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Fibre optic communication subsystem test procedures – Digital systems

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

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES – DIGITAL SYSTEMS –

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

FOREWORD

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

The text of this standard is based on the following documents:

FDIS	Report on voting
86C/485/FDIS	86C/505/RVD

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

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

The committee has decided that the contents of this publication will remain unchanged until 2010. At this date, the publication will be

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- withdrawn;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

FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES – DIGITAL SYSTEMS –

Part 2-8: 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 4) and the variable optical threshold method (Clause 5). In addition, a third method, the sinusoidal interference method, is described in Annex B.

2 Definitions and abbreviated terms

2.1 Definitions

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

2.1.1
amplified spontaneous emission
ASE
impairment generated in optical amplifiers

2.1.2
bit error ratio
BER
the number bits in error as a ratio of the total number of bits

2.1.3
intersymbol interference
ISI
mutual interference between symbols in a data stream, usually caused by non-linear effects and bandwidth limitations of the transmission path

2.1.4
Q-factor
Q
ratio of the difference between the mean voltage of the 1 and 0 rails, and the sum of their standard deviation values

2.2 Abbreviations

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

3 Measurement of low bit-error ratios

3.1 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

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 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 4) and the variable optical threshold method (Clause 5). 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 standard 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

3.2 Background to Q-factor

The Q-factor is the signal-to-noise ratio (SNR) at the decision circuit and is typically expressed as [3][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, and 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 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 [4]. 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.

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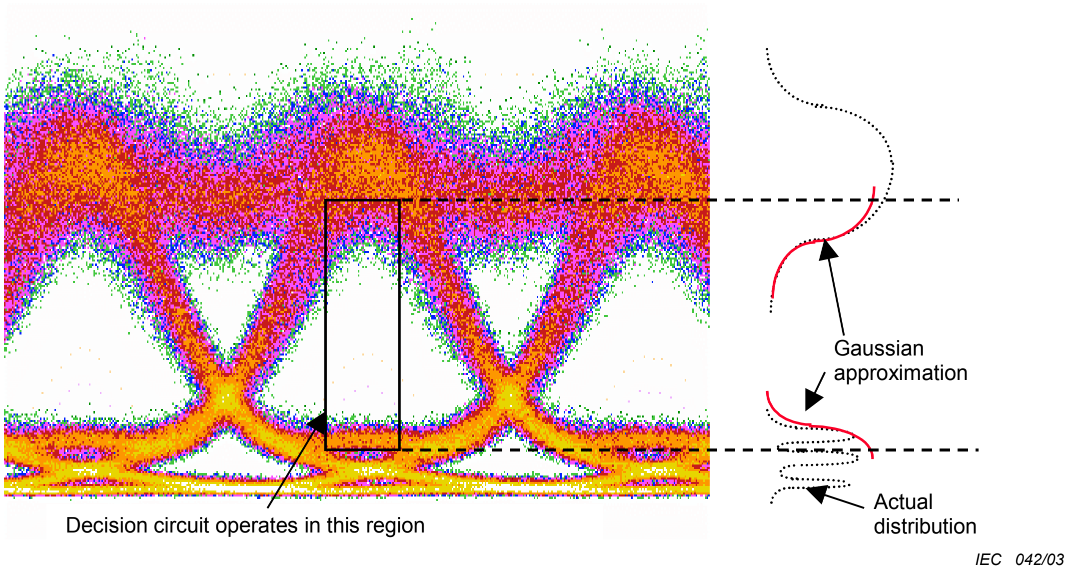
[1] Figures in square brackets refer to the bibliography.

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 is obtained from the tail of the Gaussian distributions.

Figure 1 – A 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.

