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Estimation of BER Bit Error Rate Using Digital Smoothing Filters

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***Abstract*—In the article, the authors present a new method of numerical determination of Q and BER parameters based on which the quality of transmission in optical fibre transmission systems is determined. The proposed method is based on the use of digital smoothing filters algorithms and does not require the knowledge of the so-called "eye diagram", which greatly simplifies the entire measurement procedure. This method can be implemented in a simple manner in real-time systems, and in particular it is crucial for ICT systems and networks with a high bit rate of more than 10 Gbps and 40 Gbps and systems with time division or wavelength division multiplexing of 100 GBE and 400 GBE.**

***Index Terms*—Estimation; Quality index Q; Bit Error Rate; Smoothing filter.**

I. INTRODUCTION

In every telecommunication system for data transmission, including optical transmission, the problem of signal attenuation or its distortion occurs, resulting from the physical properties of the transmission medium. At the same time, the transmitted signal between the transmitter and the receiver may be overlapped by interference (noise) generated by physical phenomena occurring in the transmission channel [1], [2]. These signals are of a random nature and are the subject of research in the field of stochastic processes theory.

The optical fibre signal transmission path - apart from the optical fibre cable - contains a number of optoelectronic devices that introduce transmission interference. Phenomena affecting the quality of the received signal include [1]–[37]:

Interference caused by the transmitter module, in particular:

- Semiconductor laser noise (phase, intensity, and mode);
- Finite spectral linewidth of semiconductor laser radiation;
- Noise and instability of generating systems.

Interference from optical fibre cables:

- Attenuation;
- Time broadening of the pulse (dispersion).

Interference generated in the receiving module:

- Detector noise (shot and thermal);
- Frequency response of the detection system.

Verification of transmission quality in radio over fibre and optical fibre systems, in accordance with the recommendations of the International Telecommunication Union - Telecommunication Standardization Sector ITU-T and International Telecommunication Union [4] - Radiocommunication Sector ITU-R [5], is based on the analysis of the "eye diagram" and the determination of two important classification parameters: Quality (*Q*) and Bit Error Rate (BER) [6], [7].

The basic criterion for assessing the quality of transmission is the characteristics of the bit error rate BER. This factor takes into account the effect of all elements of the optical fibre path and transmission system on its quality, i.e., differentiation in the receiving part of the signal sent by the transmitter, i.e., the possibility of the so-called "eye diagram mask": hexagonal or rectangular. BER measurements are used to evaluate the quality of the operation of a telecommunications system during the acceptance tests and normal operation.

One of the methods of estimating BER is the analysis of the so-called "eye diagram". It can be used to obtain a significant amount of information enabling the determination of the quality of digital signal transmission in an optoelectronic system. This diagram is obtained by overlapping all possible bit data combinations, then determining the Q parameter and estimating the BER [3], [4], [7].

A typical interpretation of the selected parameters on an eye diagram is presented in Fig. 1.

Figure 1 shows some of the more important parameters of the eye diagram: minimum and maximum voltage values for high and low state levels (V_{min}, V_{max}, V'_{min}, and V'_{max}), determining mean levels of voltage interference in these states and amplitude distortion, signal distortion when switching from high to low state and from low to high state, margins determining the decision level whether a signal is a logical zero or a logical one and sampling interval.

In [35], a new accurately statistical method is proposed to estimate the worst-case eye diagrams and bit-error-rate eye diagrams for communication systems applications. The probability distribution of the coded bus bit vectors is modeled based on the coding rule constraints.

The paper [36] described a special optimization method to find the bit patterns causing the lowest received high symbol and the highest received low symbol at the sampling time point. The proposed approach is based on a mapping

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method and Bayesian optimization for solving non-linear and non-convex distortion problems, which provides a significant speedup compared to the traditional transient eye.

The article [37] proposes eye diagram estimation methods in pseudorandom binary sequence (PRBS) test and scrambling.

A more accurate method is a real-time probabilistic analysis. However, the analysis of the bit error rate in an actual system at the level of 10^{-12} ... 10^{-15} would take more than a year or several years, while the protocols of the measurement points should be implemented over a maximum of several hours to put the installation into service. ITU-T standards allow to shorten this process by the method of eye diagram analysis.

The basis for calculating the bit error rate BER is the Q parameter [29]–[34]

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

where μ_1 is the mean value of the electrical signal in high state, μ_o is the mean value of the electrical signal in low state, σ_1 is the standard deviation of the electrical signal in high state, and σ_0 is the standard deviation of the electrical signal in low state.

Figure 2 illustrates a typical measurement eye diagram made for a temporary electrical waveform at the output of an optical fibre line.

