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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**



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INTERNATIONAL
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INTERNATIONALE

ICS 33.180.10

ISBN 978-2-8322-9497-0

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FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES –**Part 2-8: Digital systems –
Determination of low BER using Q-factor measurements**

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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 μ s	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 μ 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
10 Gbit/s	15 μ s	150 μ s	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 μ s	38 μ s	380 μ s	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 μ s	15 μ s	150 μ s	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.

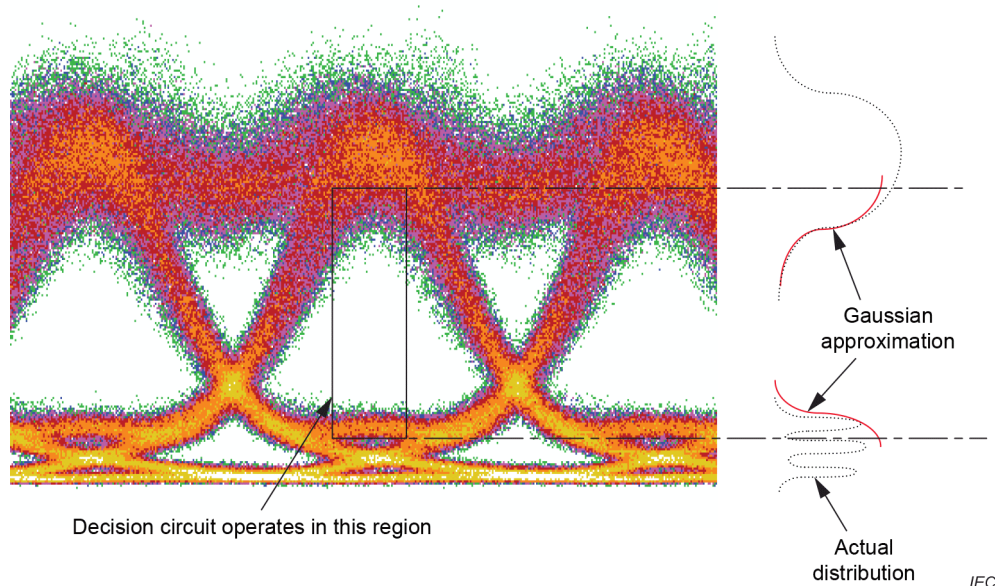
An accurate estimation of a system's transmission performance, or Q-factor, shall take into consideration the effects of all sources of performance degradation, both fundamental and those due to real-world imperfections. Two important sources are amplified spontaneous emission (ASE) noise and intersymbol interference (ISI). Additive noise originates primarily from ASE of optical amplifiers. ISI arises from many effects, such as chromatic dispersion, fibre nonlinearities, 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.

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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.

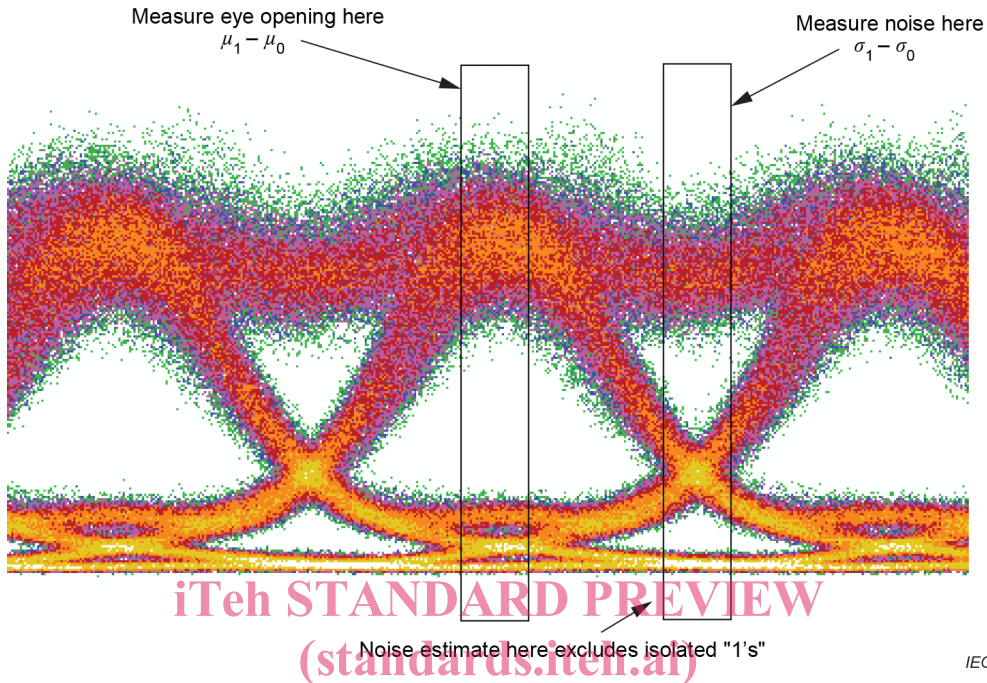


Figure 2 – More accurate measurement technique using a DSO that samples noise statistics between eye centres

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;

$\text{erfc}(\cdot)$ is the complementary error function given by

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

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.