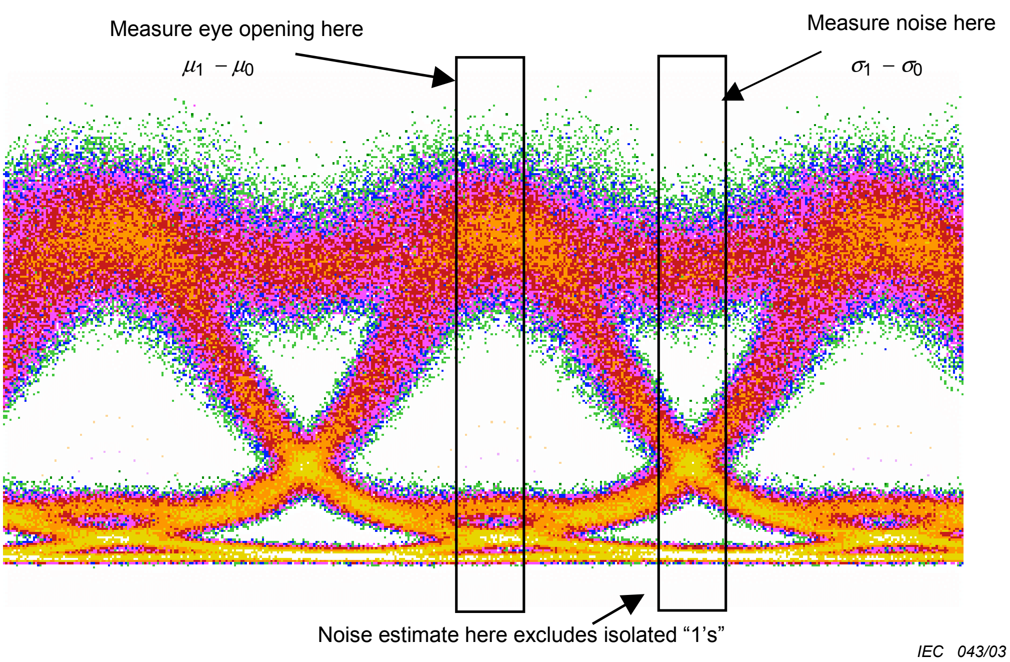


Figure 2 – A more accurate measurement technique using a DSO that samples the noise statistics between the eye centres

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.

4 Variable decision threshold method

4.1 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:

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

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

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

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

The BER, given in equation 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). Equation 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 equation 2. To make the conversion, the approximation is made that the BER is dominated by only one of the terms in equation 2 according to whether the threshold is closer to the “1's” or the “0's” rail of the eye diagram.

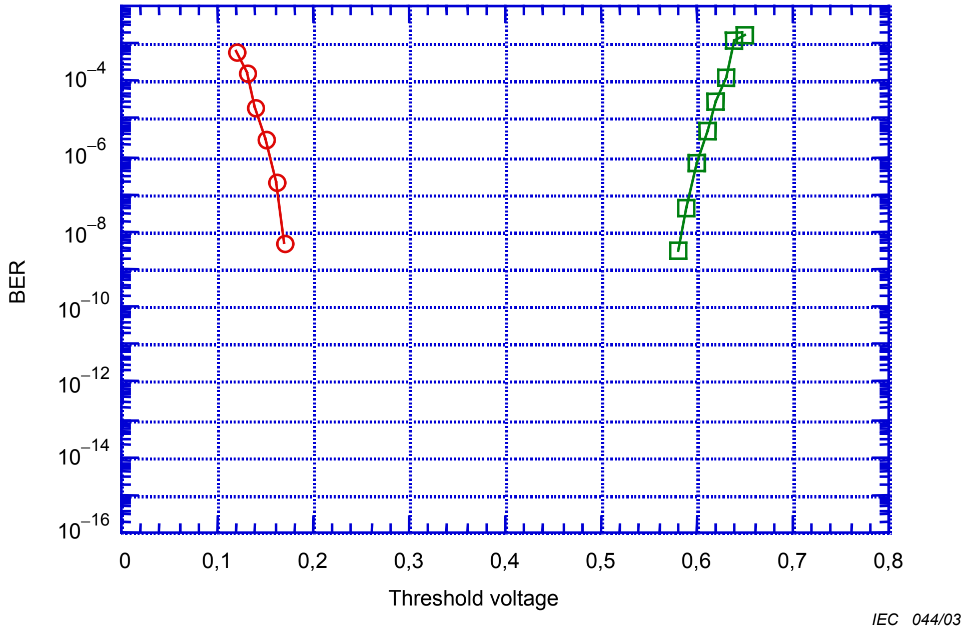


Figure 3 – Bit error ratio as a function of decision threshold level

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 is obtained from the intersection of the two best-fit lines through the data. This technique is described in detail in [2].