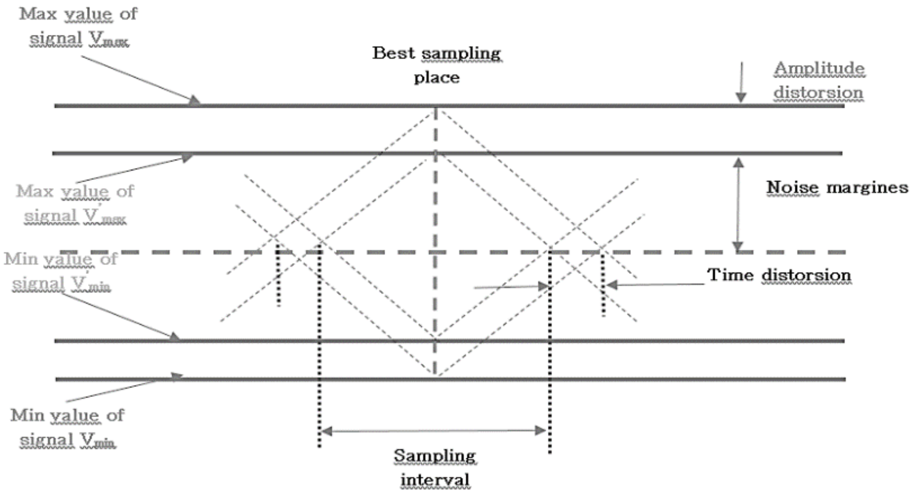

Fig. 1. Parameters of the eye diagram.

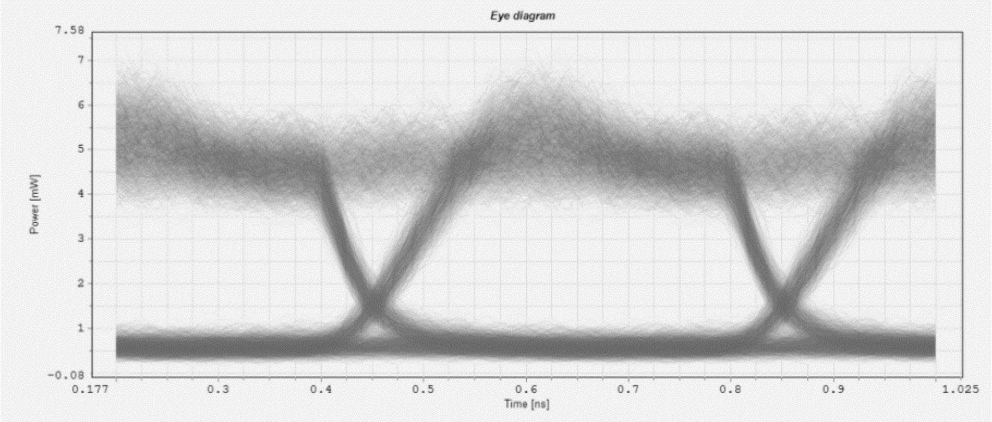

Fig. 2. Typical measurement eye diagram made for a temporary electrical waveform at the output of an optical fibre line.

The relationship between the BER and the Q parameter used in telecommunications to determine the quality of the transmission is described by the relationship

$$BER = \frac{1}{2}\left[erfc\left(\frac{Q}{\sqrt{2}}\right)\right]. \tag{2}$$

The Q parameter in the decibel scale is converted from the linear scale by the relationship

$$Q_{dB} = 20 \times \log(Q). \tag{3}$$

The graph showing the dependence of Q parameter on the bit error rate is presented in Fig. 3.

Transmission standards in access networks require a bit error rate below the threshold BER = 10^{-12}. It is defined in detail by the standards in [8]–[15], and the most important of them are [4], [5], [8]–[15]:

– ITU-T G.983 and ITU-T G.984 for 2.5 Gbps access networks and Ethernet networks, the criterion for bit error rate is BER < 10^{-10},

– ITU-T G.987 (XG-PON, X-Generation Passive Optical Network -10 Gbps) and ITU-T G.989 (NG-PON2, Next

Generation Passive Optical Network 40 Gbps), the level is BER < 10^{-12},

– ITU-T G.695 (CWDM, Coarse Wavelength Division Multiplexing, Nx10 Gbps), and

– ITU-T G.698 (DWDM, Dense Wavelength Division Multiplexing, terabit networks) for access and transport networks with wavelength division multiplexing, applied criterion BER < 10^{-12}.

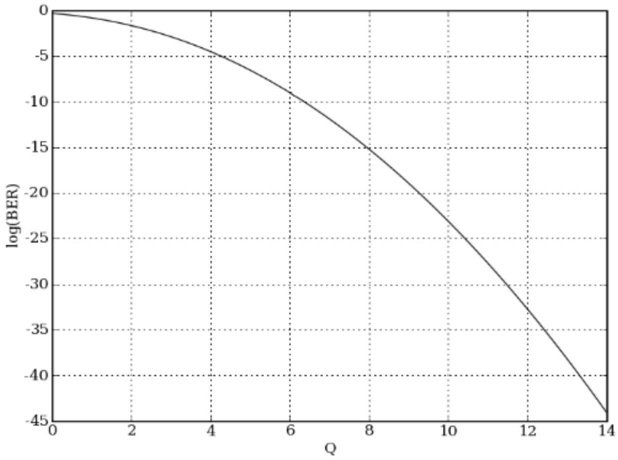

Fig. 3. The relationship of the Q parameter and the bit error rate.

