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INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

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

Procédures d'essai des sous-systèmes de télécommunication à fibres optiques – Systèmes numériques –
Partie 2-8: Détermination de faible Taux d'Erreur Binaire (TEB) en utilisant des mesures du facteur Q

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FOREWORD

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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.

The French version of this standard has not been voted upon.

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- withdrawn;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.

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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.

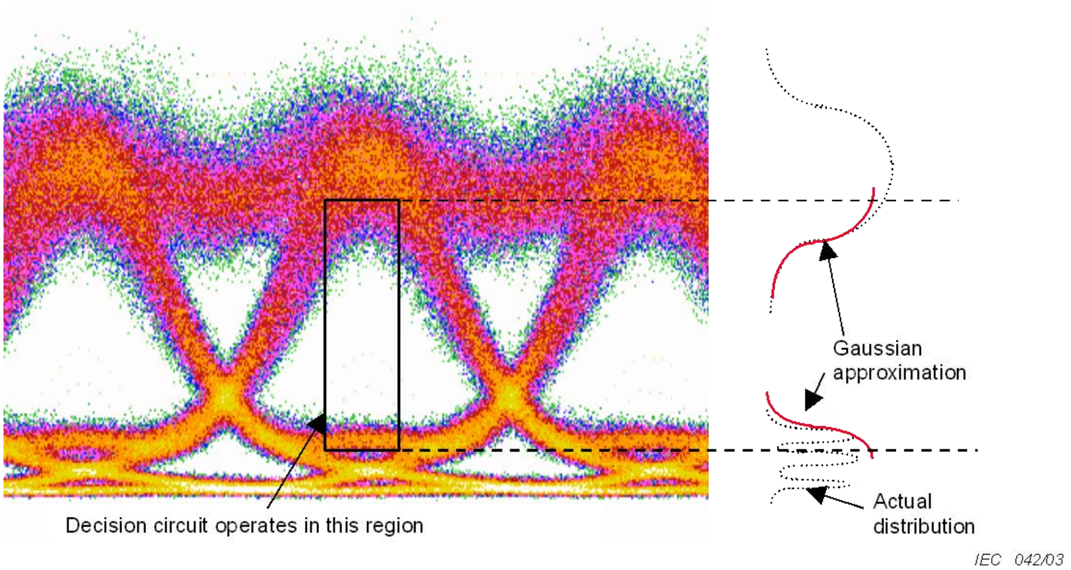
An accurate estimation of a system’s transmission performance, or Q-factor, must take into consideration the effects of all sources of performance degradation, both fundamental and those due to real-world imperfections. Two important sources are amplified spontaneous emission (ASE) noise and intersymbol 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.

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.