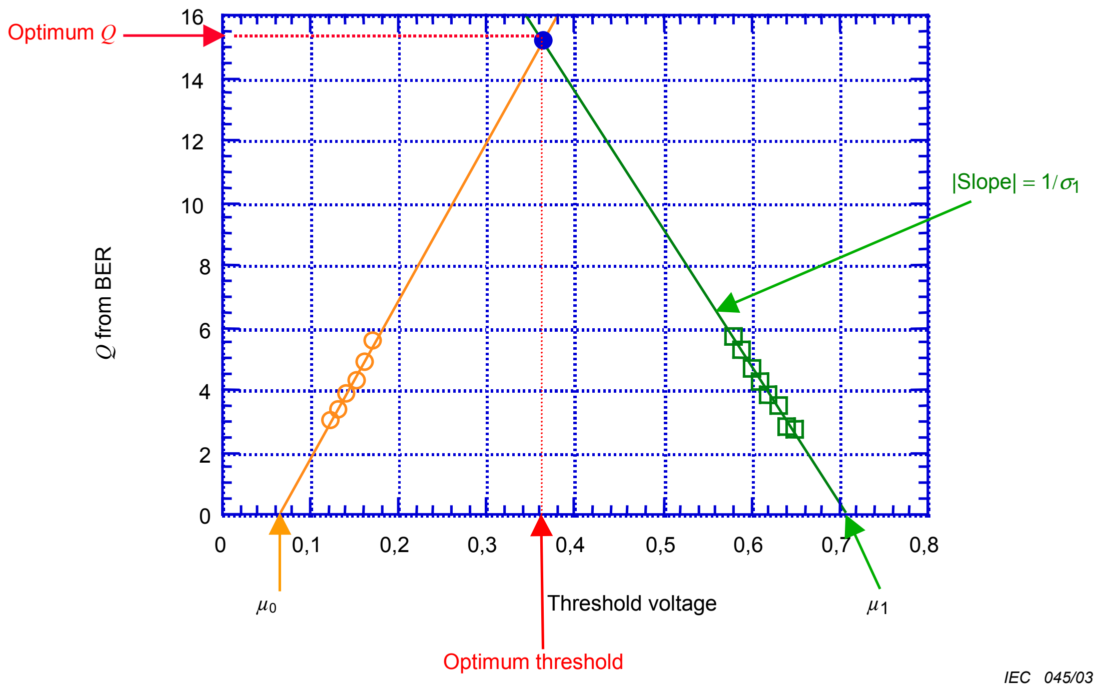


Figure 4 – Plot of Q-factor as a function of threshold voltage

The optimum threshold as well as the optimal Q can be obtained analytically by making use of the following approximation [1] for the inverse error function:

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

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}.

After evaluating the inverse error function, the data is 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, $V_{\text{th-optimal}}$, when the two terms in the argument in equation 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 equation (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 equation 1. The residual BER at the optimal threshold can be obtained from equation 2 and is approximately

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

NOTE 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 [4]. 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 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.

4.2 Apparatus

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

4.3 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).

4.4 Procedure

Data for the "Q" measurement is 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 1s and 0s are determined by fitting this data to a Gaussian characteristic.

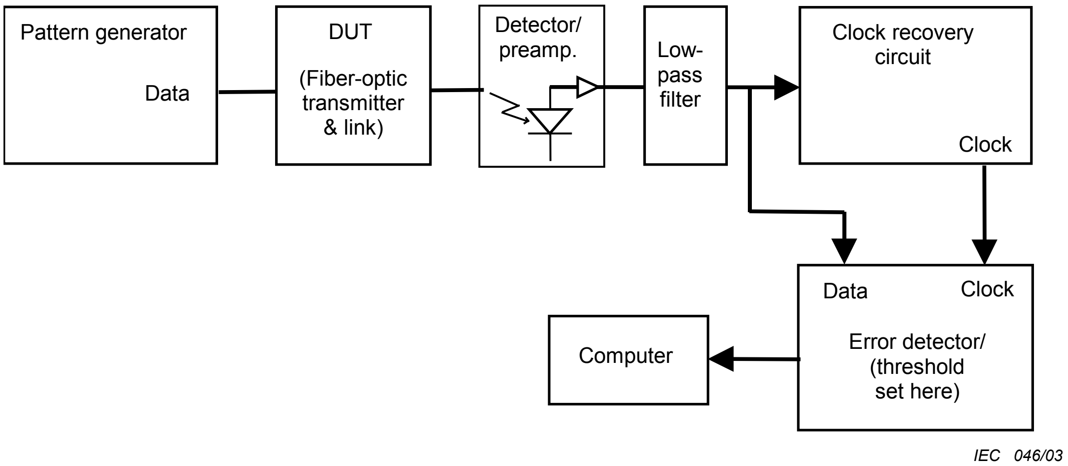


Figure 5 – Set-up for the variable decision threshold method

The Q-factor is then calculated using equation 1.