The BER standard, based on the *Q* parameter, was developed for transmissions up to 10 Gbps, and currently for transmissions with bit rate above this value, the BER values obtained with this method do not always reflect the real quality of transmission in optical networks (10 Gbps and above).

For this reason, in networks with bit rates above 10 Gbps, it is often necessary to use the observation method to estimate the quality of transmission. An expert observes the output signals or eye diagram on an ongoing basis and estimates whether the transmitted signal meets the transmission requirements.

However, this method is time-consuming and requires significant experience on the part of the individual observing the diagrams. Taking into account the development of networks and increasing the bit rate in the transmission channel, new transmission solutions [16] and the disadvantages of the "classic" use of the Q index to determine the bit error rate, this paper proposes a new, objective numerical method for estimating the value of the Q parameter with the use of digital smoothing filters.

II. Q PARAMETER ESTIMATION USING DIGITAL SMOOTHING FILTERS

The value of a single sample of the observed process *x[n]* may result from the deterministic signal model or from its statistical features that can be described by Probability Density Function (PDF). For the assumed probability distribution type, to define it unambiguously, it is enough to determine the mean value μ and the standard deviation σ (or variance σ^2). In practice, it is unlikely that the exact values of the distribution parameters are known. For this reason, it is necessary to estimate them on the basis of the values of the observed process. In many cases, this is a difficult task, therefore the estimation process is simplified by assuming that the process is stationary and also ergodic. Adopting these assumptions enables the determination of PDF parameters solely on the basis of one observed process realization [17].

The stationary stochastic process is ergodic if, when determining any statistical characteristics, averaging over the set of realizations can be replaced by the averaging over time. In such a case, the expected value is equal to the fixed component of the selected realization, while the variance represents the average power of the realization.

These findings are the basis for estimation of the *Q* parameter on the basis of the statistical properties of the signal (4), assuming that it is the realization of a certain stochastic process, and the observed samples are random variables of this process such that

$$X_k = S_k + N_k, \tag{4}$$

where S_k is the useful signal at the input, X_k is the useful signal at the output, N_k is the additive interference with normal distribution $N(0, \sigma_n)$, the average value of zero $E(N) = 0$, and variance $Var(N) = \sigma_n^2$.

The authors of the article suggest that the Q parameter should be estimated by means of the following relationship

$$Q_{est} = \frac{1}{p} \times \frac{E\left(X_{High}\right) - E\left(X_{Low}\right)}{\sqrt{Var\left(N_{High}\right)} + \sqrt{Var\left(N_{Low}\right)}}, \tag{5}$$

where $E(X_{High})$ is the mean value of high signal level, $E(X_{Low})$ is the mean value of low signal level, $Var(N_{High})$ is the interference variance N in high state, $Var(N_{Low})$ is the interference variance N in low state, and p is the correction coefficient.

In (5), there is the interference variance ($Var(N) = \sigma_n^2$), which is to be estimated.

Methods based on signal smoothing [21]–[27] are proposed for noise variance estimation. This means that the elements of a series (data set) with an irregular diagram will be replaced by a set with a smoother diagram with suppressed interference. In the literature, such methods are also referred to as signal averaging or averaging (smoothing) filters.

Assuming that the observed signal is in the form of (4), the variance determined on the basis of the signal samples is [17]

$$Var\left(X\right) = Var\left(S\right) + Var\left(S\right) + 2 \times \operatorname{cov}\left(S, N\right), \tag{6}$$

where $cov(S, N)$ is the covariance of random variables S and N.

Assuming that the random variables S and N are stochastically independent (not correlated), then $cov(S, N) = 0$ and further

$$Var\left(X\right) = Var\left(S\right) + Var\left(S\right). \tag{7}$$

To determine the interference variance, signal (4) must be filtered. For this purpose, an exponential smoothing filter was selected, described by the relationship [18]

$$y_k = \alpha \times x_k + (1-\alpha) \times y_{k-1}, \qquad k = 1 \ldots K, \tag{8}$$

where x_k and y_k are the elements of the input and output data sets, respectively, and $y_0 = x_0$. This means that the initial evaluation of the signal is the value of the chronologically earliest observation x_n. Parameter $\alpha \in (0, 1)$ is called the "smoothing constant".

