Channel Performance Criteria in Optical Transport Systems with Forward Error Correcting Codes

A.V. Lobzov, L.N. Isaeva
Moscow Technical University of Communications and Informatics
Moscow, Russia
l.n.isaeva@mtuci.ru

S.S. Kogan
LLC «T8»
St-Peterburg, Russia
kogan@t8.ru

***Abstract*— In this paper we discuss the channel performance criteria in the optical transport networks (OTN)/dense wavelength division multiplexing (DWDM) networks with forward error correction (FEC) codes. The interdependent parameters used to evaluate the optical signal quality in OTN/DWDM channels are presented in this article: signal to noise ratio (SNR), optical signal to noise ratio (OSNR) and the Q-factor. The main role of FEC is to reduce the permissible the OSNR in the optical channel of OTN/DWDM systems. To monitor the status of optical channels, bit error rate (BER) on pre-FEC level of the receiving side of the optical channel can be used. By setting the appropriate threshold and interval of the error control at the pre-FEC level, the proactive actions can be taken even before the limit of FEC's error detection and correction capabilities is reached. In this article we presented our investigation of relationship between SNR/OSNR and Q-factor measurements.**

Keywords*— *optical signal to noise ratio (OSNR), Q-factor, bit error rate (BER,) forward error correction (FEC), optical spectrum analyzer (OSA).

I. INTRODUCTION

The optical telecommunication systems based on optical transport network (OTN)/dense wavelength division multiplexing (DWDM) systems provide fast, secure, and reliable long-distance data transmission. As the transmission rate increases, more and more factors limit the signal transmission distance: chromatic dispersion, polarization mode dispersion, nonlinear effects, etc.

The main directions of development of OTN/DWDM systems are to increase the rate and the distance of data transmission over optical channels. The forward error correction (FEC) is a technique for encoding/decoding a signal with the ability to detect errors and correct information using the FEC method [1, 2]. FEC dramatically reduces the number of the bit error rate (BER), which allows you to increase the distance of signal transmission over an optical channel without regeneration, that is, without optical-electrical-optical (OEO) conversion.

The main role of FEC is to reduce the permissible the optical signal-to-noise ratio (OSNR) value in the optical channel [3, 4]. To monitor the status of optical channels, the pre-FEC level on the receiving side of the optical channel is used.

This paper is devoted to the optical channels performance criteria in optical transport systems with FEC. In this paper we consider of the interdependent parameters used to evaluate the optical signal quality in OTN/DWDM channels, namely signal to noise ratio (SNR), OSNR and Q-factor.

The SNR, OSNR and the Q-factor can be measured using special measuring equipment, for example, the optical spectrum analyzers (OSA). The issues of OSNR and Q-factor measurements are the points of the investigation.

II. THE OPTICAL CHANNEL SIGNAL QUALITY EVALUATION

A measure of the “noisiness” of a signal is the SNR value – the ratio of signal power to noise power:

$$SNR = \frac{P_S}{P_{NOISE}} = \frac{P_S}{N_{NOISE} \cdot B_{SYM}} \qquad (1)$$

where

P_S - the signal power;

P_{NOISE} - the noise power;

B_{SYM} - the symbol rate;

N_{NOISE} - the noise power spectral density.

The difference between SNR and OSNR: in OSNR noise power is measured in the reference band, and not in the signal band:

$$OSNR = \frac{P_S}{P_{NOISE,ref}} = \frac{P_S}{N_{NOISE} \cdot \Delta \nu_{ref}} \qquad (2)$$

where

$P_{NOISE,ref}$ - the noise power at the optical signal wavelength;

$\Delta\nu_{ref}$ - the reference bandwidth in which noise is considered.

OSNR is

978-1-5386-1786-1/17/$31.00 ©2017 IEEE

- a measure of signal quality on an optical link. OSNR demonstrates how much the signal power exceeds the noise power. OSNR is the ratio of signal power to optical channel noise power after passing through the optical network. By increasing OSNR value, the quality of the optical signal in the channel improves [5].
- the main parameter characterizing the quality of transmission of modulated optical signals [6].
- the ratio of the optical signal power to the noise power within a certain bandwidth, as opposed to SNR, that is the ratio of the power of any signal, including optical, to the noise power over all frequency range.