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

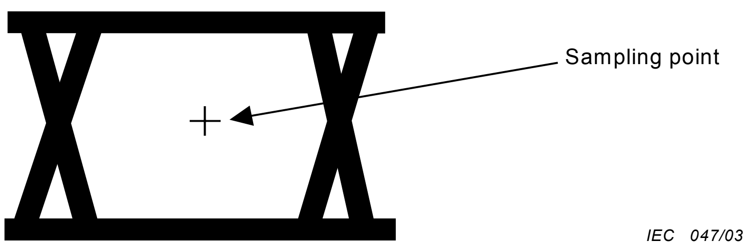


Figure 6 – Set-up of initial threshold level (approximately at the centre of the eye)

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 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) 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 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.

4.5 Calculations and interpretation of results

4.5.1 Sets of data

The procedure in 4.7 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

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

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

Table 2 – BER as 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		

4.5.2 Convert BER using inverse error function

Each BER value is then converted through an inverse error function, using the following approximation given in equation 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 $x_i = \log_{10} (\mathrm{BER}_i)$.

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

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

that should approximately fit a straight line.

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

Table 3 – f_i as a function of D_i

"1" rail		"0" rail	
D_i (volts)	f_i	D_i (volts)	f_i
–1,75	3,7578	–4,37	3,6360
–1,80	3,9638	–4,34	3,9847
–1,85	4,1956	–4,31	4,2706
–1,90	4,4043	–4,28	4,6052
–1,95	4,6257	–4,25	4,9293
–2,00	4,9449	–4,22	5,2757
–2,05	5,1629	–4,19	5,6823
–2,10	5,3799	– 4,16	6,0975
–2,15	5,6858		
–2,20	5,8390		

4.5.3 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 = $erf_c(BER)$ (inverse error function of BER),

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 [6]:

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

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

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:

Table 4 – Values of linear regression constants

"1" rail			"0" rail		
A	**B**	**R**	**A**	**B**	**R**
–4,6125	–4,7638	0,9989	53,989	11,5307	0,9984

4.5.4 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:

Table 5 – Mean and standard deviation

"1" rail		"0" rail	
μ1	**σ1**	**μ0**	**σ0**
–0,9682	0,2099	–4,6822	0,0867249

4.5.5 Optimum decision threshold

$$Q_{\text{opt}} = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0}$$

And thus the optimum decision threshold = $\dfrac{\sigma_0\mu_1 + \sigma_1\mu_0}{\sigma_1 + \sigma_0}$

For the example given earlier, using the value derived for Q_{opt} of 12.52, the optimal decision threshold is –3,596 volts.

4.5.6 BER optimum decision threshold

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

$$\text{BER} = \frac{e^{-\left(\frac{Q^2}{2}\right)}}{Q_{\text{opt}}\sqrt{2\pi}}$$

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}.

4.5.7 BER non-optimum decision threshold

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

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

4.5.8 Error bound

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

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

4.6 Test documentation

Report the following information for each test.

a) Test date
b) This document number
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 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

4.7 Specification information

The following details shall be specified.

a) IEC document number
b) Any special test requirements
c) Failure or acceptance criteria

5 Variable optical threshold method

5.1 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 d.c.-coupled receivers only. The effect of adding a pre-set bias is shown in Figure 7.

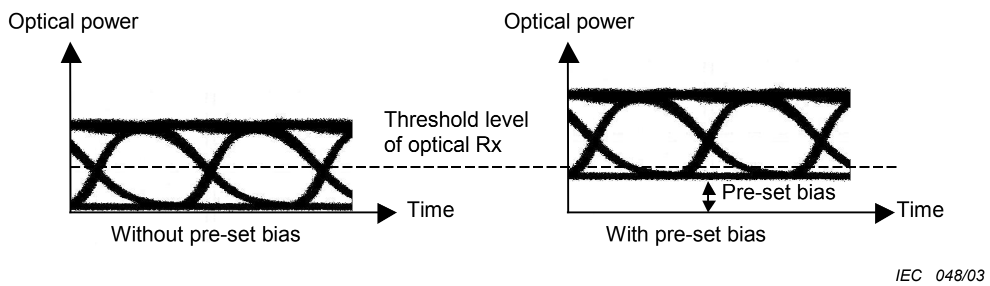


Figure 7 – Effect of optical bias

The method can be used to evaluate the error performance of an optical link or active device as shown in Figure 1. Alternatively, the error performance of a complete system can be evaluated using the set-up shown in Figure 2. 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.

