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SERIES O: SPECIFICATIONS OF MEASURING EQUIPMENT

Equipment for the measurement of optical channel parameters

Q-factor test equipment to estimate the transmission performance of optical channels

ITU-T Recommendation O.201

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SPECIFICATIONS OF MEASURING EQUIPMENT

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ITU-T Recommendation O.201

Q-factor test equipment to estimate the transmission performance of optical channels

Summary

This Recommendation describes the requirements of Q-factor measurement equipment (QFME) currently based on the level shifting method used for estimating the digital transmission performance of an optical channel.

Source

ITU-T Recommendation O.201 was approved by ITU-T Study Group 4 (2001-2004) under the ITU-T Recommendation A.8 procedure on 22 July 2003.

Keywords

BER, Bit Error Ratio, decision threshold, Optical Transport Network, Q-factor, Q-factor Measurement Equipment, Signal-to-Noise Ratio.

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Q-factor test equipment to estimate the transmission performance of optical channels

1 Scope

Q-factor measurement is an established method for characterization of optical channels (see e.g., ITU-T Recs G.972 [7] and G.976 [8]). Particularly at low bit error rates the method has the advantage of taking less time than a traditional BER measurement, where bit errors need to be counted over a statistically significant time period.

The Q-factor is defined as the (electrical) signal-to-noise ratio at the decision circuit of a digital signal receiver (see Annex A, Appendix I and [B1]).

There are various methods of implementing Q-factor measurements, which can be mathematically related to the bit error ratio (see also the methods referred to in ITU-T Recs G.972 [7] and G.976 [8] for submarine systems). This Recommendation deals with the level shifting method and applies to QFME using it.

The objectives of this Recommendation with regard to Q-factor measuring equipment (QFME) are:

- **Compatibility between measurement equipment produced by different manufacturers:**

  Optical channel transmission performance measurements made by QFME compliant to this Recommendation shall provide results to within the specified accuracy limits defined in this Recommendation.

- **Estimate of the actual system performance:**

  The objective of an estimate by QFME of the bit error ratio (BER) achievable over a given optical channel is to provide the minimum BER that can be achieved with an optimally designed piece of network equipment.

This Recommendation does not intend to define the particular applications of the Q-factor measurement method. Some possible fields of applications are described in the appendices of this Recommendation.

While requirements are given for the QFME, the realization of the equipment configuration is not covered and should be given careful consideration by the designer and user.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[1] ITU-T Recommendation G.691 (2000), *Optical interfaces for single channel STM-64, STM-256 and other SDH systems with optical amplifiers*.

[2] ITU-T Recommendation G.707/Y.1322 (2000), *Network node interface for the synchronous digital hierarchy (SDH)*.

[3] ITU-T Recommendation G.709/Y.1331 (2001), *Interfaces for the Optical Transport Network (OTN)*.

[4] ITU-T Recommendation G.825 (2000), *The control of jitter and wander within digital networks which are based on the synchronous digital hierarchy (SDH)*.

[5] ITU-T Recommendation G.8251 (2001), *The control of jitter and wander within the optical transport network (OTN)*.

[6] ITU-T Recommendation G.957 (1999), *Optical interfaces for equipment and systems relating to the synchronous digital hierarchy*.

[7] ITU-T Recommendation G.972 (2000), *Definition of terms relevant to optical fibre submarine cable systems*.

[8] ITU-T Recommendation G.976 (2000), *Test methods applicable to optical fibre submarine cable systems*.

[9] ITU-T Recommendation O.3 (1992), *Climatic conditions and relevant tests for measuring equipment*.

[10] ITU-T Recommendation O.181 (2002), *Equipment to assess error performance on STM-N interfaces*.

[11] IEC 61300-3-29, *Measurement techniques for characterising the amplitude of the spectral transfer functions of DWDM components*.

3 Definitions

This Recommendation defines the following term:

3.1 Q-factor: Electrical Signal-to-Noise Ratio (ESNR) at the input of a receiver's decision circuit (see Annex A and Appendix I).

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations:

AGC	Automatic Gain Control
APD	Avalanche Photo Diode
BER	Bit Error Ratio
BERT	Bit Error Ratio Tester
DFB	Distributed Feed-Back
DWDM	Dense Wavelength Division Multiplex
EDFA	Erbium Doped Fibre Amplifier
ER	Extinction Ratio
ESNR	Electrical Signal-to-Noise Ratio
FEC	Forward Error Correction
IEC	International Electrotechnical Commission
ISI	Inter-Symbol Interference
ISO	International Organization for Standardization
OADM	Optical Add-Drop Multiplexer

OCh	Optical Channel
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal-to-Noise Ratio
OTM	Optical Termination Multiplexer
OTN	Optical Transport Network
OTUk	Optical Transport Unit-k
OXC	Optical Cross Connect
QFME	Q-factor Measurement Equipment
PRBS	Pseudo-Random Binary Sequence
RX	Receiver
SNR	Signal-to-Noise Ratio
SPM	Self Phase Modulation
STM-N	Synchronous Transport Module-N
TIA	Telecommunications Industry Association
WDM	Wavelength Division Multiplex

5 Introduction to Q-factor

In Annex A and Appendix I, the theory of the Q-factor evaluation is described. Under ideal conditions, it is assumed that the Q-factor is given by the logic levels μ_0 and μ_1 and Gaussian noise distributions around the logic levels, which are described by the standard deviations σ_0 and σ_1. The overlap region of the distribution tails represents the probability for the occurrence of errored decisions. In Appendix IV, some methods for the measurement of the noise distributions and the determination of the Q-factor are described.

In practice, there are a number of influences causing distortions with the effect that the shape of distributions no longer is Gaussian (see list of influences in Appendix III). However, it can be shown, that these distortions mainly affect the top regions of the distribution, while the tails can still be very accurately approximated by Gaussian distribution.

The applicability of a Gaussian tail approximation shall be confirmed by calculating the correlation coefficient according to Annex A. For every Q-factor measurement that is required to meet the accuracy limits of clause 6, the correlation coefficient shall be in the range 0.95 to 1.0.

While the Gaussian fit is the basic proven method for "tail extrapolation" there may exist more sophisticated distribution models, which also meet the accuracy requirements defined in clause 6. Such models are for further study.

6 Requirements of Q-factor measurement equipment

6.1 Physical interfaces and bit rates

6.1.1 Interfacing to the transmission systems

The Q-factor measurement equipment shall be capable of operating at optical amplifier monitoring points in the case of in-service measurements and, additionally, as a replacement for the system receivers in the case of out-of-service measurements.

In the first case, care has to be taken that the signal at the monitoring point is properly dispersion compensated.

Further, in the case of DWDM systems, an optical channel filter is necessary to select the desired channel for the Q-factor measurement and, in addition, an optical amplification prior to being able to use the filter.

Some concern was raised that in-service measurements at optical monitoring points may not reflect the optical channel performance due to the implementation of various optimization devices, such as chromatic dispersion compensation or line equalization, in order to achieve appropriate end-to-end transmission performance. The applicability for these types of in-service measurements and which provisions have to be considered needs further study.

6.1.2 Bit rates and jitter tolerance

The QFME shall operate at one or more bit rates defined in ITU-T Rec. G.707/Y.1322 [2] for STM-N signals or in ITU-T Rec. G.709/Y.1331 (OTN) for OTUk signals.

The maximum tolerable jitter at the specified bit rates supported by the QFME shall conform to the appropriate ITU-T Recs G.825 [4] or G.8251 [5].

6.1.3 QFME receiver response

The overall amplitude versus frequency response of the receiver (RX), including the O/E converter and, if applicable, low pass filtering, automatic gain control (AGC) and decision or sampling circuitry, shall be chosen for overshoot-free and minimum inter-symbol interference (ISI) pulse response.