The reduction of noise variance in the case of exponential smoothing for random interference $\{n_k\}$ of the average value of zero $E(n) = 0$ and variance $V(n) = \sigma^2_n$, is expressed by the relationship

$$\sigma_y^2 = \sigma_n^2 \times \frac{\alpha}{2-\alpha}, \tag{9}$$

where σ^2_n is the input noise variance, σ^2_y is the noise variance after smoothing, and $q = \alpha/(2-\alpha)$ is the noise suppression factor.

It is a type of digital filter where the y_k signal evaluation can be presented as a weighted average of the values of the signal from the previous period y_{k-1} and the latest observation x_k.

Assuming that the filtration process affects only the random variable of interference N, the new random variable Y takes the following form

$$Y_k = S_k + q \times N_k. \tag{10}$$

The choice of this filter was dictated by the fact that the assumption concerning reduction of just the interference is difficult to fulfil since all methods of smoothing in the frequency domain have low-pass characteristics, and thus also attenuate the useful signal [18]–[20]. For this reason, $\alpha = 0.95$ (smoothing factor) was used in the calculations, which caused the filter to interfere only slightly with the processed signal.

The variance of random variable Y is expressed by the relationship

$$Var(Y) = Var(S) + q \times Var(N), \tag{11}$$

where q is the noise suppression factor determined analytically for the given smoothing filter.

Subtracting the sides of equations (7) and (11) and transforming, we finally obtain the relationship for the variance of the interference of the form (1), which was used to determine the values of $Var(N_{High})$ and $Var(N_{Low})$ in (5)

$$Var(N) = \frac{1}{1-q} \times \left[Var(X) - Var(Y) \right]. \tag{12}$$

The method of determining the variance of interference (12) proposed by the authors is very simple to calculate as it requires only the determination of the variance of the interfered signal and the variance of the smoothed signal Y, as well as the knowledge of the noise suppression coefficient q - no specialist equipment is required for its determination.

Ultimately, the estimated value Q_{est} was calculated on the basis of the relationship

$$Q_{est} = \frac{1}{6} \times \frac{E(X_{High}) - E(X_{Low})}{\sqrt{Var(N_{High})} + \sqrt{Var(N_{Low})}}, \tag{13}$$

where correction parameter $p = 6$.

The value of this coefficient results from the fact that the calculated $Var(N)$ value represents the average power of interference, whereas σ in (1) is a measure of the dispersion from the mean value of the signal. The assumption of $p = 6$ is due to the fact that practically all values of the random variable N are within the range of six standard deviations from the mean value of normal distribution ($\sigma \sim 6 \cdot Var(N)^{½}$).

III. TEST RESULTS

To verify the effectiveness of the method proposed by the authors of the article for determining the Q parameter of optical fibre transmission, a number of tests were carried out. The tests were conducted in the Laboratory of Teleinformatic Technologies and Photonics of the West Pomeranian University of Technology in Szczecin (see Fig. 4).

Fig. 4. Photograph of the laboratory workstation.

The first tests to evaluate and verify the method were performed in a 1 Gbp network in the Fibre To The Home Passive Optical Network (FTTH-PON) system and were described in article [28].

The studies for 10 Gbps bit rate were conducted in a unique Alcatel-Lucent Dense Wavelength Division Multiplexing (DWDM) terabit transport network operating in C (1530 nm–1565 nm) and L (1565 nm–1625 nm) bands with the single-channel bit rate of 10 Gbps.

The results for 40 Gbps bit rate of the 10 GHz, 40 GHz, and 100 GHz laser linewidths of the transmitter were obtained using the eye diagram analysis method based on the nonlinear Schrödinger equation (NLSE) system using licensed RSOFT Optsim software (numerical certificate up to 160 Gbps per channel - 2010) and VPI Software (numerical certificate 2010–2015 and 2019–2021). The software listed above enables the analysis of transmissions above 1 Tbp.

The existing Alcatel-Lucent and Orange systems have numerical and hardware certificates for 10 Gbps single-channel transmission in the C (1530 nm–1565 nm) an L (1565 nm–1625 nm) band, as well as support on three software levels.

The system was designed with RSOFT software and then verified with Alcatel-Lucent's service software. The licence enables generating the bit rate of 1 Tbp in the C band, and in the case of Orange - 800 Gbps in the C and L bands. The certificate allows to expand the equipment and software up to the bit rate of 10 Tbps.

The measuring equipment owned and used by the laboratory comes from and has certificates of a recognised EXFO company in the field of power measurement devices, Optical Time Domain Reflectometer (OTDR), optical spectrum analysis, chromatic and polarization mode dispersion; the eye diagrams are prepared on equipment certified by Alnair Labs (optical oscilloscope operating in the C band), eye diagram analysis for any None Return to Zero (NRZ) and Return to Zero (RZ) codes, (band-width 500 GHz, 640 Gbps in a single channel), and Tektronix equipment (eye diagram analysis up to 2.5 GHz) (see Fig. 5).