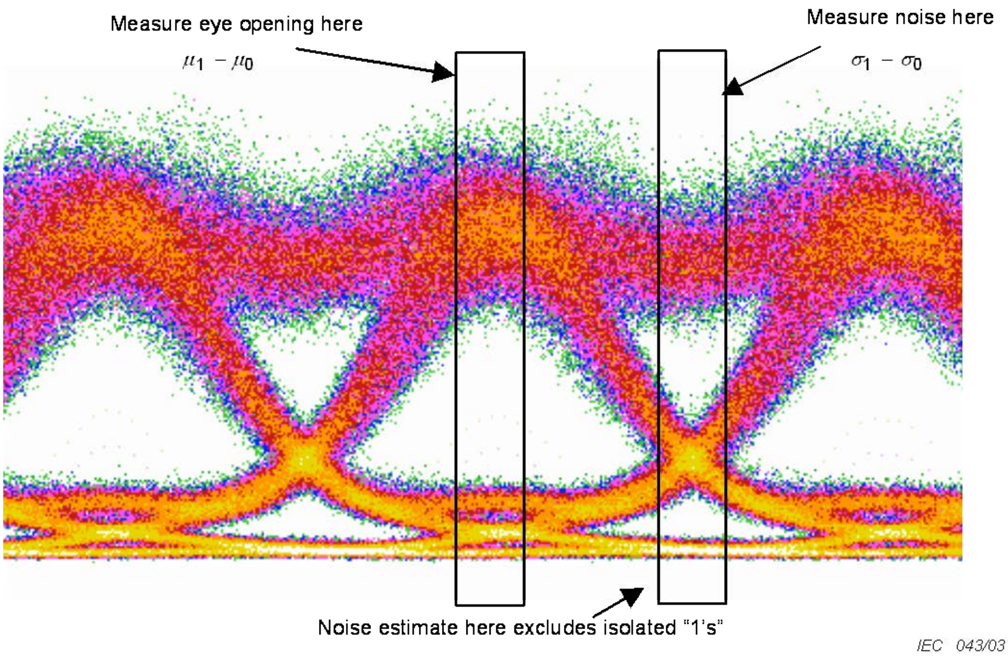


Figure 2 – A more accurate measurement technique using a DSO that samples the noise statistics between the eye centres

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:

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

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

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

(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.

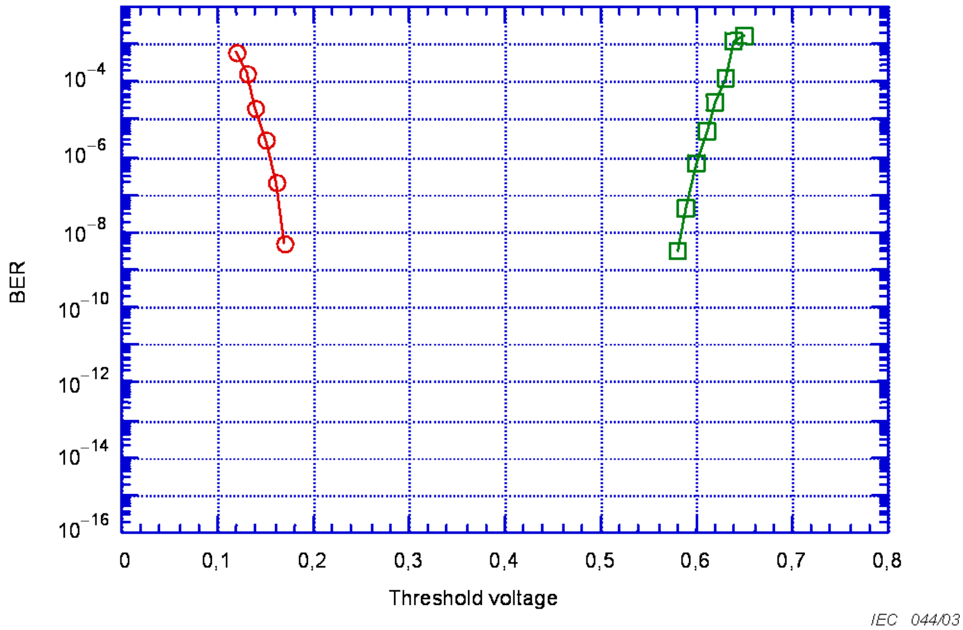


Figure 3 – Bit error ratio as a function of decision threshold level

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].