As a general design goal, the 4th order Bessel-Thompson low pass characteristics (or equivalent), according to the reference receiver definitions of ITU-T Recs G.957 [6] and G.691 [1] should be taken.

The nominal electrical noise bandwidth B_e of the RX shall be:

$$0.75 \times f_{clk}$$

with f_{clk} being the clock frequency expressed in Hertz (see 6.1.7 for the details of the bandwidth correction procedure).

Instead of defining a tolerance mask for the frequency response, it is preferable to use a pulse mask for appropriate characterization of the receiver pulse response. The definition and verification of the pulse mask is for further study.

Possible alternative methods for characterization of the receiver pulse response can be found in Appendix V.

6.1.4 Optical channel filter

If an optical channel filter is required for the Q-factor measurement it shall meet the following requirements. The optical 3 dB bandwidth B_{ch} shall be greater than $2 \times f_{clk}$ with a flat top having a –1 dB width of at least $1 \times f_{clk}$ (f_{clk} being the clock frequency expressed in Hertz).

The total inter-channel crosstalk attenuation measured according to IEC 61300-3-29 [11] shall be better than 20 dB.

6.1.5 Optical input level range

For multi bit rate instruments up to 10.7 Gbit/s, the optical input level range shall be at least –6 to –13 dBm for PIN diode receivers, and –9 to TBD dBm for APD receivers.

For "single" bit rate instruments covering 9.95 to 10.7 Gbit/s, the ranges shall be –6 to –13 dBm for PIN diode receivers, and –9 to TBD dBm for APD receivers, and –18 to –25 dBm for 2.5 Gbit/s APD receivers.

The optical input level range for the 40 Gbit/s range is for further study.

Non-linear effects should be minimized, as the Q-factor method requires linear operation.

6.1.6 Taking into account the receiver noise

In general, the receiver (RX) of the QFME and the system receiver will be different in terms of sensitivity and bandwidth resulting in differing performance prediction. It is possible to remove the influence of the QFME receiver from the Q-factor result by calculation and to arrive at the Q-factor of the optical signal alone.

Further, it is possible to estimate the error performance of this signal in combination with the system receiver, if the input power dependency of the receiver BER is known.

6.1.6.1 Receiver noise parameters

To facilitate system BER estimation from Q-factor results, the QFME shall display the intrinsic RX noise voltage at the actual optical input power and the actual operating bit rate. These noise voltages shall be displayed in normalized form representing intrinsic *Q* values:

$$Q_{i1} = \frac{\mu_1 - \mu_0}{\sigma_{i1}}; Q_{i0} = \frac{\mu_1 - \mu_0}{\sigma_{i0}}; Q_i = \frac{\mu_1 - \mu_0}{\sigma_{i1} + \sigma_{i0}} \tag{6-1}$$

The intrinsic *Q* values are calibrated with a back-to-back measurement using a reference transmitter as described in Figure 1, but with the following modifications:

The EDFA and one variable attenuator in the signal path are removed as well as the crosstalk source. As the modulation pattern a framed STM-N or OTUk signal or a pure PRBS-23 shall be used.

The extinction ratio of the signal is supposed to be infinite for the displayed intrinsic Q values. If the calibration of the QFME-RX is performed with a finite ER, the intrinsic Q values have to be multiplied by (ER + 1)/(ER – 1) prior to display.

6.1.6.2 Calculation of the signal *Q* values (optional)

According to Annex A, along with the evaluation of the *measured Q* the quantities μ_0, μ_1, σ_0 and σ_1 are available and the following quantities can be calculated:

$$Q_0 = \frac{\mu_1 - \mu_0}{\sigma_0}, \quad Q_1 = \frac{\mu_1 - \mu_0}{\sigma_1}$$

Knowing the receiver noise parameters (Equation 6-1), it is possible to compensate the intrinsic noise of the QFME, which is contained in σ_0 and σ_1 and to arrive at Q values of the signal *alone*.

$$\frac{1}{Q_{sig1}^2} = \frac{1}{Q_1^2} - \frac{k^2}{Q_{i1}^2}; \quad \frac{1}{Q_{sig0}^2} = \frac{1}{Q_0^2} - \frac{k_2}{Q_{i0}^2};$$

with $k = (ER + 1)/(ER - 1)$, ER = signal extinction ratio.

$$\frac{1}{Q_{sig}} = \frac{1}{Q_{sig0}} + \frac{1}{Q_{sig1}} \tag{6-2}$$

As the *ER* of the signal is unknown in many practical applications, it shall be possible to perform the noise compensation with $k = 1$, corresponding to infinite *ER* (yielding some under-compensation of noise in practical cases).

In any case, it shall be clearly indicated in the display of the Q-factor results, whether the intrinsic noise compensation is active; additionally, the *ER* taken into account shall be displayed if it is not infinite.

6.1.6.3 Estimation of the system *Q* values (optional)

Knowing the Q_{sig} of the signal at the receiver input, it is possible to estimate the overall Q-factor Q_{syst} including the properties of the (e.g., worst-case) system receiver. This can be supported by an optional function of the QFME, which uses the following procedures and equations:

First the system-RX is characterized by its own intrinsic Q-factor Q_{RX}, which is a function of the optical RX input power and can be derived from the known BER versus input power behaviour of the receiver. If the characterization of the RX was done with an ER_{char} different from the actual value, the Q_{RX} has to be modified according to:

$$Q_{RXactual} = \frac{ER_{char}+1}{ER_{char}-1} \times \frac{ER_{actual}-1}{ER_{actual}+1} \times Q_{RX}$$

If the system-RX has an electrical bandwidth B_{RX} different from the nominal value of B_e, the Q_{sig} results have to be corrected by the factor:

$$\sqrt{\frac{B_e}{B_{RX}}}$$

Using the Q_{sig0} and Q_{sig1} values from (Equation 6-2), the estimated system Q-factor is then given by:

$$\frac{1}{Q_{syst}} = \sqrt{\frac{B_{RX}/B_e}{Q_{sig0}^2} + \frac{1}{4Q_{RX}^2}} + \sqrt{\frac{B_{RX}/B_e}{Q_{sig1}^2} + \frac{1}{4Q_{RX}^2}} \qquad (6\text{-}3)$$

The corresponding estimated BER is calculated with Equation A-5.

6.1.7 Receiver calibration

The purpose of this calibration is to eliminate the influence of electrical bandwidth deviations from the nominal values defined in 6.1.3. The calibration is performed at the highest allowed optical input level to ensure that intrinsic receiver noise can be neglected.

The calibration is performed with a Q-factor of 7, corresponding to a BER of $\approx 10^{-12}$ and a framed STM-N or OTUk signal, or a pure PRBS-23, is taken as the modulation signal.

As B_e is different for different bit rates, the procedure shall be applied at every bit rate supported by the QFME.

The calibration set-up is shown in Figure 1.