5.2 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 0,1dB 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.

5.3 Items under test

The item under test may be a digital fibre optic system consisting of a digital transmitter and a d.c. 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.

5.4 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.

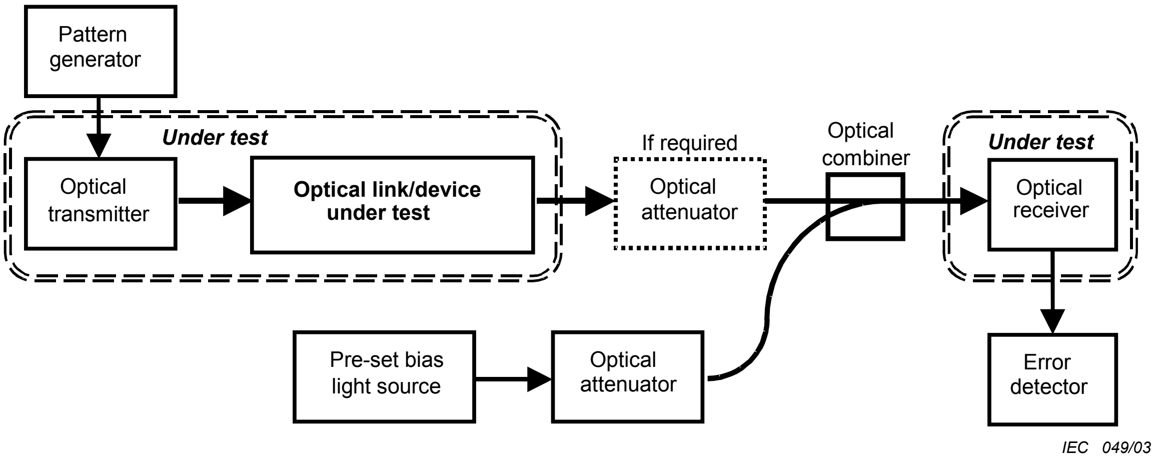


Figure 8 – Set-up for optical link or device test

5.5 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.

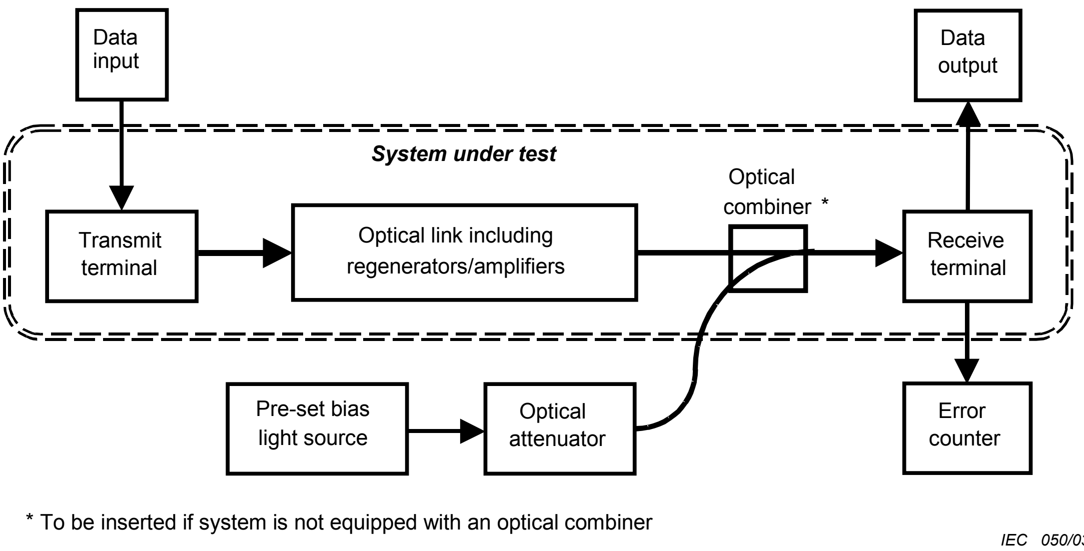


Figure 9 – Set-up for system test

5.6 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:

$$Y = A + BX,$$

where

Y 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	BER	Log BER
6,00 µW	$1,0 \times 10^{-4}$	–4,00
5,75 µW	$2,7 \times 10^{-5}$	–4,57
5,50 µW	$7,0 \times 10^{-6}$	–5,15
5,25 µW	$1,4 \times 10^{-6}$	–5,85
5,00 µW	$3,0 \times 10^{-7}$	–6,52
4,75 µW	$5,0 \times 10^{-8}$	–7,30
4,50 µW	$1,0 \times 10^{-8}$	–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, 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 the basic value of BER can be determined by extrapolation as shown in Figure 9.

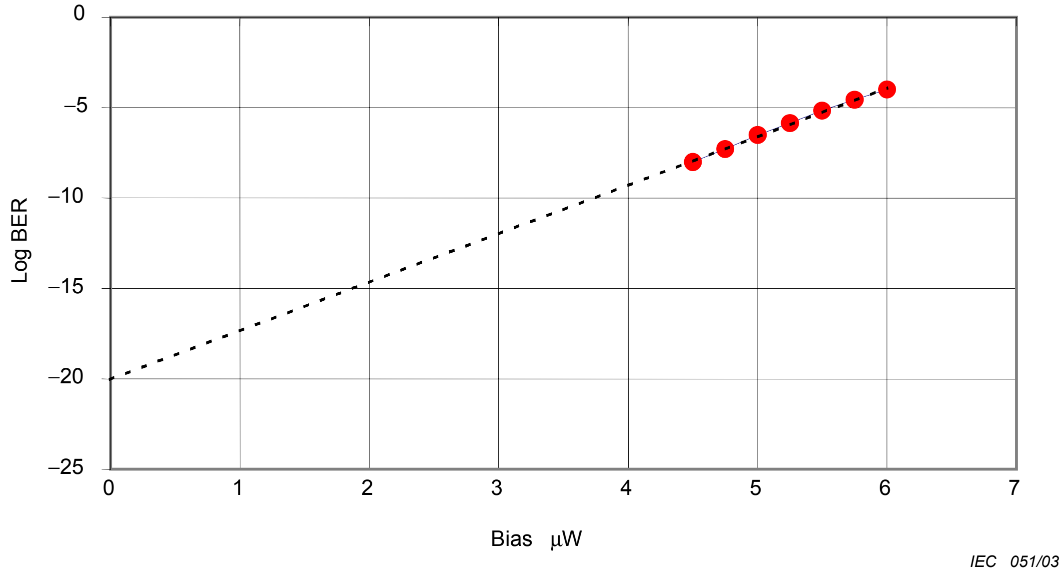


Figure 10 – Extrapolation of log BER as function of bias

For the results given in Table 6, the BER value, as shown by the extrapolation in Figure 9, 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” rail as follows:

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

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

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

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

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

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

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. Equation A.5 gives the absolute maximum spread in the value of Q.

These variances are given in [7] to be:

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

where N is the number of data points

$$\Delta = N \sum X^2 - \left(\sum X\right)^2 \text{ and}$$
$$S^2 = \frac{1}{N-2} \sum \left(Y - A - BX\right)^2$$

Annex B
(informative)

Sinusoidal interference method

B.1 Introduction

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 a.c.-coupled receiver, while the electrical method is applicable to an a.c.- or d.c.-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 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.

