Measuring of Optical Signal to Noise Ratio in High-Speed Coherent Channels of Optical Transmission Systems

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***Abstract*— In this paper we discuss the methods for measuring optical signal to noise ratio (OSNR) in high-speed coherent channels of optical transmission systems. The following OSNR measurement methods are presented in this article: out-of-band without channel disabling (but such a method has its own limitations in the field of application) and in-band with or without disabling the optical channel. In-band or in-service methods of measuring of the OSNR in next generation optical dense wavelength division multiplexing (DWDM) systems with coherent optical channels, polarization multiplexing and quadrature amplitude modulation (QAM) format is still under discussion. This article states that it is preferable to calculate OSNR without disabling the optical channels based on an estimation of the correlation relationships between spectral components at predetermined pairs of spaced wavelengths.**

Keywords*— optical signal to noise ratio (OSNR), amplified spontaneous emission (ASE), optical polarization splitting (OPS) , spectral correlation method (SCorM), optical spectrum analyzer (OSA).

I. Introduction

Noise inherent in optical line amplifiers, as well as linear (chromatic and polarization dispersion) and nonlinear effects in the linear path of dense wavelength division multiplexing (DWDM) systems limit the ability to transmit high-speed services through channels of optical systems over long distances without intermediate regeneration at the level of an electric signal, that is, without optical-electrical-optical (OEO) conversion.

Optical signal-to-noise ratio (OSNR) is the main parameter characterizing the transmission quality of modulated optical signals [1].

The OSNR parameter is typically obtained by measuring the total signal power in the channel bandwidth and noise levels between optical channels [2]. This method is called out-of-band OSNR measurement. In networks with reconfigurable optical add-drop multiplexers (ROADMs) in intermediate nodes of the line path of optical transport network (OTN)/DWDM systems, noise between optical channels is suppressed by the optical filters built into the ROADM. This feature of modern optical networks limits the ability to measure OSNR by the out-of-band method. By measuring the noise power within the optical channel bandwidth, it is possible to obtain a "true" OSNR value called in-band OSNR [3].

Telecommunications standards describe several methods for measuring OSNR in DWDM systems, but until now, for systems using polarization multiplexing and ROADM nodes in network topology, there is no universal method for measuring the in-band OSNR value in operating OTN/DWDM systems, that is, without interruption of communication, namely, without the disabling of the optical channel.

The paper provides the overview and the comparison of methods for measuring out-of-band as well as in-band OSNR, including methods for measuring in-band OSNR that do not require the disabling off of optical channel during OSNR measurement.

II. OSNR in the Optical Transmission Systems

The signal-to-noise ratio (SNR) is equal to the ratio of the power of the desired signal to the noise power in the spectral interval of the optical channel and is determined [4]:

$$SNR = \frac{P_{ch}}{P_{ASE} + P_{NLI}} \quad (1)$$

where,

P_{ch} – the channel power within the bandwidth of the optical channel (CH);

P_{ASE} – the noise power amplified spontaneous emission (ASE) generated by all the optical amplifier along the signal transmission path in the optical channel bandwidth;

P_{NLI} – the overall equivalent nonlinear interference (NLI) power in the channel frequency band due to the noises generated by interfering the optical channel under test and others optical channels.

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A. *Linear component of the noise impact on the optical channel*

In general, these are linear signal distortions that do not cause additional components due to the amplitude-frequency characteristic non-uniformity and phase-frequency characteristic non-linearity and the like. Meanwhile, compensation for fiber losses using the optical erbium-doped fiber amplifiers (EDFA) to increase the transmission range leads to the appearance of ASE. The noise component of ASE occurs if the pumping level in the optical amplifier is so high that the "spontaneous" radiation is amplified by stimulated emission. In this case, the optical amplifier, in the presence of optical/electrical pumping, spontaneously emits light.

ASE optical sources typically possess:

- the broadband spectrum;
- the low coherence.