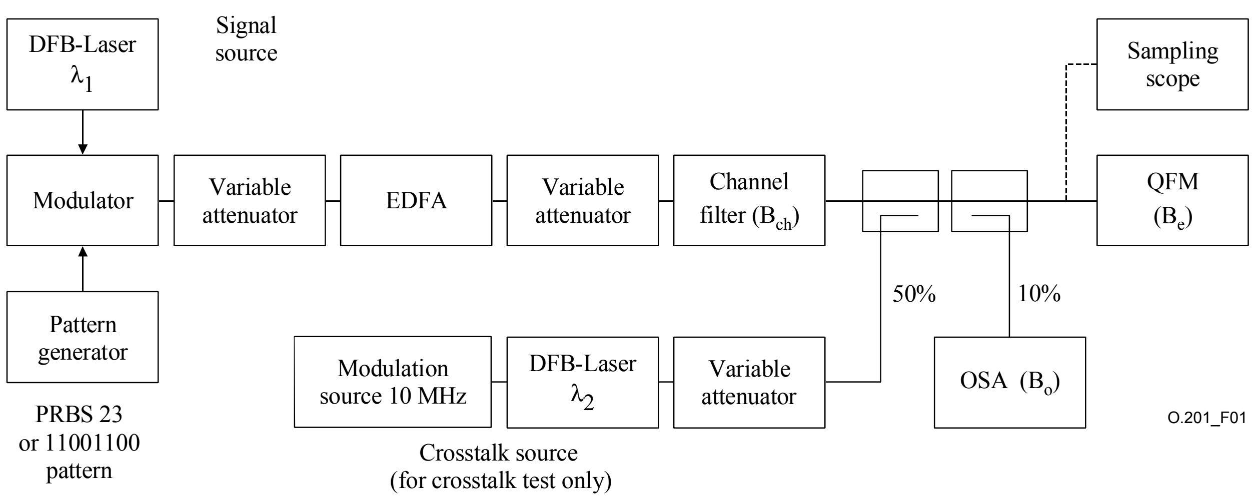


Figure 1/O.201 – Set-up for calibration and crosstalk test

The basic idea is to generate a digital optical transmission signal, which is only degraded by ASE noise. In this case, it is possible to predict the Q of the signal from the $OSNR$ (measured with an OSA) and from the extinction ratio ER (measured with a sampling scope).

Note that the calibration signal has to be visually free from ISI, overshoot or eye closure due to insufficient modulation bandwidth.

In the case that the receiver intrinsic noise can be neglected, the relation between Q, $OSNR$ and ER for NRZ signals is given by:

$$OSNR = \frac{(ER+1)}{(ER-1)^2} \times \left[Q^2 \times \left(\frac{B_e}{B_o} \right) \times (ER+1) + Q \times \sqrt{\frac{B_e \times (8ER \times Q^2 \times B_e + (ER-1)^2 \times (2B_{ch} - B_e))}{2B_0^2}} \right] \tag{6-4}$$

Assuming that $Q = 7$ and $B_e = 0.75\ f_{clk}$, the $OSNR$ is calculated with Equation 6-4.

The calibration signal is adjusted to this $OSNR$ value and measured with the QFME (Q-factor result = $Q_{measured}$).

Now the correction factor:

$$CF = \frac{7}{Q_{measured}}$$

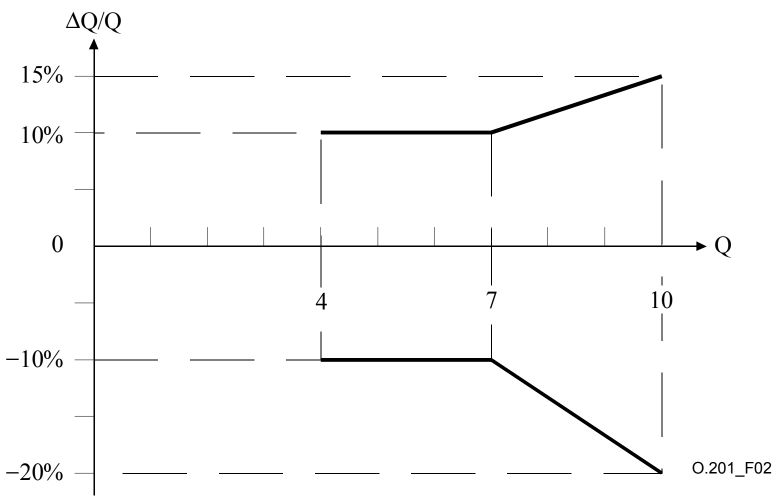
is calculated and all future Q results of the QFME are multiplied with it.

Note that a modification of Equation 6-4 is required in the case of RZ signals.

6.2 Accuracy requirements and acceptance tests

6.2.1 Accuracy

Any QFME according to this Recommendation, irrespective of the measurement technique employed by it, shall be accurate to within the following limits of an equivalent mathematically derived Q-factor result obtained from an OSNR and ER measurement (as defined in 6.1.7, Equation 6-4 made on a test signal with $ER \geq 8$ dB.



NOTE – QFME operated at the optimum optical input power.

Figure 2/O.201 – Accuracy limits as a function of the Q-factor

The optimum optical input power shall be specified by the manufacturer.

If the QFME is not operated at the optimum optical input power, the additional error shall remain within the limits as indicated in Figure 3:

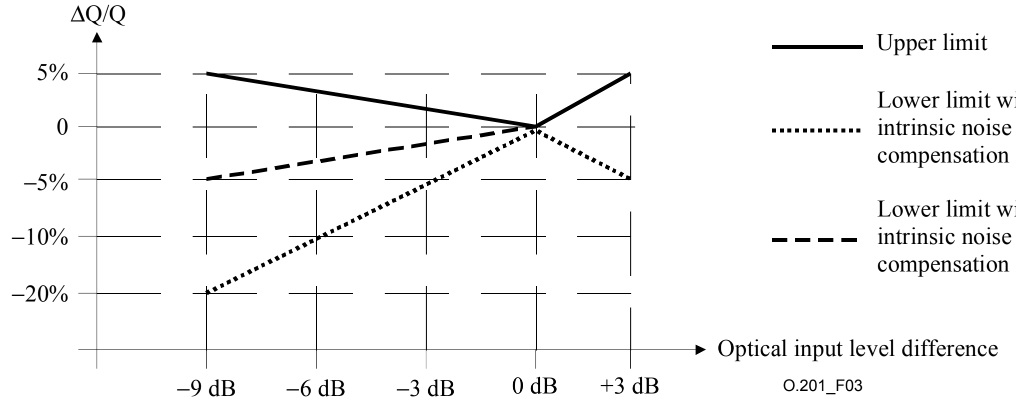


Figure 3/O.201 – Tolerance limits for the additional level dependent inaccuracy

6.2.2 Acceptance tests

6.2.2.1 Crosstalk test

As described in Appendix III, a number of effects (such as ISI, SPM and crosstalk) can distort the eye diagram and lead to non-Gaussian distributions because of logic level splitting. However, even in these cases, it is possible to apply Gaussian fitting only to measurement points close to the centre of the eye and take the fitting curves to extrapolate Q.

QFME according to this Recommendation shall be able to correctly evaluate distorted eyes under the condition of the following crosstalk test.

According to Figure 1, a crosstalk source is added to the calibration set-up, which provides a ≈10 MHz/100% on-off modulated DFB laser signal with 50% ± 1% duty cycle and rectangular shape. The laser wavelength should be more than 1 nm apart from the calibration signal, but in the same wavelength band.

The idea of this test is to reduce the eye opening by non-synchronous crosstalk by a factor of approximately:

$$1-\frac{1}{Q}$$

For this purpose, measured with an OSA at the input of the QFME, the optical crosstalk power P_{xt} shall have the following relation to the power of the calibration signal P_{av}:

$$P_{xt} = \frac{1}{Q} \times P_{av} \times \frac{ER-1}{ER+1} \tag{6-5}$$

With the crosstalk source switched off, the calibration signal is adjusted to yield a reading of $Q_{no\ xt} \approx 7$ at the QFME in the same way as in 6.1.7.

Now the crosstalk source is adjusted according to Equation 6-5 using the measured $Q_{no\ xt}$ value and the Q-factor is measured again. Taking into account that the eye opening is reduced by the crosstalk, but only for 50% of the time because of the 50% duty cycle, the resulting change of the Q-factor shall be:

$$\Delta Q_{xt} = Q_{no\,xt} \times \frac{P_{xt}}{P_{av}} \times \frac{ER+1}{ER-1} + 0.08 \pm 0.2 \qquad (6\text{-}6)$$

6.3 Presentation of results

The Q-factor of the signal shall be displayed as well as the estimated optimum BER.

A numerical or graphical representation of the quality of fitting may be given to provide the user with an indication for the validity of the measurement.

Other parametric data relating to the Q-factor and its measurement may be made available.

