décision

La Figure 4 présente les résultats de la conversion des données de la Figure 3 en un tracé du facteur Q en fonction du seuil. La valeur optimale du facteur Q ainsi que le réglage du seuil optimal nécessaire pour atteindre ce facteur Q sont obtenus à partir de l'intersection des deux droites de meilleur ajustement des données. Cette technique est décrite en détail dans la référence [3].

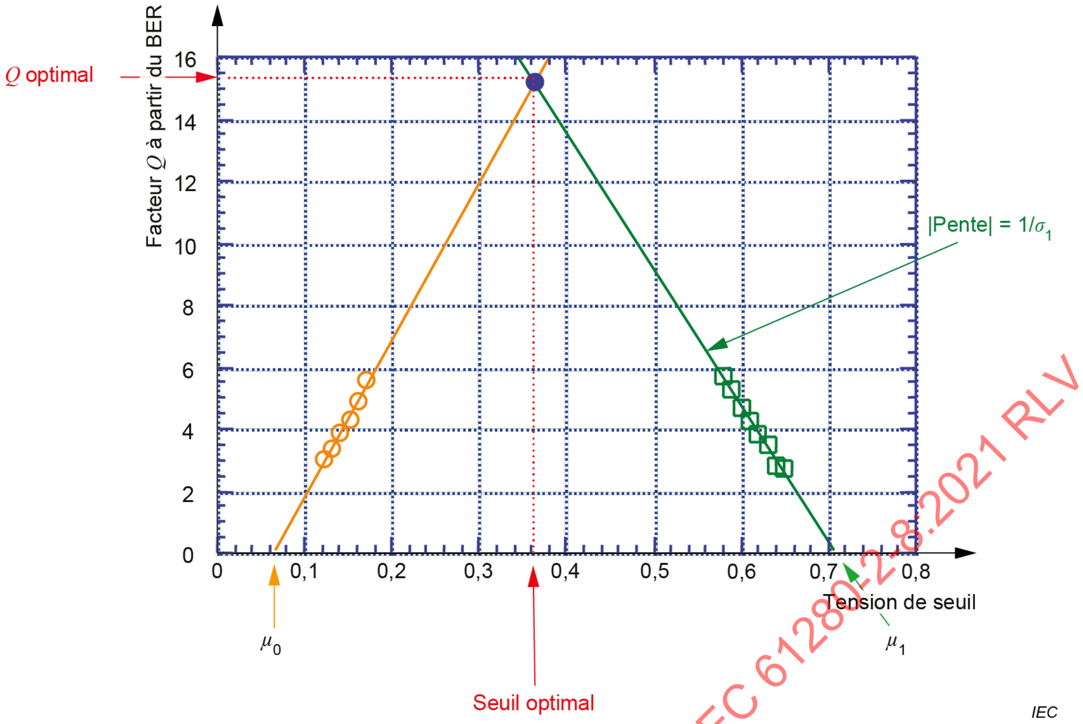


Figure 4 – Tracé du facteur Q en fonction de la tension de seuil

Le seuil optimal ainsi que le facteur Q optimal peuvent être obtenus de manière analytique en utilisant l'approximation [4] suivante pour la fonction d'erreur inverse:

$$\left[\log\left\{\frac{1}{2}\operatorname{erfc}(x)\right\}\right]^{-1} \approx 1{,}192 - 0{,}6681x - 0{,}0162x^2 \tag{4}$$

où

x est $\log(P_e)$.

NOTE 1 La Formule (4) est précise à ±0,2 % sur la plage de P_e allant de 10^{-5} à 10^{-10}.

Après l'évaluation de la fonction d'erreur inverse, les données sont tracées en fonction du niveau du seuil de décision, V_{th}. Comme le montre la Figure 4, une ligne droite est ajustée à chaque ensemble de données par régression linéaire. La variance et la moyenne équivalentes pour le calcul du facteur Q sont respectivement données par la pente et le point d'interception.