The systems use certified components from Thorlabs, FCA, and Hewlett Packard.

A reference test signal (see Fig. 6) with $N = 8192$ samples and the following parameters were used for the tests:

– Q ~ 30 dB;

– µ1 ~ 2.5 × 10^{-5} - mean value of the signal in high state;

– µo ~ 2.5 × 10^{-6} - mean value of the signal in low state.

The time diagram of the reference test signal is presented in Fig. 6.

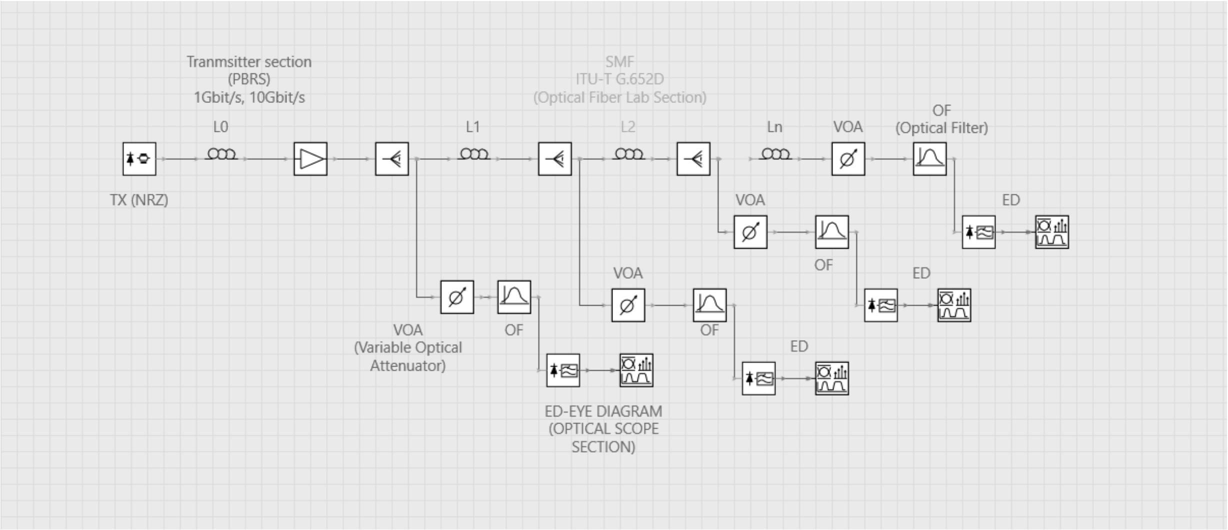

Fig. 5. Schematic diagram of the measuring circuit.

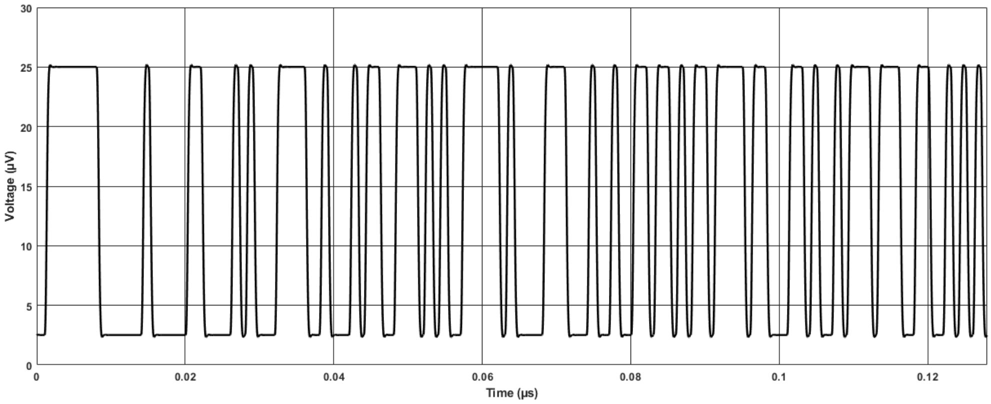

Fig. 6. Reference signal at transmitter output, Q ~ 30 dB, µ1 ~ 2.5 × 10^{-5} - mean value of the signal in high state, µo ~ 2.5 × 10^{-6} - mean value of the signal in low state.

To verify the effectiveness of the method proposed by the authors, a number of experiments were carried out.

The first experiment consisted of an artificial distortion of the reference signal with noise $\{n_k\}$, with normal distribution (Gauss), average value of zero $E(n) = 0$, and variance $V(n) = \sigma_n^2$, where the standard deviation value σ_n changed in the range of $\sigma_n = 1.0 \times 10^{-6}$–$2.0 \times 10^{-6}$, which corresponds to Q = 20 dB–14 dB.

Then the value of Q_{est} was estimated using (13). The results of the experiment are presented in Table I.