OSNR are most important to the receiver. When the OSNR value is low, the signal will not be detected by the receiver. In general, the value of OSNR within the optical channel is defined as [7]:

$$OSNR = 10\log\frac{P_i}{N_i} + 10\log\frac{B_m}{B_r}, dB \qquad (3)$$

where:

P_i – the optical signal power transmitted within the optical channel bandwidth;

N_i – the noise power at the optical signal wavelength;

B_m – the optical bandwidth taken by the optical channel;

B_r – the reference bandwidth in which noise is considered.

It is recommended, $B_r = 0.1$ nm.

Despite the fact that OSNR does not show and does not allow to assess the effect of temporary disturbances on the performance of the optical channel, OSNR is one of the most used parameters obtained from the measured spectrum of the optical signal and is one of the optical interface parameters indicated in ITU-T G.692, G.959.1. OSNR is associated with BER [8]. OSNR allows you to obtain information about BER indirectly through the equation given in [9].

The quality of the transmitted signal is determined by the BER, which increases with increasing noise level, because the source of errors is noise.

Poor SNR leads to a deterioration of BER; ITU-T G.692 suggests determining the minimum required OSNR for a given system design. Since OSNR is a low-speed measurement of average power, it does not detect rare bit errors and does not disclose the consequences of temporary violations. Note here that OSNR relationship with BER makes OSNR the main parameter derived from optical signal spectrum to perform pre-estimation of DWDM performance or to monitor DWDM system and to receive warning about potential deterioration of BER in measured optical channel. The measurement of OSNR in DWDM systems is described in IEC 61280-2-9:2009.

OSNR is measured by OSA. There are several methods for measuring OSNR: out-of-band without channel disabling, out-of-band with functional interpolation, in-band with channel disabling, in-band without channel disabling [10]. You can measure OSNR using both out-of-band methods by OSA, for example, ANRITSU MS9740B [11, 12]. The in-band method without channel disabling is implemented in OSA of Viavi Solutions Inc. [13].

The Q-factor (quality) is a parameter that directly reflects the signal quality of a digital transmission system, it is a measure of optical signal quality, which is a function of BER, optical signal power and noise power [14, 15, 16]. In general, BER refers to the ratio of the number of erroneous bits to their total transmitted number. The measurement of the Q-factor occupies an intermediate position between the classical optical parameters, namely, the optical power level, OSNR, wavelength, and the performance parameters like BER [6]. Q-factor is a complex measure of the optical channel signal quality, in consideration the influence of noise, filtering and linear/nonlinear distortions on the pulse shape, which cannot be determined using classical the optical parameters alone.

In accordance with [17], Q-factor measurement is a common method for determining the characteristics of optical channels. This technique is particularly advantageous at low bit error rates because it requires less time than traditional BER measurement when bit errors need to be counted for a statistically significant period of time. In the optical systems, for example DWDM, measurement of the error coefficient must be performed in each optical channel, which takes a lot of time. To reduce the time of monitoring the channel without interruption of information transmission, a method based on the evaluation of the Q-factor is used, which is the ratio [17]

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

where,

μ_1 and μ_0 – the mean voltage level of the 1 and 0 levels;

σ_1 and σ_0 – the standard noise distribution deviations on the 1 and 0 levels.