Il est possible de démontrer que le BER minimal apparaît à un seuil optimal, $V_{th\text{-optimal}}$, lorsque les deux termes dans l'argument de la Formule (2) sont égaux, c'est-à-dire que

$$\frac{\left(\mu_1 - V_{th-optimal}\right)}{\sigma_1} = \frac{\left(V_{th-optimal} - \mu_0\right)}{\sigma_0} = Q_{opt} \tag{5}$$

Une expression explicite de $V_{th\text{-optimal}}$ en termes de $\mu_{1,0}$ et $\sigma_{1,0}$ peut être déterminée à partir de la Formule (5):

$$V_{th-optimal} = \frac{\sigma_0\mu_1 + \sigma_1\mu_0}{\sigma_0 + \sigma_1} \tag{6}$$

La valeur de Q_{opt} est obtenue à partir de la Formule (1). Le BER résiduel au seuil optimal peut être obtenu à partir de la Formule (2) et est approximativement:

$$P_{\text{e-optimal}} \cong \frac{e^{-\left(Q_{opt}^2/2\right)}}{Q_{opt}\sqrt{2\pi}} \tag{7}$$

NOTE 2 Cette approximation est pratiquement exacte pour $Q_{opt} > 3$.

Il convient de noter que même si la méthode à seuil variable utilise des statistiques gaussiennes, elle donne des résultats exacts pour les systèmes dont les statistiques de bruit ne sont pas gaussiennes, ainsi que, par exemple, pour les statistiques non gaussiennes qui apparaissent dans un système à amplification optique typique [5] [6]. La Figure 1 explique ces résultats. Le circuit de décision d'un récepteur fonctionne uniquement sur la région intérieure de l'œil. Ceci signifie que la seule partie de l'histogramme vertical qu'il utilise est la "queue" qui s'étend dans l'œil. La méthode à seuil de décision variable revient à construire une approximation gaussienne au niveau de la queue de la distribution réelle dans la région du centre de l'œil où elle affecte directement le fonctionnement du récepteur. Comme le montre l'exemple de la Figure 1, cette approximation gaussienne ne reproduit pas du tout la distribution réelle de l'histogramme, ce qui n'est pas utile dans le cadre de l'estimation du facteur Q.

Une autre façon d'appréhender la technique du seuil de décision variable est d'imaginer remplacer l'œil de données réel par un œil factice ayant des statistiques gaussiennes. Les deux diagrammes des yeux ont le même BER en fonction du comportement de la tension de seuil de décision. Il semble donc raisonnable de leur attribuer la même valeur Q équivalente, même si les détails du diagramme de l'œil complet peuvent être très différents. Cependant, cette analyse ne fonctionne pas pour des systèmes dominés par des sources de bruit dont les "queues" ne sont pas facilement approximées comme étant de forme gaussienne, ce qui se produirait, par exemple, dans un système dominé par de la diaphonie ou un bruit modal. En réalisant ces mesures, l'impossibilité d'ajuster les données du facteur Q en fonction du seuil sur une ligne droite donnerait une bonne indication de la présence de telles sources de bruit.

Il a été constaté de manière expérimentale que les valeurs de facteur Q mesurées en utilisant la méthode à seuil de décision variable ont un niveau statistiquement valide de corrélation avec les mesures de BER réelles.

5.2 Appareillage

Un analyseur de performances en termes d'erreur constitué d'un générateur de motifs d'impulsions et d'un détecteur de taux d'erreur sur les bits.

5.3 Echantillonnage et spécimens

Le dispositif en essai (DUT) est un système fibronique numérique, constitué d'un émetteur électro-optique à une extrémité et d'un récepteur opto-électronique à l'autre extrémité. Un réseau optique avec des liaisons par fibres optiques (par exemple, un réseau DWDM) peut être placé entre l'émetteur et le récepteur.

5.4 Procédure

Les données pour la mesure du facteur Q sont collectées dans la région "1" supérieure et dans la région "0" inférieure de l'œil en tant que BER (sur la plage allant de 10^{-5} à 10^{-10}) en fonction du seuil de décision. La moyenne (μ) et la variance (σ) équivalentes des "1" et "0" sont déterminées en ajustant ces données sur une caractéristique gaussienne.

Le facteur Q est ensuite calculé à l'aide de la Formule (1).

a) Raccorder le générateur de motifs d'impulsions et le détecteur d'erreurs au système en essai conformément à la Figure 5.