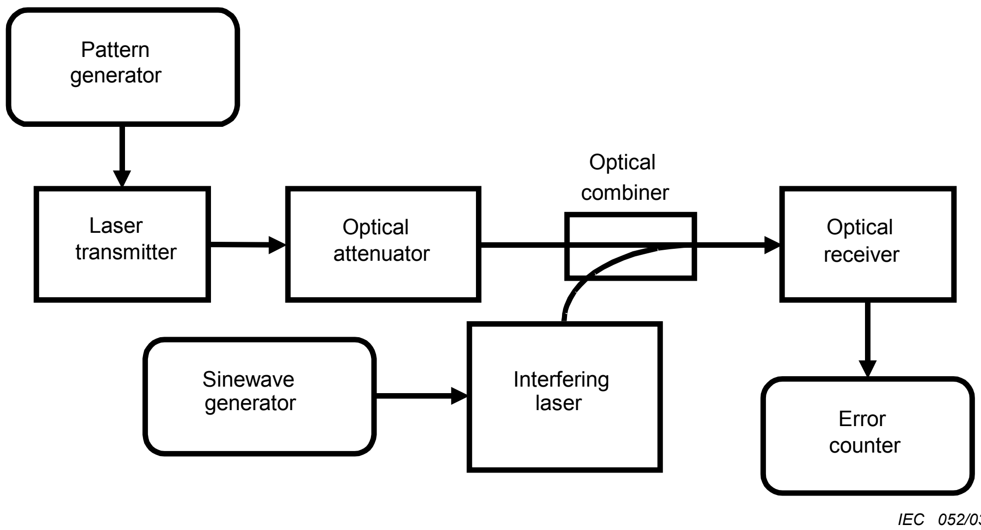


Figure B.1 – Set-up for the sinusoidal interference method by optical injection

The following 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, 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 of this document.

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.

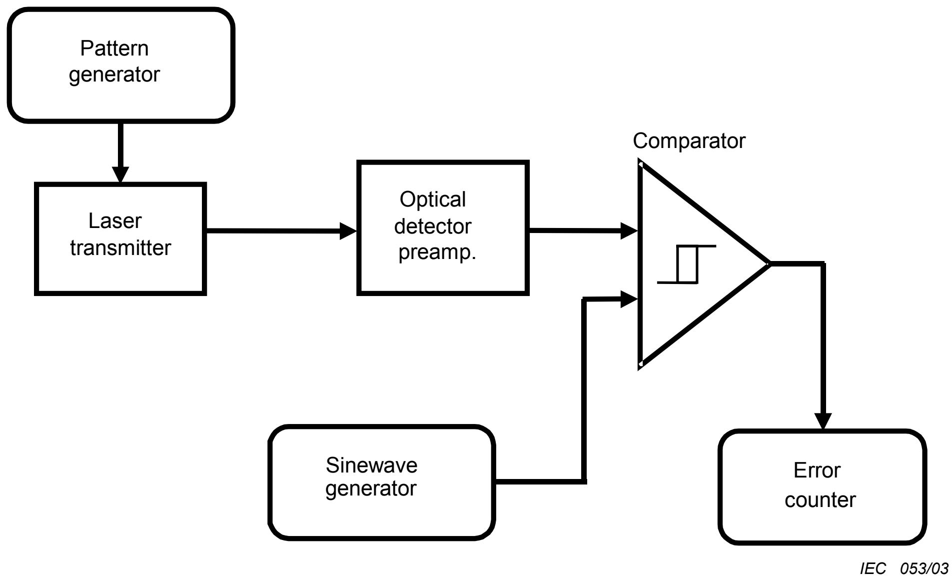


Figure B.2 – Set-up for the sinusoidal interference method by electrical injection

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$_i)$. Transform the BER values using the function:

$$\Psi(BER_i) = \frac{-c_2 + \sqrt{c_2^2 - 4c_1(c_3 + x_i)}}{2c_1}$$

where

$x_i = \ln(2 * \mathrm{BER}_i)$

c_1 = 0,4926, c_2 = 0,2948, c_3 = 0,7921

B.5.2 Extrapolation

Fit a straight line to the values $\Psi(\mathrm{BER}_i)$ versus A_i. Extrapolate it to the ordinate where $A_0 = 0$, giving the value $\Psi(BER_0) = Q$. (The curve is not a very good fit for BER values greater than 10^{-4} because of the *erfc* approximation used in the equation. Therefore, data with BER values higher than 10^{-4} should not be used.)

Calculate the system BER as

$$BER = \tfrac{1}{2}\, erfc\left(\frac{Q}{\sqrt{2}}\right) \cong \frac{1}{Q}\, e^{-Q^2/2} \bullet \frac{1 - Q^{-2} + 3Q^{-4}}{\sqrt{2\pi}}$$