The values of μ_1 and μ_0, σ_1 and σ_0 are fixed at the photodetector device output in the eye diagram parameters form: Q-factor can be determined by statistical processing of the results of measuring the signal amplitude, phase at the electrical level, namely, directly from the eye diagram. The higher the value of the Q-factor, the better the optical signal quality. The Q-factor is usually estimated in decibels [17]:

$$Q_{(decibels)} = 20\lg Q_{(linear)} \qquad (5)$$

To evaluate signal quality in optical channels, two main interdependent parameters are used - OSNR and Q-factor. A change in one parameter affects the other [5]. The acceptable range of OSNR and Q-factor depends on the particular using and design of DWDM system. Higher OSNR and Q-factor values usually occur in an optical signal with better quality. Moreover, a small change in OSNR can lead to a serious change in the Q-factor, than is characteristic of the logarithmic dependence of these parameters. Usually, the Q-factor increases as the OSNR increases. However, at the high OSNR values, the Q-factor value achieves the saturation point and further the increasing OSNR does not improve Q-factor. The improvement of OSNR and Q-factor in an optical channel is possible by reducing noise sources, optimizing system design, and using higher components.

The measuring of the OSNR and Q-factor in an optical channel in real-time possible by using measurement instruments such as OSA and BER tester. To measure Q-factor, it is possible to use, for example, OSA-501M of Viavi Solutions Inc. measurement equipment. It has a channel-drop function, which allows to select one optical channel from the spectrum in order to analyze the signal in more detail using BER testing (BERT) or a quality indicator meter (Q-factor).

III. THE MONITORING OF THE OPTICAL CHANNELS STATE

Since errors are monitored on the receiving side of the optical systems on all ports of all optical channels, then by the value of the BER control at the pre-FEC level, the preliminary data on the degradation of the channel parameters can be obtained. It should be noted that both the BER threshold for signal degradation and the BER measurement interval must be adjusted:

- the threshold defines the BER criteria for the signal degradation state: if the BER in the fiber-optic line is below the threshold value of the FEC circuit, then all errors are corrected by the FEC circuit and the data loss does not occur;
- the interval defines the minimum time interval (minimum amount of data) during the BER must exceed the threshold value before an alarm is raised.

By setting the appropriate threshold and interval of the error control at the pre-FEC level, proactive actions can be taken even before the limit of FEC's error detection and correction capabilities is reached.

IV. THE MAIN TYPES AND CRITERIA FOR THE EFFECTIVENESS OF USING FEC CODES IN THE OPTICAL CHANNELS

The error detection is an action aimed at monitoring the integrity of data when recording/reproducing information or when transmitting it over communication lines. The error correction is a procedure for restoring information after reading it from a storage device or communication channel. The corrective ability determines how many code transmission errors can be guaranteed to be corrected. To do this, when writing (transmitting), specially structured redundant information (a control number) is added to the payload, and when reading (receiving) it is used to detect or correct errors.

The methods for detecting and correcting errors significantly affect the optical channel performance of OTN/DWDM systems. Thus, in channels with a capacity of 100 Gbit/s, the minimum OSNR value should be about 10 dB higher than in channels with a capacity of 10 Gbit/s. Without specific correction or compensation, the OSNR for the optical signal will limit data transmission over 100 Gbit/s capacity channel to very short distances. The maximum transmission distance over a standard single-mode optical fiber can be about 40 km.

In order to maintain high quality (i. e. low BER) transmission of a useful signal over optical channels over long distances, in accordance with [1], a variety of FEC codes with the error detection and correction are used.

Two types of FEC technologies are known:

- the in-band FEC: defined by ITU-T G.707. This method allows to detect and correct the data errors on the receiving side without increasing the data rate or returning information to the transmitting side. To add redundant bytes of codes such as Reed-Solomon, BCH, and others, free positions are used in the service part of synchronous digital hierarchy (SDH) frame. FEC bytes are loaded at the position of a portion of the free overhead byte in the SDH frame. The net gain from encoding does not exceed 3-4 dB;
- the out-of-band FEC: defined by ITU-T G.975. The FEC bytes are placed in the overhead part of the OTU. This type of FEC has great coding redundancy, advanced error correction capabilities, high flexibility and high coding gain of at least 5-6 dB. For the OTN system, the Reed-Solomon FEC (RS-FEC) is defined.

There are three main criteria of the FEC efficiency:

- the net coding gain (NCG);
- the required number of additional bytes for FEC in the OTN frame overhead;
- pre-FEC BER threshold.