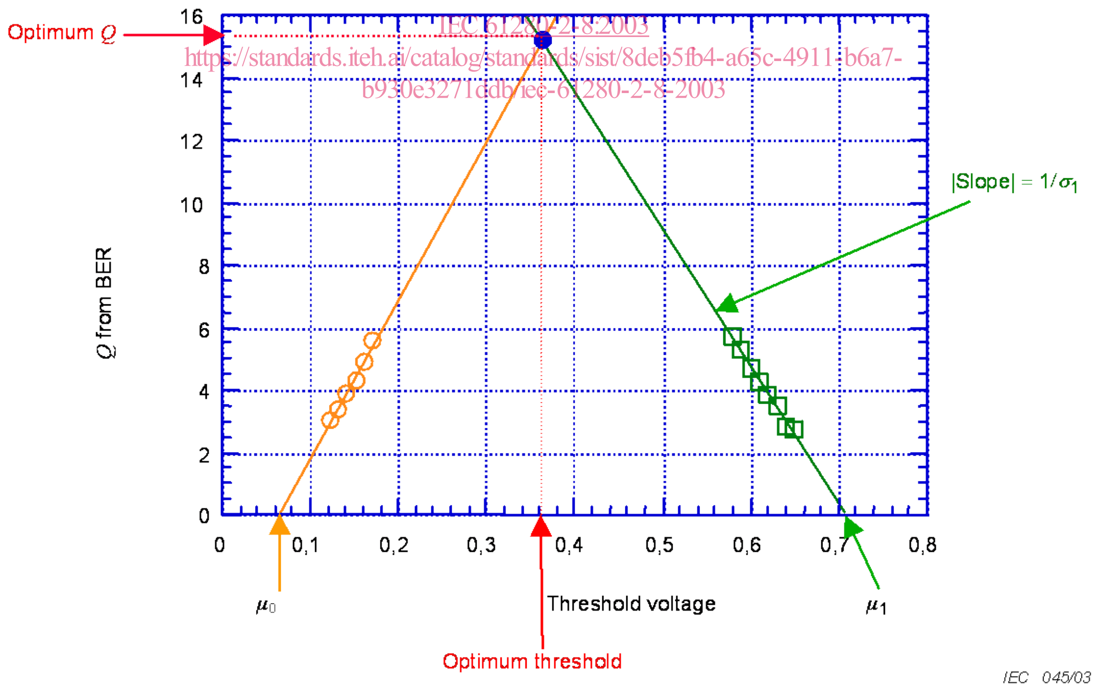


Figure 4 – Plot of Q-factor as a function of threshold voltage

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:

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

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}.

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

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

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:

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

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

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

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.

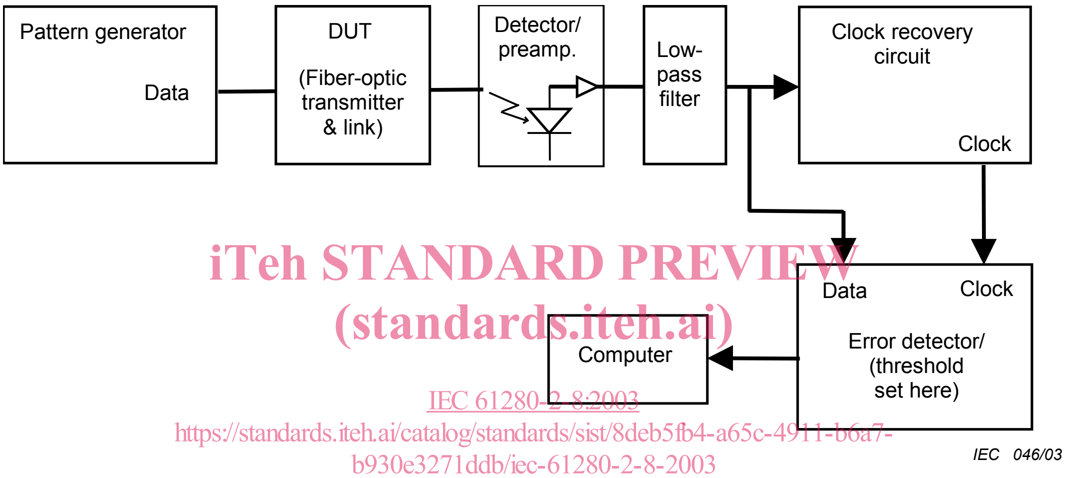


Figure 5 – Set-up for the variable decision threshold method

The Q-factor is then calculated using equation 1.

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

Set the clock source to the desired frequency.

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

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

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.

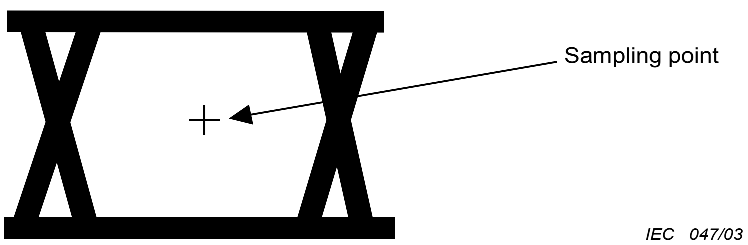


Figure 6 – Set-up of initial threshold level (approximately at the centre of the eye)

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