The experiment confirmed the effectiveness of the proposed method in the range of the assumed interference level. The results shown in Table I are highly consistent with the setpoint parameters of interference. Relative error value Q_{est} did not exceed 1.4 % and had a decreasing tendency. The lowest value (0.338 %) was observed for σ = 2,0 × 10^{-6}, i.e., at a relatively high level of interference.

The second experiment was based on the estimation of the Q parameter value from the output signals obtained for 10 Gbps transmission and 10 GHz laser linewidth for sections with the length of 10 km, 15 km, ..., 35 km.

The third experiment was based on the estimation of the Q parameter value from the output signals obtained for 40 Gbps transmission and 10 GHz, 40 GHz, and 50 GHz laser linewidths for sections with the length of from 10 m to 1600 m.

The obtained results are presented in Tables II and III. Examples of the time diagrams of the output signals are shown in Figs. 7–9. As can be noted, the individual signals are attenuated and increasingly distorted.

The results of the studies presented in Tables II and III indicate that the proposed algorithm is highly effective. It is especially visible in the case when the classic (described in the standards) method of analysing the eye diagram indicates the value of BER significantly deviating from the norm for transmission at a given bit rate due to problems with mask application (Fig. 10 - closed eye). In this case, the expert can estimate the quality of the output signal.

TABLE I. RESULTS OF THE EXPERIMENT CONSISTING IN THE ESTIMATION OF σ (σ2 - NOISE POWER) AND Q FROM THE REFERENCE SIGNAL, PRESENTED IN FIG. 6, DISTURBED BY NOISE OF NORMAL DISTRIBUTION N(0, σ),WHERE $\sigma = 1.0 \times 10^{-6}$–$2.0 \times 10^{-6}$, WHICH CORRESPONDS TO Q = 20 dB–14 dB.

No.	**σ - set point value**	**Q [dB]**	**BER**	**Estimated value of σ**	**Q_{est} [dB]**	**BER calculated from Q_{est} estimated**	**Relative error in % of Q estimate in dB**
1	1.0×10^{-6}	20.32	$1.61\cdot\times 10^{-25}$	$1.033\cdot\times 10^{-6}$	20.044	$4.56\cdot\times 10^{-24}$	1.378
2	$1.1 \times\cdot 10^{-6}$	19.49	$2.10 \times\cdot 10^{-21}$	$1.129 \times\cdot 10^{-6}$	19.269	$1.91\cdot\times 10^{-20}$	1.169
3	$1.2 \times\cdot 10^{-6}$	18.74	$2.58\cdot\times 10^{-18}$	$1.226 \times\cdot 10^{-6}$	18.553	$1.28 \times\cdot 10^{-17}$	1.001
4	$1.3 \times\cdot 10^{-6}$	18.04	$7.32\cdot\times 10^{-16}$	$1.324\cdot\times 10^{-6}$	17.889	$2.21 \times\cdot 10^{-15}$	0.865
5	1.4×10^{-6}	17.40	$6.17\cdot\times 10^{-14}$	$1.422\cdot\times 10^{-6}$	17.271	$1.40 \times\cdot 10^{-13}$	0.752
6	$1.5 \times\cdot 10^{-6}$	16.80	$2.28\cdot\times 10^{-12}$	$1.520\cdot\times 10^{-6}$	16.692	$4.16\cdot\times 10^{-12}$	0.656
7	$1.6\cdot\times 10^{-6}$	16.24	$4.40\cdot\times 10^{-11}$	$1.618\cdot\times 10^{-6}$	16.149	$6.87\cdot\times 10^{-11}$	0.575
8	1.7×10^{-6}	15.72	$4.99\cdot\times 10^{-10}$	$1.716\cdot\times 10^{-6}$	15.636	$7.21\cdot\times 10^{-10}$	0.504
9	$1.8\cdot\times 10^{-6}$	15.22	$4.02\cdot\times 10^{-9}$	$1.815\cdot\times 10^{-6}$	15.152	$5.24 \times\cdot 10^{-9}$	0.442
10	$1.9\cdot\times 10^{-6}$	14.75	$2.33\cdot\times 10^{-8}$	$1.914\cdot\times 10^{-6}$	14.692	$2.86\cdot\times 10^{-8}$	0.387
11	$2.0\cdot\times 10^{-6}$	14.30	$1.06\cdot\times 10^{-7}$	$2.013 \times\cdot 10^{-6}$	14.256	$1.22\cdot\times 10^{-7}$	0.338

TABLE II. RESULTS FOR 10 GBPS BIT RATE.