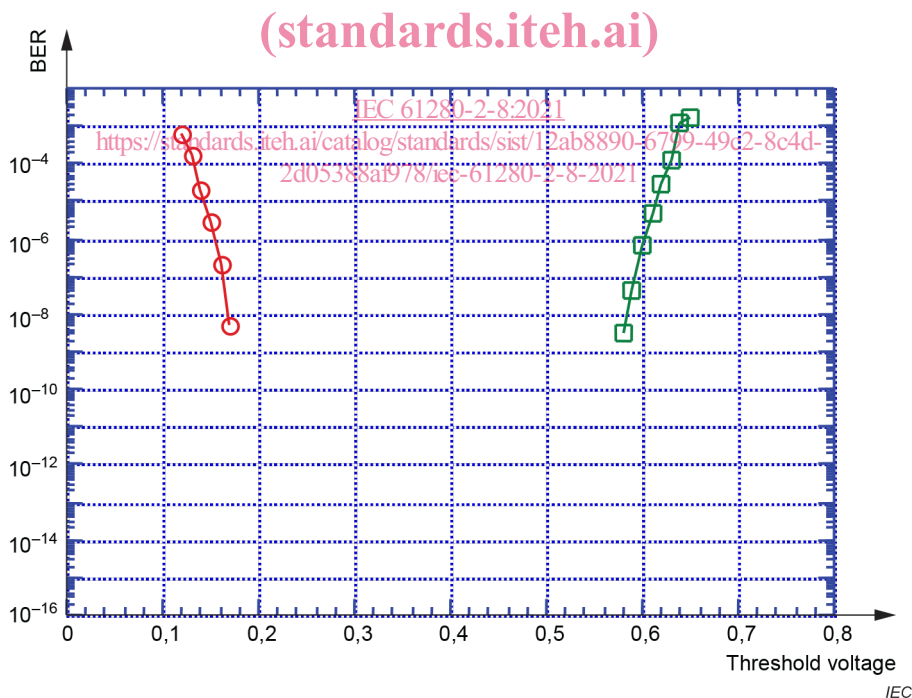


Figure 3 – Bit error ratio as a function of decision threshold level

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].

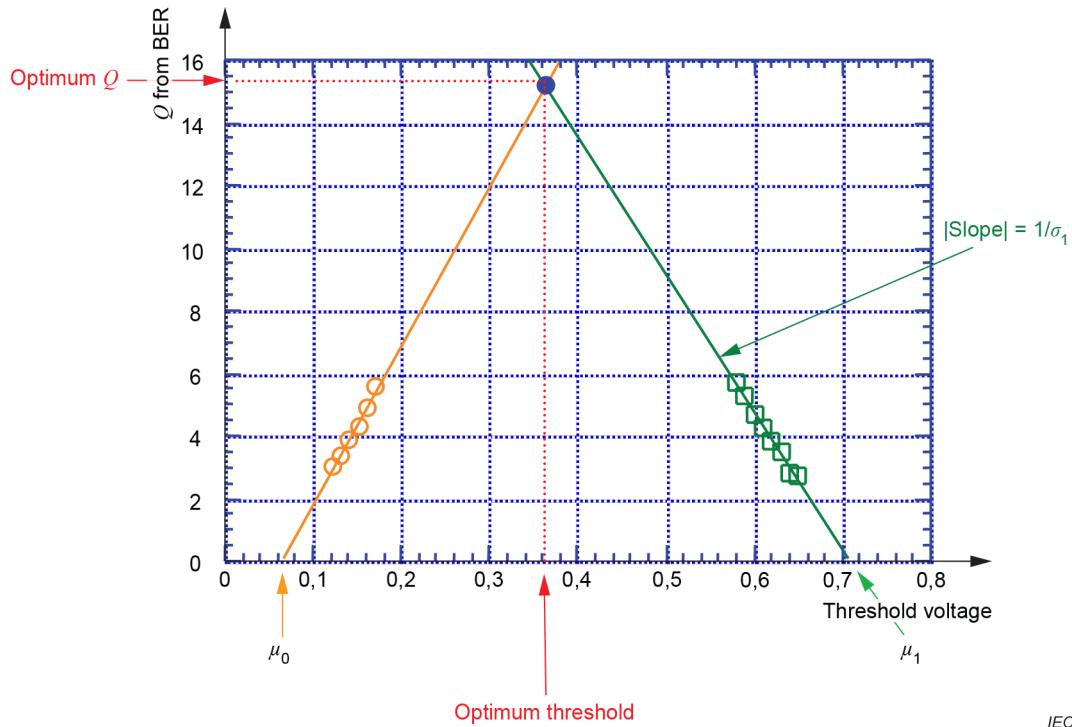


Figure 4 – Plot of Q-factor as a function of threshold voltage

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:

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

where

x is $\log(P_e)$.

NOTE 1 Formula (4) is accurate to $\pm 0,2\%$ 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, $V_{th-optimal}$, when the two terms in the argument in Formula (2) are equal, that is

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

An explicit expression for $V_{th-optimal}$ 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

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

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. 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.