In case of FEC applications, the BER estimated from Q-factor measurements is the raw BER, which would be observed without FEC in operation. The reason for this is that the Q-factor measurement is based on an evaluation in the physical layer (eye diagram). The BER improvement by FEC in the network is a known function and can be taken into account by the user.

The theory presented in this Recommendation requires that no FEC correction is applied prior to Q-factor evaluation. If FEC correction is applied, for reasons outside the scope of this Recommendation, it shall be indicated together with the results.

7 Miscellaneous functions

These functions do not directly influence the Q-factor measurement definitions and shall be considered as optional for the measuring equipment.

7.1 Remote control port

The measuring equipment may be remotely controlled by using a standardized interface (e.g., IEEE 488/IEC 625).

7.2 TMN interface

The measuring equipment may have an appropriate Q interface providing TMN facilities.

8 Operating conditions

8.1 Environmental conditions

The electrical and functional performance requirements shall be met when operating the QFME under the conditions specified in ITU-T Rec. O.3 [9].

8.2 Behaviour in case of power failure

A power failure during the measurement shall be recognized by the QFME.

9 Bibliography

[B1] HUMBLET (P.A.) and AZIZOGLU (M.): On the bit error rate of lightwave systems with optical amplifiers, *IEEE/OSA J. Lightwave Technol.*, Vol. LT-9, 1991, pp. 1576-1582.

10 Background reading

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Annex A

Mathematical procedure for the Q-factor evaluation with the decision level shifting method

A.1 Preconditions

The mathematical procedure presented here is only valid if the BER is determined without using FEC.

A.2 Theoretical dependence of the BER on the threshold

The theoretical relation is:

$$BER = \frac{1}{4}\,\mathrm{erfc}\left(\frac{\mu-\mu_0}{\sqrt{2}\,\sigma_0}\right) + \frac{1}{4}\,\mathrm{erfc}\left(\frac{\mu_1-\mu}{\sqrt{2}\,\sigma_1}\right) \qquad \text{(A-1)}$$

where μ_1 and μ_0 are the mean voltage levels of the 1 and 0 levels. σ_1 and σ_0 are the standard deviations of the noise distribution on the 1 and 0 levels. μ is the position of the decision threshold.

The task is to find μ_1, μ_0 ,σ_1 and σ_0 from the measured values of $BER = f(\mu)$ and to calculate the optimum BER and the Q-factor from these values.

A.3 Separation of BER(0) and BER(1)

As the total error probability is the sum of two terms corresponding to the half of the conditional bit error probability, the following separation process is applied:

First step

The two distributions are handled separately:

$$BER1(\mu) = 1/4 \times \mathrm{erfc}\,(V_1/\sqrt{2}) \text{ for the upper half of the eye diagram} \qquad \text{(A-2)}$$

$$BER0(\mu) = 1/4 \times \mathrm{erfc}\,(V_0/\sqrt{2}) \text{ for the lower half of the eye diagram} \qquad \text{(A-3)}$$

with $V_1(\mu) = (\mu_1 - \mu)/\sigma_1$ and $V_0(\mu) = (\mu - \mu_0)/\sigma_0$

Resolving Equations A-2 and A-3 to V_0 and V_1 and using the inverse error function, the μ-dependence of V_1 and V_0 is calculated from the measured BER values via regression lines. This yields the first set of estimation values for μ_1, μ_0, σ_1 and σ_0 (see Figure A.1).

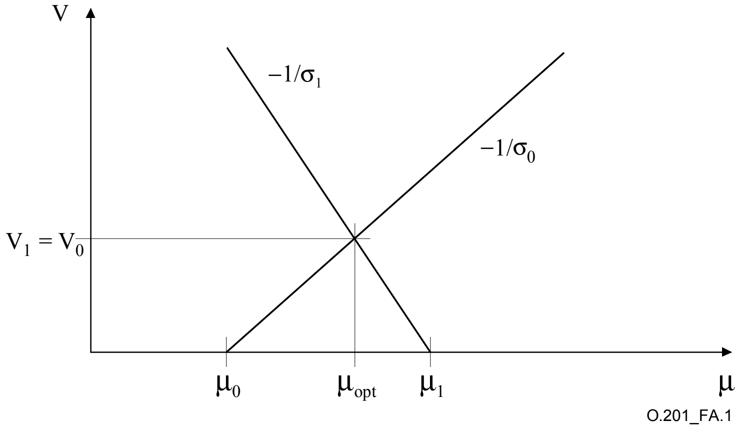

Figure A.1/O.201 – Extrapolation with regression straight lines

$V_1(\mu)$ is calculated from the measurement points of the "1" level;

$V_0(\mu)$ is calculated from the measurement points of the "0" level.

Second step

Now the complete equation (Equation A-1) is used for further calculation. To improve the μ_1 and σ_1, the estimated values for μ_0 and σ_0 are inserted in equation (Equation A-1) and V_1 vs μ is determined again, yielding a more precise set of μ_1 and σ_1. On the basis of this new set, an improved set of μ_0 and σ_0 is determined analogously.

The second step is repeated iteratively. If the V_{opt} value of Figure A.1 changes by less than 10^{-3}, the iteration is stopped.

A.4 Calculation of the results

The final set of μ_1, μ_0 ,σ_1 and σ_0 is taken to calculate the results for the optimum BER and for the Q-factor.

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \qquad \text{(A-4)}$$

The optimum estimated BER is found using Equation A-1 and setting $\mu = \mu_{opt}$ according to Figure A.1. This leads to:

$$optBER = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \qquad \text{(A-5)}$$

A measure for the validity of the results is the regression straight line fitting quality represented by the correlation coefficients of the two regression lines. For the accuracy requirements of this Recommendation (clause 6), the correlation coefficients shall be in the range of 0.95 to 1.0.

Appendix I

Q-factor theory

I.1 Q-factor theory

I.1.1 Assumptions

Ones and zeroes uncorrelated; P(0) = P(1) = 0,5

Additive noise is statistically independent from the signal

I.1.2 Q-factor

Q is defined for a digital transmission signal as a signal-to-noise ratio (SNR) at the receivers decision circuit and is expressed as:

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

The Q-factor can be written in terms of decibels rather than in linear values:

$$Q\,(\text{decibels}) = 20 \times \log_{10} Q\,(\text{linear}) \tag{I-2}$$

where μ_1 and μ_0 is the mean voltage level of the 1 and 0 levels. σ_1 and σ_0 are the standard deviations of the noise distribution on the 1 and 0 levels.

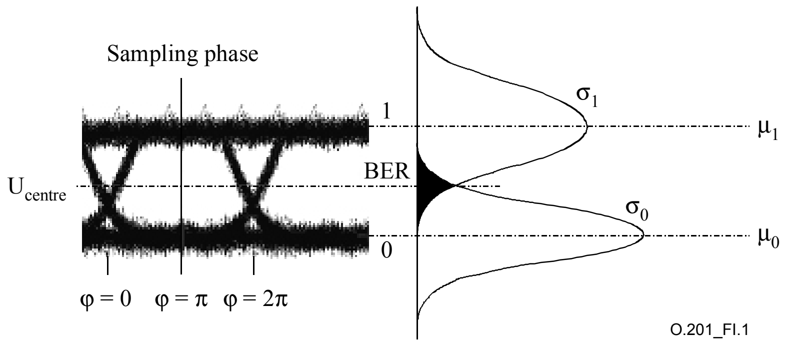

Figure I.1/O.201 – Relationship between probability density function and bit error ratio

The relation between the BER and μ and σ values is described in Equation A-1.