A. *The net coding gain (NCG)*

The NCG is a net gain from encoding, that is, an improvement in OSNR requirements provided by a signal with FEC compared to a signal without FEC. The modern FEC algorithm usually provides a net gain from encoding of the order of 10-12 dB [4].

G.709 defines the error correction for OTN/DWDM channels, which can lead to an SNR improvement up to 6.2 dB. This means that it is possible to receive a signal with a certain BER with an optical power level 6.2 dB lower than without FEC.

This result allows:

- to increase the maximum length of the optical transport section (OTS) and/or the number of the OTS, which will increase the communication distance. At the same time, chromatic dispersion, polarization mode dispersion does not become limiting factors;
- to increase the number of channels (wavelengths) in the OTN/DWDM group signal by reducing the optical power level in the optical channel and increasing the channels number. At the same time, nonlinear interactions change due to a decrease in power in optical channel are also taken into account;
- to reduce the requirements for optical channel parameters such as the optical output power level on the transmitting side, eye diagram parameters, attenuation coefficient, noise coefficient, etc., as well as reduce the cost of components. An eye diagram is a convenient

graphical way to evaluating the digital signal quality on the receiving side of an optical channel. It is the result of superimposing all possible pulse sequences over a time interval equal to two clock intervals of a linear signal.

B. The required number of additional bytes for FEC in the OTN frame overhead

The redundancy factor is the FEC bits ratio to the transmitted data bits. The NCG value and network parameters increase as the service bits used for FEC increase (up to a certain limit). Today's high performance FECs work with 15-25% extra overhead bytes in the OTN frame overheader

C. Pre-FEC BER threshold

The pre-FEC BER threshold is the worst BER, which is still corrected by the FEC algorithm. The advantage of modern FECs is that they accept distorted incoming signals, correct errors, and convert an error-prone data stream into an almost error-free data stream.

V. THE RELATIONSHIP BETWEEN OSNR AND Q-FACTOR

Q-factor parameter can be measured using OSA or bit error rate tester.in any optical channel without interrupting communication based on BER at the pre-FEC level. But at a high level of OSNR, it is impossible to estimate OSNR based on the results of Q-factor measurements.

The situation with carrying out measurements of OSNR without interruption of communication is more complicated. It means that this question is still the subject of debate. Of the known effective methods implemented in OSA, only the correlation method is known so far [10, 11].

It is possible to increase the values of OSNR and Q-factor, it is necessary to reduce sources of noise, to optimize the design of the DWDM system, and to use better components.

VI. CONCLUSIONS

In this article we presented the results if our investigation of the relationship between electrical SNR vs optical SNR vs Q-factor.

Electrical SNR – ratio of signal power to noise power in the signal band. Optical SNR - the ratio of signal power to noise power in a fixed band (independent of the signal band) is used due to the convenience of measurements using OSA. OSNR is the degree quantify of noise interference on optical signals.

In the case of errors occurs in optical channels the direct (interdependent) logarithmic relationship between OSNR and BER or Q-factor exist.

At high level of OSNR, for errors free optical channel, it is impossible to estimate OSNR based on the results of Q-factor measurements, because Q-factor reaches a saturation point.

As a result of our investigation, in error free cases OSNR and the Q-factor can be foreseen as the independent parameters to evaluate the signal quality in optical channels of OTN/DWDM systems.

Promising development of OTN/DWDM system is in the direction of increasing OSNR and Q-factor values, developing new modulation methods, using machine learning algorithms to optimize OTN/DWDM system parameters.

REFERENCES

[1] ITU-T Recommendation G.709/Y.1331 “Interfaces for the optical transport network”.

[2] C. Kachris, G. Tzimpragos, D. Soudris and I. Tomkos, "Reconfigurable FEC codes for software-defined optical transceivers," 2014 13th International Conference on Optical Communications and Networks (ICOCN), Suzhou, China, 2014, pp. 1-4, doi: 10.1109/ICOCN.2014.6987087.