Transmission distance [m]	**Transmitter laser spectrum linewidth [GHz]**	**Q parameter**	**BER**	**Expert Evaluation**	**Q_{est} Estimated**	**BER Calculated from Q estimated**
10	5	21.17	0.00	1	15.01	5.3×10^{-51}
100	5	13.70	3.8×10^{-41}	1	12.32	5.5×10^{-35}
500	5	10.27	3.5×10^{-25}	2	11.30	7.0×10^{-30}
700	5	7.14	3.8×10^{-13}	2	10.34	3.1×10^{-24}
900	5	3.76	8.1×10^{-5}	3	8.22	1.2×10^{-16}
1100	5	2.73	0.0031	3	5.61	1.1×10^{-8}

Note: where expert evaluation: 1 - Transmission quality very good, 2 - ITU-T-compliant quality, 3 - Laboratory quality (below standards, but correction of errors possible).

TABLE III. RESULTS FOR 40 GBPS BIT RATE.

Transmission distance [m]	**Transmitter laser spectrum linewidth [GHz]**	**Q parameter**	**BER**	**Expert Evaluation**	**Q_{est} Estimated**	**BER Calculated from Q estimated**
10	10	52.59	0.00	1	29.10	4.4×10^{-179}
100	10	25.79	0.00	1	22.70	3.0×10^{-114}
500	10	11.10	4.6×10^{-29}	2	20.73	9.7×10^{-96}
700	10	7.50	2.3×10^{-14}	2	15.99	6.8×10^{-58}
900	10	6.15	2.7×10^{-10}	2	15.26	7.4×10^{-53}
1100	10	5.11	1.3×10^{-7}	3	13.55	3.9×10^{-42}
1600	10	4.10	1.6×10^{-5}	3	11.24	1.3×10^{-29}
200	50	11.74	3.0×10^{-32}	2	21.95	4.5×10^{-107}
400	50	5.67	5.6×10^{-9}	2	16.51	2.0×10^{-61}
600	50	4.20	1.1×10^{-5}	3	8,712	1.1×10^{-16}
800	50	3.37	3.1×10^{-4}	3	3.12	9.1×10^{-4}
200	100	8.14	1.7×10^{-16}	2	35.51	0.00
400	100	4.07	1.9×10^{-5}	3	6.41	7.3×10^{-11}
600	100	3.08	8.8×10^{-4}	3	4.53	2.9×10^{-6}
800	100	2.23	0.0125	No eye diagram	3.43	3.0×10^{-4}

Note: where expert evaluation: 1 - Transmission quality very good, 2 - ITU-T-compliant quality, 3 - Laboratory quality (below standards, but correction of errors possible).

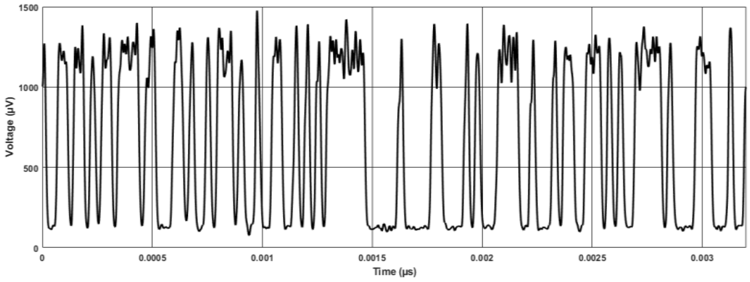

Fig. 7. Signal at detector output - optical fibre cable length L = 500 m, bit rate 40 Gbps and spectrum linewidth 10 Ghz, Q ~ 11 µ1 ~ 1,2·× 10^{-3} - mean value of the signal in high state, µo ~ 1.2·× 10^{-4} - mean value of the signal in low state reference signal at transmitter output, Q ~ 30 dB, µ1 ~ 2.5·× 10^{-5} - mean value of the signal in high state, µo ~ 2.5·× 10^{-6} - mean value of the signal in low state.

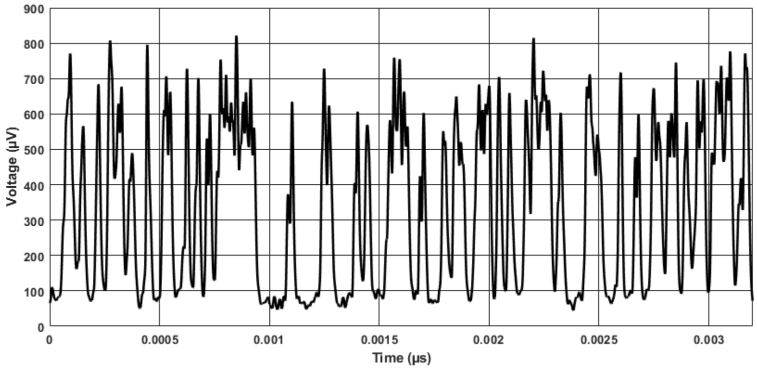

Fig. 8. Signal at detector output - optical fibre cable length L = 400 m, bit rate 40 Gbps and spectrum linewidth 100 Ghz, Q ~ 4.1 µ1 ~ 6 × 10^{-4} - mean value of the signal in high state, µo ~ 1 × 10^{-4} - mean value of the signal in low state.