I.2 Approximation of the erfc function

For ease of computation, it is proposed to use an approximation for the erfc according to Equation I-3.

$$BER(Q) = \frac{1}{2} \times \left[2 \times e^{-\left(\frac{Q}{\sqrt{2}}\right)^2} \times \frac{a0 + a1 \times \frac{Q}{\sqrt{2}} + a2 \times \left(\frac{Q}{\sqrt{2}}\right)^2}{\left[b0 + b1 \times \frac{Q}{\sqrt{2}} + b2 \times \left(\frac{Q}{\sqrt{2}}\right)^2 + b3 \times \left(\frac{Q}{\sqrt{2}}\right)^3 \right] \times \sqrt{\pi}} \right] \tag{I-3}$$

With:

a0 = 1.69071595	b0 = 1.90764542
a1 = 1.45117156	b1 = 3.79485940
a2 = 0.50003230	b2 = 2.90845448
	b3 = 1.00000000

As shown in Figure I.2, the accuracy of this approximation is better than 2×10^{-6} for $Q > 1.5$, which is more than sufficient for the Q-factor application. The approximation BER3(Q) yields larger errors below $Q = 5$ and should therefore not be taken.

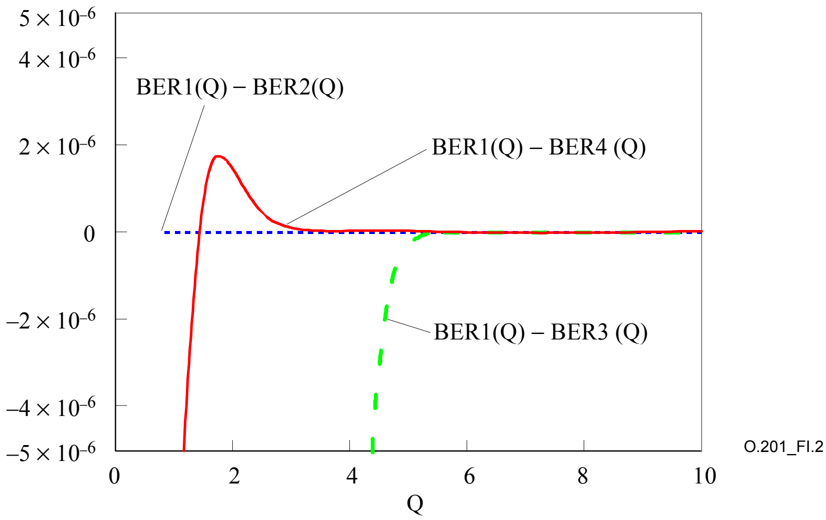

Figure I.2/O.201 – Accuracy of various erfc approximations

NOTE – Figure I.2 shows the deviations from the theoretical *BER*1*(Q)*

*BER*2*(Q)*, dotted line: approximation via numerical integral method

*BER*3*(Q)*, broken line: approximation with Equation $\left(BER3(Q) = \frac{1}{Q \times \sqrt{2}} \times e^{\frac{-Q^2}{2}} \right)$

*BER*4*(Q)*, solid line: approximation with Equation I-3

I.3 Inverse erfc(x), erfc^{-1} (x)

The calculation of μ_0, μ_1, σ_0, σ_1 and Q needs also the inverse erfc-function. As the accuracy of Equation I-3 is very good, the erfc^{-1} (x) is determined via iterations of erfc(x), starting with a value from a look-up table.

The iteration is aborted if the match is better than 10^{-6}.

Appendix II

Optical channel performance and characteristics

II.1 Optical channel performance

II.1.1 Q-factor measurement application

Figure II.1 depicts an example of the application of a Q-factor measurement. This Q-factor measurement allows an accelerated measurement of the performance within an optical channel trail (OCh trail). Such an optical channel trail may be part of a more complex optical network including OXCs and/or OADMs.

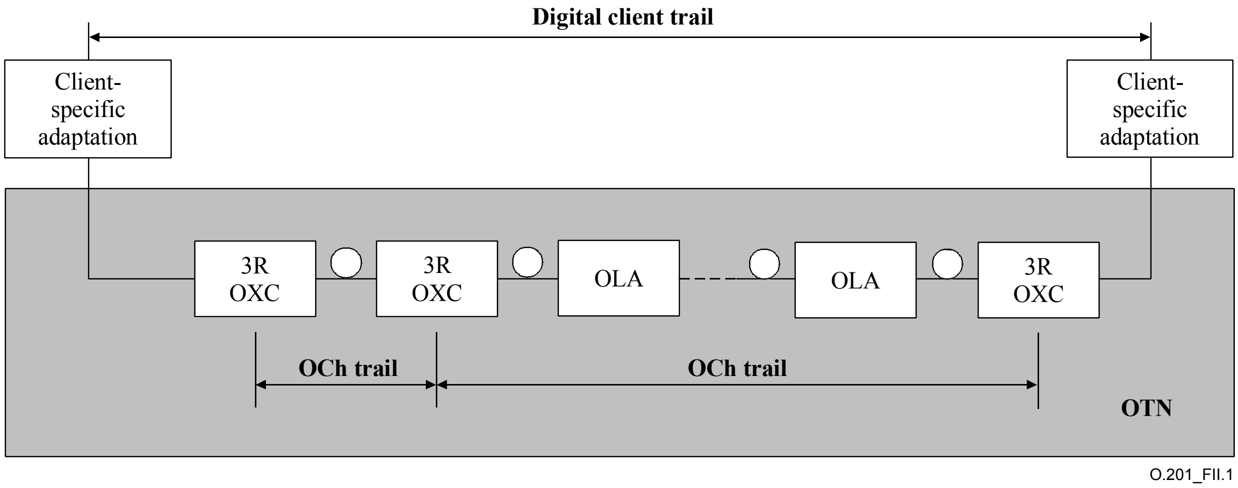

Figure II.1/O.201 – Optical Transport Network (OTN)

II.2 Optical channel characteristics

II.2.1 Optical characteristics

Optical channels are characterized by the following primary attributes:

- wavelength;
- power;
- Optical Signal-to-Noise Ratio (OSNR);
- supported Bandwidth.

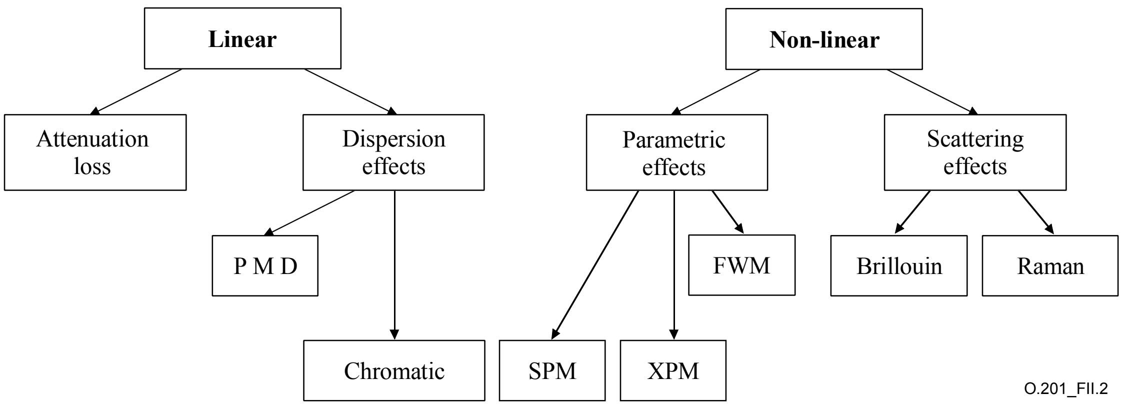

Figure II.2/O.201 – Sources of impairments in DWDM transmission

Figure II.2 shows that the OSNR is determined by amplifier noise and the accumulated effect of the numerous linear and non-linear distortions present in high-speed fibre-optic transmission systems.

The Q-factor test method can cover all these impairments and offers, therefore, additional performance information which is not accessible by optical spectrum and OSNR measurements.

II.2.2 Bit error ratio

From a digital client's viewpoint, the end-to-end bit error ratio (BER) is a fundamental performance metric of any digital transmission system. Due to the many inter-related optical impairments, there is no straightforward relation between BER and the optical characteristics.