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

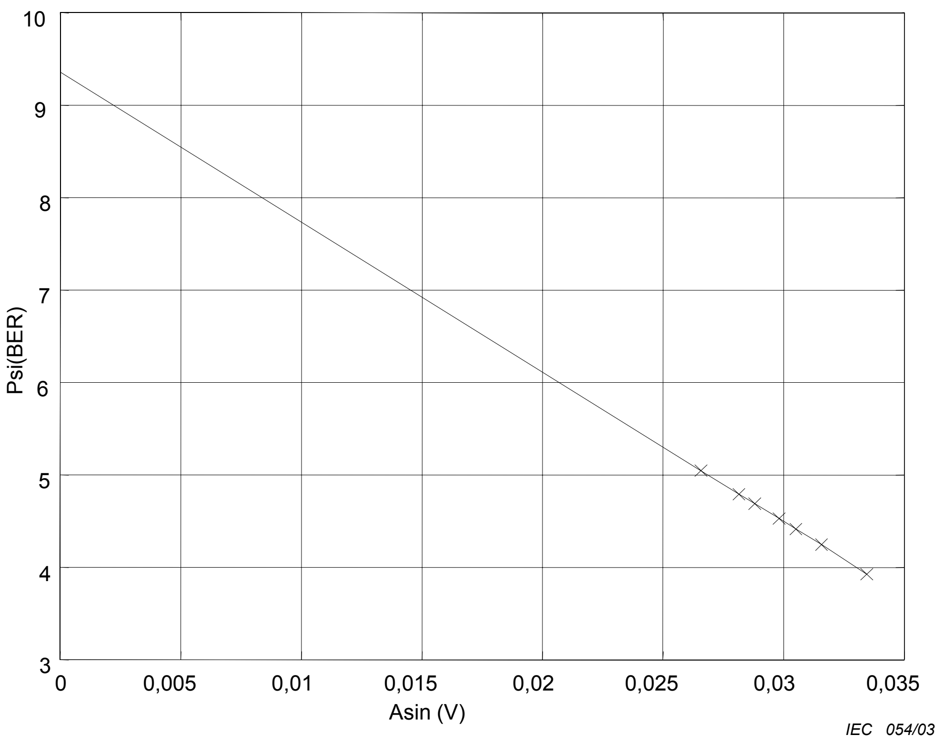


Figure B.3 – BER Result from the sinusoidal interference method (data points and extrapolated line)

B.5.3 Expected results

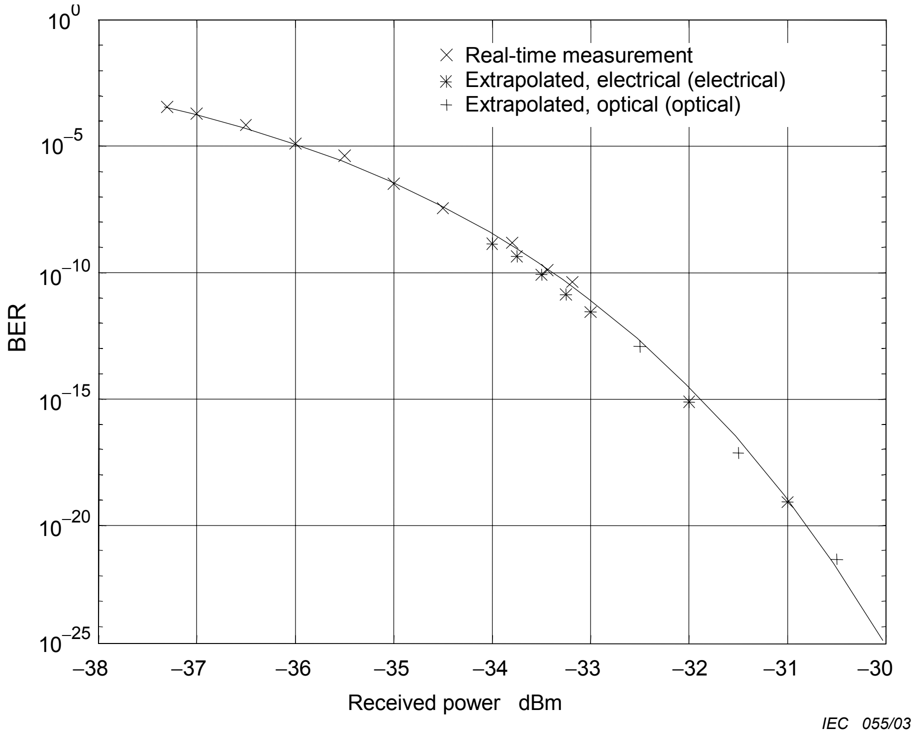


Figure B.4 – BER versus optical power for three methods

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.

B.6 Documentation

The following information shall be reported with each test.

a) Date of test
b) This document number
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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