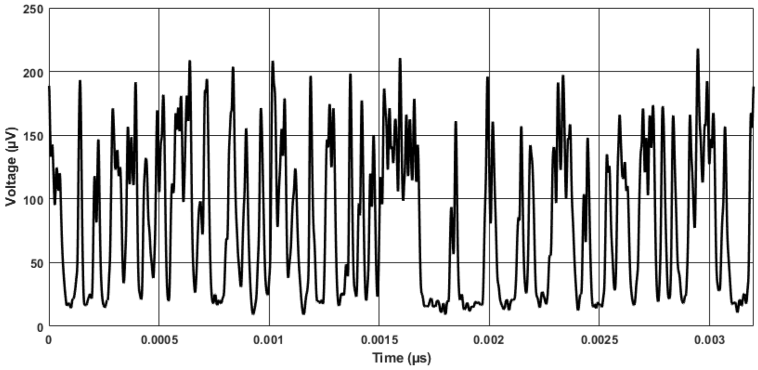

Fig. 9. Signal at detector output - optical fibre cable length L = 500 m, bit rate 40 Gbps and spectrum linewidth 50 Ghz, Q ~ 5.7 µ1 ~ 1.4 × 10^{-4} - mean value of the signal in high state, µo ~ 2 × 10^{-5} - mean value of the signal in low state.

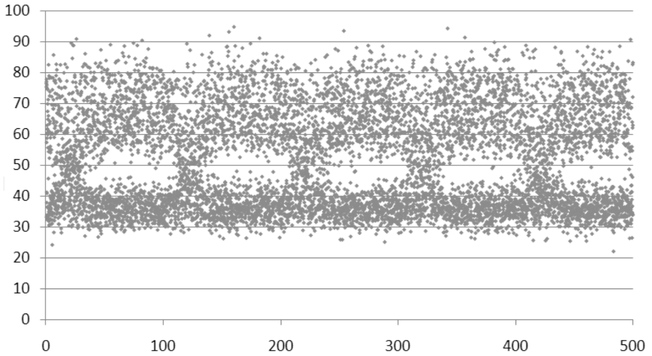

Fig. 10. Actual eye diagram for the Alcatel-Lucent system (B = 10 Gbps, FWHM = 10 GHz, 35 km) - critical case BER = 0.0031 (copy of the oscilloscope screen).

The intervention of an expert is unnecessary, which greatly simplifies and speeds up the measurement procedure.

It is also possible to recover the parameters of the eye diagram by means of forward error correction (FEC) and determine whether the signal is suitable for transmission despite significant interference after error correction - so-called "laboratory quality". In this case, the BER parameter, determined by the algorithm presented by the authors, unambiguously defines the quality of transmission as satisfactory.

The results of the experiments collected in the tables show that the method proposed in this paper works in each case. It is worth noting that the method is also effective in cases of a critical decrease of the transmission distance resulting from high bit rate.

IV. CONCLUSIONS

The proposed method has been evaluated in the Laboratory of Teleinformatic Technologies and Photonics of the West Pomeranian University of Technology in Szczecin. The laboratory has dedicated modern equipment for testing access and transport systems with 1 Gbp, 2.5 Gbps, and 10 Gbps bit rate in a single channel and 40 Gbps, 80 Gbps, 400 Gbps, and 800 Gbps in systems with multiplexing. The equipment was provided by Orange and Alcatel-Lucent. The Alcatel Lucent system can provide transmissions of 3.2 Tbps (88 channels at 40 Gbps).

The conducted research indicates good applicability of the existing classic algorithms of eye diagram evaluation for networks with bit rates up to 10 Gbps, and in particular:

– 1 Gbp (1 Gigabit Ethernet);
– 1.25 Gbps (GPON, Gigabit Passive Optical Network);
– 2.5 Gbps (GPON);
– Up to 10 Gbps (10 Gigabit Ethernet).

While in systems with bit rates:

– Over 10 Gbps with a range exceeding 10 km–20 km (WDM, XG-PON);
– 40 Gbps and higher (NG-PON2, DWDM);
– There are additional interference effects in the eye diagrams which cause that the classic determination of the Q parameter and the following determination of the bit error rate BER may lead to incorrect estimates and conclusions. In such cases, the method based on expert observation plays an important role. However, this method is time-consuming and requires a high level of knowledge and experience.

The method proposed by the authors in this study clearly correlates with classic methods (described in standards) for bit rates up to 10 Gbps, confirming its effectiveness. Its main advantage is the unambiguous and objective result of diagnostic analysis in the case of tests at bit rates above 10 Gbps. For this range of bit rates, the proposed method provides results consistent with the expert assessment made on the basis of observation (subjective assessment) of the initial diagrams and eye diagram correction. An additional advantage of the proposed method is its simplicity - it can be implemented in real-time devices, where the measurement of the transmission parameters is performed on an ongoing basis.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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