BER measurements are out-of-service measurements, since they rely on a bit-by-bit comparison between the received bit stream and a known test pattern.

II.2.3 Block error ratio

In-service measurement of the block error ratio can replace BER performance testing, but the information is only available at the boundaries of the OTN.

II.2.4 Q-factor

The Q-factor is defined as the electrical signal-to-noise ratio (ESNR) at the input of a receiver's decision circuit. The ESNR reflects all impairing optical and electrical defects at the examined point inside the optical network. In the absence of being able to perform a true BER measurement, (e.g., due to test time, test access, etc.) the Q-factor method can be used to provide an estimation of the performance than can be expected in-service.

The definition of the Q-factor is given in Appendix I and in Equation A-4. It should be noted that the accuracy of the BER estimation strongly depends on the measurement points used for the calculation of the Q-factor. For best results the μ and σ values of Equation A-4 should be determined from the Gaussian "trailing-off" close to the centre of the eye diagram, as described in 5.5.

As such, the Q-factor measurements will only reflect the network performance as it operates into the QFME receiver. The sensitivity and the bandwidth of the QFME receiver, therefore, have to be known very accurately, to allow for conclusions on the performance of the system receiver.

In contrast to BER and Block Error monitoring, the Q-factor measurement requires only optical/electrical conversion and timing recovery but no frame decoding and overhead analysis and can, therefore, also be used on optical channel connection points between 3-R regenerators (see Figure II.1). Details on the Q-factor theory can be found in Appendix I.

Appendix III

Imperfections to be considered under conditions found in practice

Appendix I discusses the Q-factor theory under ideal conditions assuming Gaussian noise as the disturbing source. In practice, the following imperfections require consideration.

III.1 Analogue impairments

Increasing wavelength density and increasing bit rates per wavelength are driving optical transmission systems to their limits, resulting in the fact that amplifier noise is no longer the dominant source of signal impairment.

Depending on fibre type, length, wavelength density, the effect of linear and non-linear impairments will lead to deviations from the ideal Gaussian distribution.

III.2 Pattern dependencies

The effect of the received patterns on the shape of the eye can influence the Q-factor results.

For out-of-service measurements, the pattern should be a framed test signal according to the appropriate standard, e.g., ITU-T Recs G.707 [2], O.181 [10], G.709 [3], etc.

For OTN signals, the pattern should be structured as per 17.4/G.709 [3].

For other protocols the most appropriate test pattern which resembles the traffic in the network under test should be used.

III.3 Receiver characteristics

Differences between the performance of the QFME's receiver and that in the Network Element connected to the Line Under Test may cause variations in the actual performance compared to the estimated performance.

With regard to the receiver characteristics, the following points need to be considered: frequency response, optical input level range, non-linearity and clipping, DWDM or tunable optical channel filtre characteristics, crosstalk, preamplifier aspects.

III.4 Sample phase position

The position of where the eye is sampled across its width may affect the repeatability of Q-factor measurement.

III.5 Effects on the Q-factor

Because of the practical imperfections described above, the evaluation of the Q-factor based on an ideal Gaussian noise model may lead to wrong extrapolation results. Therefore, this model needs to be implemented with some caution.

As some effects (e.g., inter-symbol-interference and crosstalk) cause the high and low logic levels to split into several levels each, the greatest deviations from the Gaussian model are found in the vicinity of these logical levels.

Other effects like cross phase modulation lead to an additional noise which may have an amplitude distribution different from the receiver and the optical amplifier noise, but adds to the overall noise constituting a new Gaussian distribution.

As a consequence, the Gaussian distribution can be severely disturbed in the vicinity of the logic levels, but is very close to ideal in the vicinity of the decision level (Gaussian "trailing-off").

To get comparable results for QFME of different vendors, it is suggested that the Q-factor evaluation shall be based on the Gaussian trailing-off only, using measured BER values of 10^{-4} or below and excluding the direct vicinity of the logic "1" and "0" levels.

Appendix IV

Implementation suggestions for QFME

IV.1 Block diagrams

For example, two potential solutions are shown in the Figures IV.1 and IV.2: one which is capable of performing in-service measurements according to Figure IV.1 using a double decision circuit, and one according to Figure IV.2 with a single decision circuit for out-of-service applications.

Other configurations that also adhere to the requirement of this Recommendation are also valid.

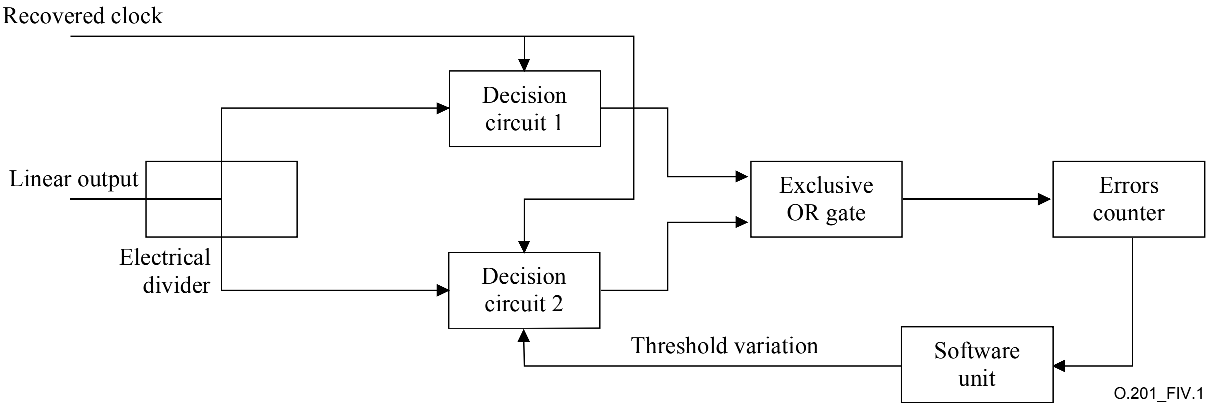

Figure IV.1/O.201 – Block diagram of a dual decision circuit implementation of Q-factor measurement equipment

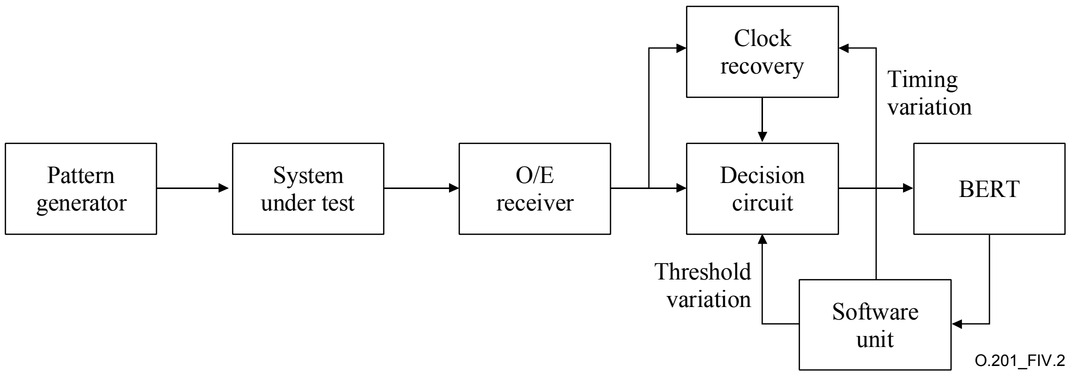

Figure IV.2/O.201 – Single decision circuit solution for Q-factor measurements

IV.2 Functional description

IV.2.1 Dual decision circuit

According to Figure IV.1, the signal from the optical/electrical converter is fed to two decision circuits which sample the electrical signal with the recovered clock. Decision circuit 1 is adjusted to its optimum position within the eye-diagram. This is used as reference. Decision circuit 2 can be adjusted to arbitrary values regarding sampling phase and threshold levels. Differences of the output of these two decision circuits are detected with an EXOR and counted as bit errors. By using a software unit the settings of the decision circuit 2 are varied and the resulting bit error rates are stored.