[3] A. Tychopoulos, O. Koufopavlou and I. Tomkos, "FEC in optical communications - A tutorial overview on the evolution of architectures and the future prospects of outband and inband FEC for optical communications," in IEEE Circuits and Devices Magazine, vol. 22, no. 6, pp. 79-86, Nov.-Dec. 2006, doi: 10.1109/MCD.2006.307281.

[4] Z. Zhao, A. Yang and P. Guo, "A Modulation Format Identification Method Based on Information Entropy Analysis of Received Optical Communication Signal," in IEEE Access, vol. 7, pp. 41492-41497, 2019, doi: 10.1109/ACCESS.2019.2907521.

[5] ITU-T Recommendation G.697 “Optical monitoring for DWDM systems”.

[6] L. N. Isaeva, A. V. Lobzov and S. S. Kogan, "Analysis of Critical Parameters of Promising Optical Interfaces of High-Speed Telecommunication Systems," 2023 Wave Electronics and its Application in Information and Telecommunication Systems (WECONF), St. Petersburg, Russian Federation, 2023, pp. 1-6, doi: 10.1109/WECONF57201.2023.10147990.

[7] ITU-T Recommendation G.Sup39. “Optical system design and engineering considerations”.

[8] S. Sahu, J. C. Clement, I. S, E. E. I and C. D. S, "BER and OSNR Based Quality Estimation in Optical Networks using Machine Learning Algorithms," 2023 2nd International Conference on Vision Towards Emerging Trends in Communication and Networking Technologies (ViTECoN), Vellore, India, 2023, pp. 1-6, doi: 10.1109/ViTECoN58111.2023.10157886.

[9] The dependence of the error coefficient on the signal power and the length of a single-span single-channel coherent communication line (100 Gbit/s) with polarization multiplexing / N. V. Gurkin, V. A. Konyshev, O. E. Naniy [et al.] // Quantum Electronics. - 2015. – vol. 45, No. 1. – pp. 69-74.

[10] L. N. Isaeva, A. V. Lobzov and S. S. Kogan, "Measuring of Optical Signal to Noise Ratio in High-Speed Coherent Channels of Optical Transmission Systems," 2024 Systems of Signals Generating and Processing in the Field of on Board Communications, Moscow, Russian Federation, 2024, pp. 1-5, doi: 10.1109/IEEECONF60226.2024.10496760.

[11] L. N. Isaeva, S. S. Kogan, A. V. Lobzov and S.N. Lukinych, "Measurement of optical signal-to-noise ratio (OSNR) in high-speed coherent DWDM channels," in Scientific and technical magazine ‘Foton-Express’, 2023, vol. 6, doi: 10.24412/2308-6920-2023-6-64-65.

[12] MS9740B Optical Spectrum Analyzer. Operation Manual.

[13] “VIAVI OSCA-710. Datasheet”, 15.05.2024; https://www.viavisolutions.com/en-us/literature/osca-710-first-service-pol-mux-optical-spectrum-spectrum-and-correlation-analyzer-data-sheets-en.pdf.

[14] B. Nebendahl et al., "Quality Metrics in optical modulation analysis: EVM and its relation to Q-factor, OSNR, and BER," 2012 Asia Communications and Photonics Conference (ACP), Guangzhou, China, 2012, pp. 1-3.

[15] W. Freude et al., "Quality metrics for optical signals: Eye diagram, Q-factor, OSNR, EVM and BER," 2012 14th International Conference on Transparent Optical Networks (ICTON), Coventry, UK, 2012, pp. 1-4, doi: 10.1109/ICTON.2012.6254380.

[16] B. Gul and F. Ahmad, "Multistage Amplified and Dispersion Compensated Ultra-long Haul DWDM Link with High OSNR," 2022 Fourth International Conference on Emerging Research in Electronics, Computer Science and Technology (ICERECT), Mandya, India, 2022, pp. 1-4, doi: 10.1109/ICERECT56837.2022.10060237.

[17] ITU-T Recommendation O.201. “Q-factor test equipment to estimate the transmission performance of optical channels”.