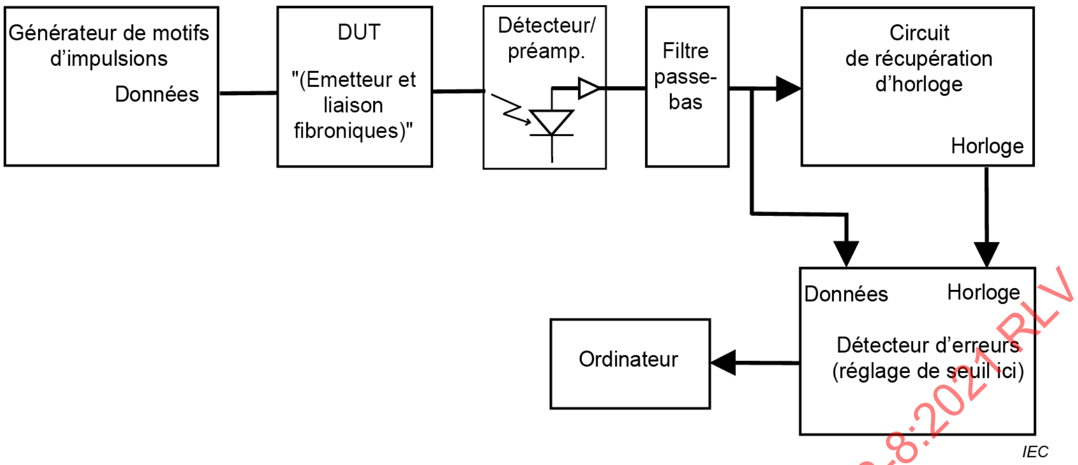


Figure 5 – Montage pour la méthode à seuil de décision variable

b) Régler la source d'horloge à la fréquence souhaitée.

c) Ajuster le motif, l'amplitude des données et de l'horloge, le décalage, la polarité et la sortie du générateur de motifs d'impulsions, selon les exigences.

d) Ajuster le motif, la polarité des données et la sortie du détecteur d'erreurs, selon les exigences.

e) Régler la tension du seuil de décision et le retard d'entrée des données pour atteindre un point d'échantillonnage qui est approximativement au centre de l'œil de données comme cela est représenté à la Figure 6. Il s'agit du point d'échantillonnage initial.

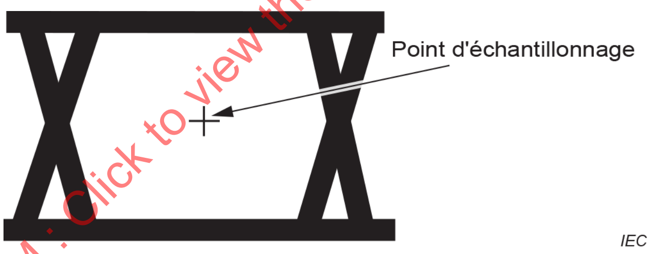


Figure 6 – Réglage du niveau de seuil initial (approximativement au centre de l'œil)

f) Activer la fonction de déclenchement du détecteur d'erreurs et le régler pour qu'il se déclenche pour un minimum de 10, 100 ou 1 000 erreurs.

g) Ajuster la tension du seuil de décision du détecteur d'erreurs dans un sens positif jusqu'à ce que le BER mesuré augmente jusqu'à une valeur supérieure à 1×10^{-10}. Noter la tension du seuil de décision (V_{b1}) et le BER.

h) Augmenter la tension du seuil de décision jusqu'à ce que le BER soit supérieur à 10^{-5} et noter la tension du seuil de décision (V_{a1}) et le BER.

i) Noter la différence entre les deux valeurs de seuil V_{a1} et V_{b1} et choisir une taille de pas (V_{step1}) qui donne un nombre raisonnable (supérieur à 5) de points de mesure entre ces deux valeurs extrêmes de seuil de décision. En partant de la valeur de seuil V_{a1}, réduire la valeur de seuil de la taille du pas, V_{step1}. A chaque pas, effectuer une mesure de déclenchement sur le détecteur d'erreurs. Enregistrer la valeur de BER mesurée et la tension du seuil de décision correspondante.