This type of equipment does not need a special test pattern, but may also use live traffic signals to perform the measurement (see also III.2).

By sampling the whole eye-diagram vs threshold voltage and phase, this measurement set-up is an eye-diagram sampler in the BER domain. In practice, the BER measurements are performed vs. threshold voltage with the sampling phase as a parameter (see Figure IV.3).

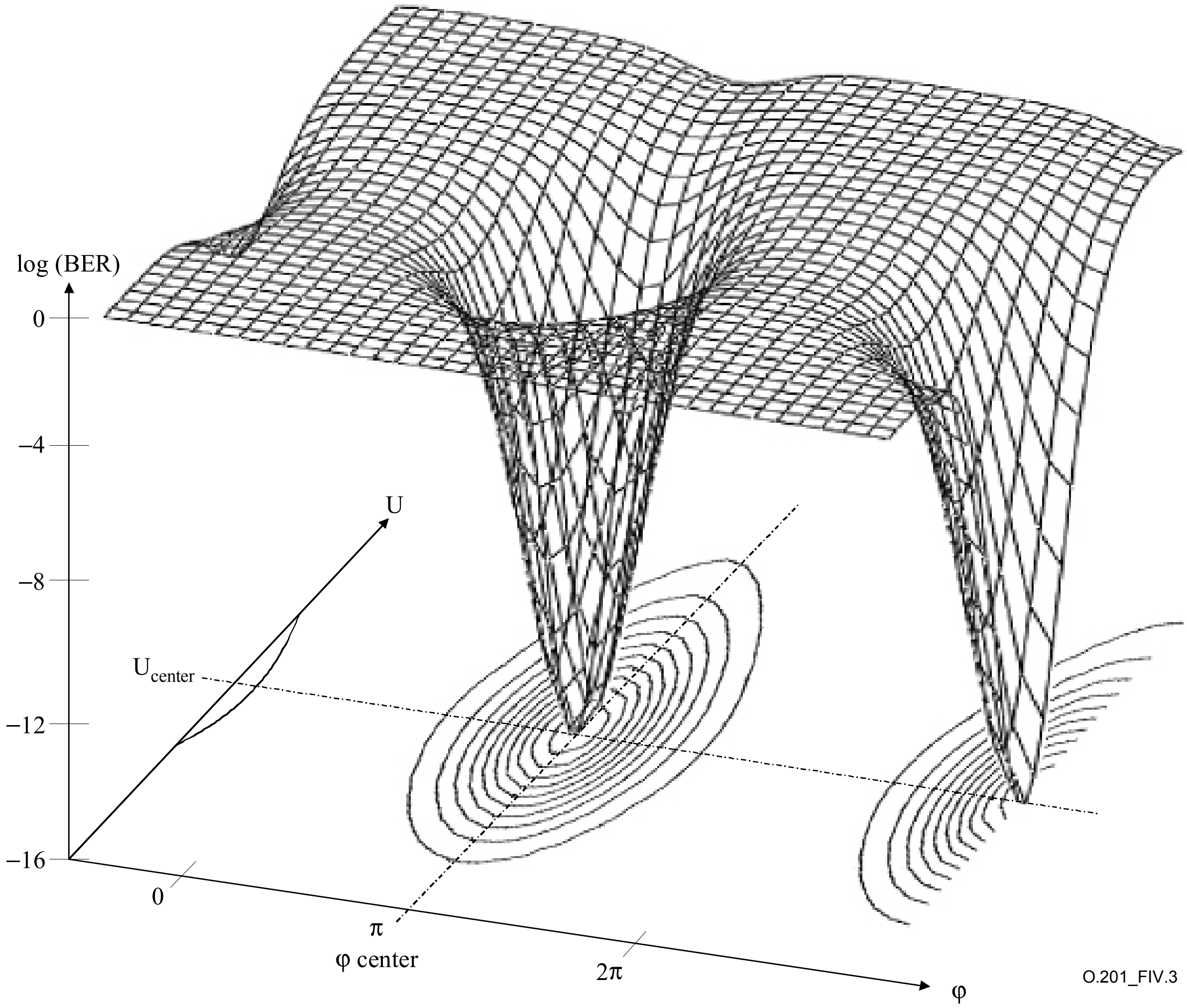

Figure IV.3/O.201 – Bit error ratio as a function of decision threshold and phase

IV.2.2 Single decision circuit

In contrast to the set-up in Figure IV.1, it is necessary to use a known data stream (PRBS from the pattern generator). Bit errors produced by varying the threshold voltage are counted by comparing the output of the decision circuit with the original data sequence, which is done in the BERT module. While the use of known test patterns may increase the repeatability of the result, this method may be limited if the pattern receiver loses synchronization if the threshold voltage or sampling phase is varied too much.

IV.2.3 Mathematical procedures and extrapolation

Referring to *P.A. Humblet and M. Azizoglu* [B1], the required result is the BER dependence on the threshold voltage.

According to Figure IV.4, there are two sets of measurement points belonging to the logic 1 and 0 respectively. For both sets of points a Gaussian fitting is applied. This can be done by calculating regression straight lines in the $V = f(\mu)$ domain. With the corresponding μ- and σ-values, Q of the signal is calculated. The detailed process is explained in Annex A.

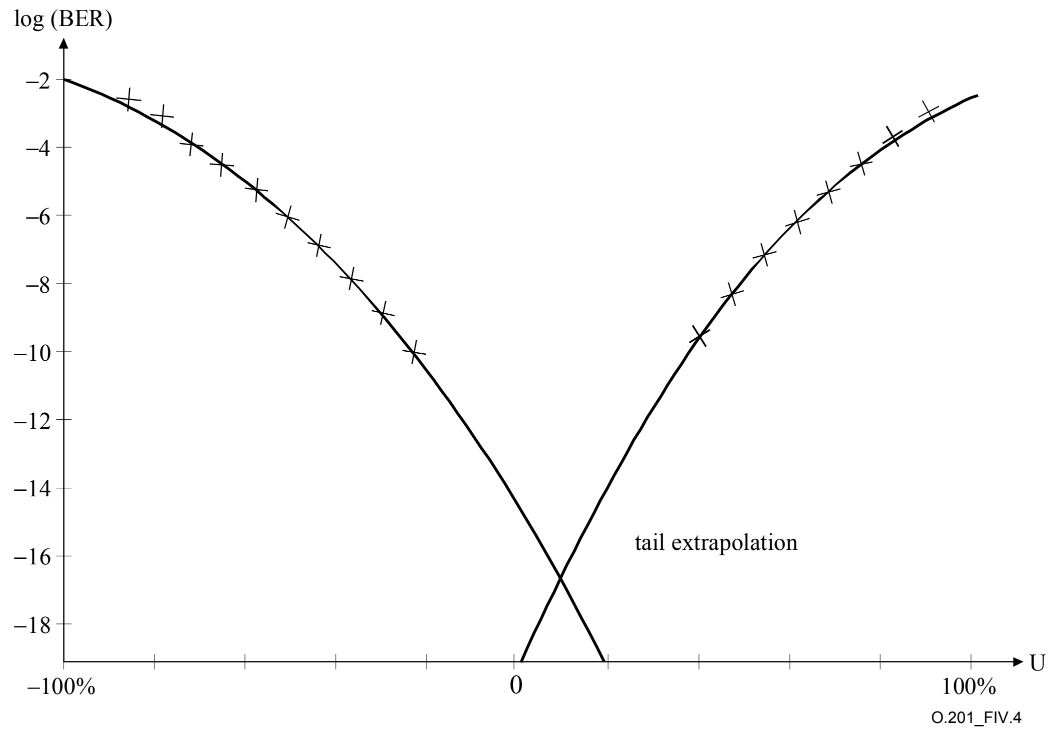

Figure IV.4/O.201 – Extrapolation of measurement points

Deviation from Gaussian distribution:

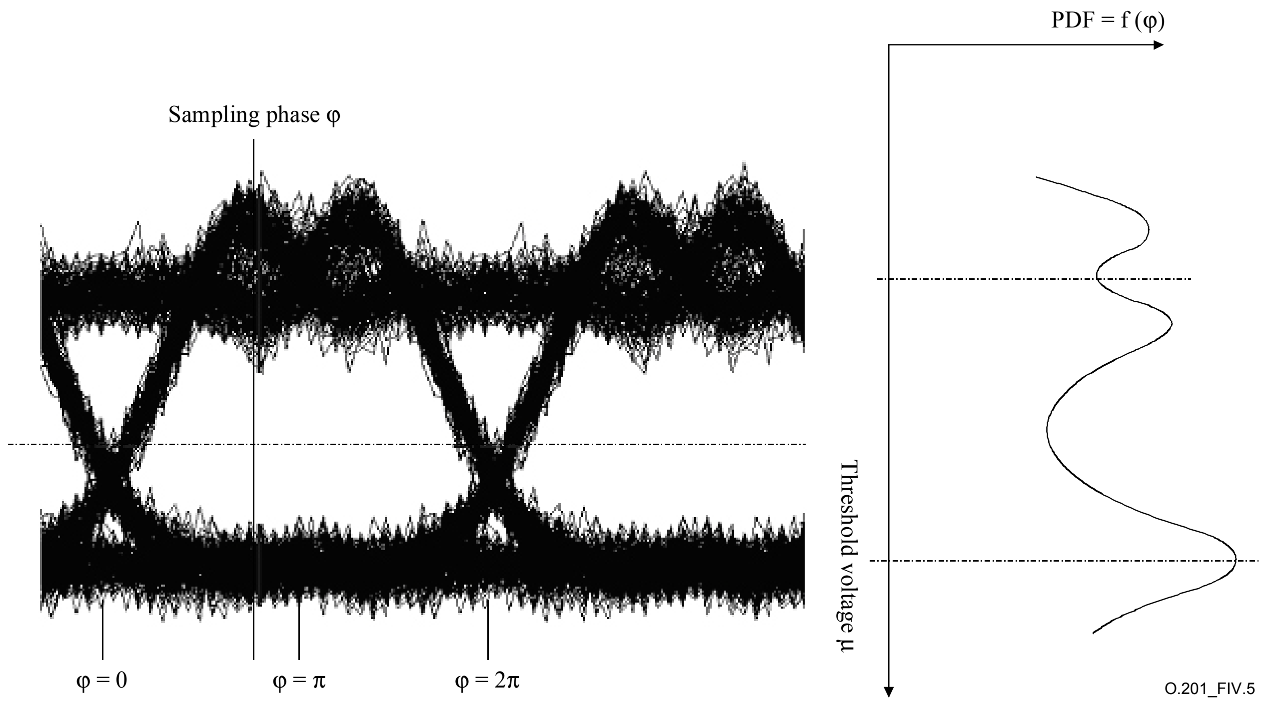

Figure IV.5/O.201 – Non-Gaussian distribution

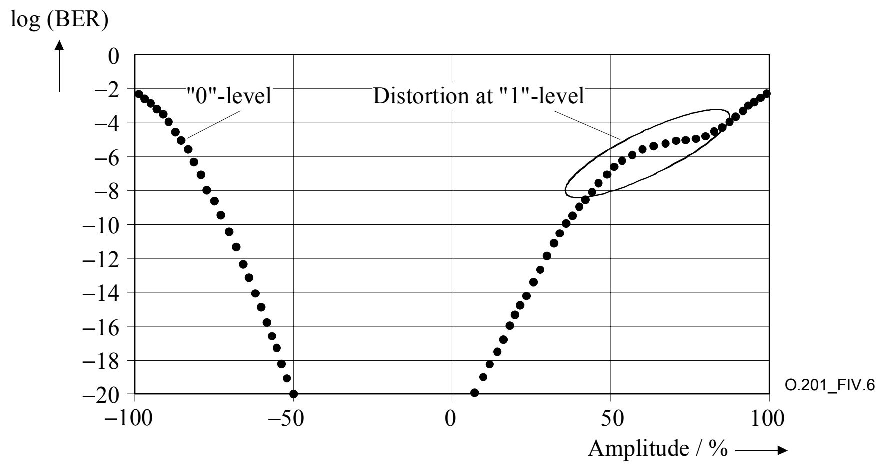

Figure IV.6/O.201 – Discrete interference line, e.g., crosstalk

When sampling a signal with non-Gaussian distribution (Figure IV.5), the fitting has to be done very carefully. The correlation coefficients (see Annex A) are no longer 1 and the fitting process has to be modified. As an example, referring to Figure IV.6, the fitting may be improved by only using data at BER below 10^{-7}.

IV.3 Measurement modes

IV.3.1 In-service measurements

In-service measurements may be performed with a measurement arrangement according to Figure IV.1, which corresponds to Figure 3/G.976 [8].

In this case, the reference decision threshold and timing is first set to a standard position in the centre of the ideal eye opening. The variable threshold decision circuit is then changed with respect to timing and level and the error ratio is recorded. Based on these data the reference decision threshold and timing is automatically adjusted for optimum.

Now the variable decision circuit parameters are varied again, the error ratio is recorded and only parameter combinations yielding error ratios below 10^{-4} are taken for further evaluation. From these data, the Q-factor is then calculated.

IV.3.2 Out-of-service measurements

Out-of-service measurements are also possible with the arrangement according to 6.3.1. As a stimulus, the signal from a live channel can be taken as well as from an appropriate pattern generator. In this case, it is also possible to use the Q-factor measurement equipment as a replacement for the system receiver.

As an alternative, an out-of-service measurement is possible with an arrangement according to Figure IV.2.

In this case, a pattern generator is necessary at the transmit side, and a special BER measuring equipment with adjustable decision threshold and timing is used at the receive side.

Starting with a standard position of threshold and timing, the BER dependence on the threshold and timing position is recorded. From these data an optimized timing is calculated and the BER measurement with the variation of the threshold is repeated with this optimized timing. From these results only those yielding BER below 10^{-4} are taken for extrapolation of the Q-factor.

Appendix V

Additional verification tests

V.1 Receiver pulse response

The ISI test and, in the case that the QFME provides phase adjustment capability for the decision point, the phase test may be used to verify the receiver pulse response.

V.1.1 ISI test

The Q-factor is measured with a test set-up according to 6.1.7, which includes a digital reference transmitter built with an externally modulated laser and which generates a pulse shape conforming to the G.957 [6] and G.691 [1] pulse masks.

As a modulation signal, either a 11001100 sequence or a $2^{23} - 1$ PRBS is used. If possible, the test should be performed with unframed patterns. No scrambling of the modulation signal is allowed for the 11001100 sequence. With the optical attenuators of Figure 1, the OSNR is set to yield a Q-factor of ≈ 7, while the input power to the QFME is set to an intermediate value in the permissible level range.

Using a sampling oscilloscope to display the eye diagram of the transmit signal, it is confirmed that the signal is visually ISI-free for both modulation patterns.

The Q-factors measured with the 11001100 sequence and with the PRBS should differ by less than (TBD)%.

V.1.2 Phase test

The PRBS signal of the calibration setup of Figure 1 is adjusted according to 6.1.7 to give a reading of $Q \approx 7$ on the QFME.

At the QFME, the sampling phase is varied by ±10% (with 0% representing the centre of the eye and 100% representing the bit width).

The measured Q should not deviate by more than 12% (1 dB) from the 0% result.

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