The ASE noise is taken into account when planning a network with the additive white Gaussian noise (AWGN) - the most common type of noise used to calculate and model the radio communication systems - with low coherence:

a) interfering noise impact of AWGN in the information transmission channel is characterized by:

- uniform, that is, the same at all frequencies, spectral power density;
- normally distributed time values;
- an additive way of influencing on the signal: the term "additive" means that this type of noise is summed up with the useful signal and is statistically independent of the signal;

b) coherence - in physics means the correlation (consistency) of several vibrational or wave processes in time, manifested when they are added. Oscillations are coherent if their phase difference is constant in time, and when the oscillations are added, a oscillation of the same frequency is obtained.

The transmitted signals may also be significantly distorted due to chromatic dispersion (CD) and polarization mode dispersion (PMD).

B. *Nonlinear component of the noise impact on the optical channel*

Transmission characteristics in multichannel optical transmission systems are influenced not only by linear AWGN of ASE type, but also by nonlinear noise occurring in the optical fiber. At high levels of power in the fiber, nonlinear optical phenomena begin to play a noticeable role, leading to various nonlinear distortions of transmitted signals. The reason for such phenomena is a change in the properties of the fiber material under the influence of high-intensity light propagating in it [5].

Nonlinear interference between channels is generally treated as noise. Understanding the features and statistical characteristics of nonlinear interference noise (NLIN) is crucial for efficient design and accurate prediction of the characteristics of the optical transmission systems [6].

The optical power level of each optical channel must be:

- higher to achieve better OSNR values;
- but not so much that non-linear effects began to appear.

The NLIN, among other things, is associated with the optical sections and their number along the signal transmission path. With a certain number of optical sections, a system limitation is achieved: with a further increase in the number of sections, nonlinear interactions become decisive.

It should be noted that nonlinear distortions in the fiber become dominant in the single-span transmission line when the value of the accumulated chromatic dispersion is low [7].

III. OUT-OF-BAND OSNR MEASUREMENT METHODS WITHOUT WITHOUT CHANNEL DISABLING

For optical 10G channels whose frequency spectrum is less than the frequency grid spacing of the optical channels of 50 GHz or 100 GHz, out-of-band OSNR measurement methods without channel disabling were used [8]:

• with linear interpolation (presented in [9]);

• with an approximation of the noise response in the optical channel frequency band (offered by ANRITSU [10]).

A. *Out-of-band OSNR Method with Linear Interpolation*

According to [8, 9], the out-of-band measurement method is to measure the noise level at the midpoints between the measured channel and the two adjacent channels, that is, P_{NL} (noise at the left interval) and P_{NR} (noise at the right interval), and then calculate the noise level in the measured channel by averaging the two above noise level values to obtain noise values (P_N), thus performing linear interpolation:

$$P_N = \frac{P_{NL} + P_{NR}}{2} \qquad (2)$$

The OSNR can then be calculated by interpolating the noise values to the right and to the left from the channel (figure 1 [9]).

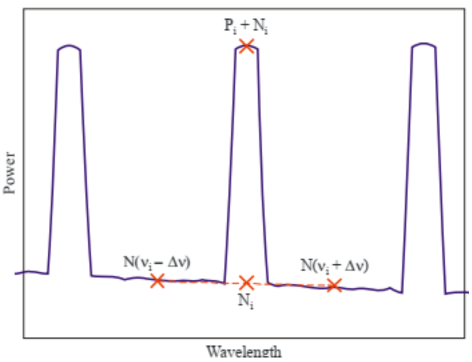

Fig. 1. Estimation of the noise level

Thus, IEC 61280-2-9 method estimates the noise level in the optical channel by linearly interpolating the noise level measurement results at the frequency boundary between adjacent optical channels. This out-of-band OSNR measurement method has the following significant limitations:

- the IEC method cannot be used when there are devices in the system that change the shape of the spectrum. In lines with ROADM implemented on the basis of optical filters, noise between channels will be suppressed. Interpolation in this case will give a smaller P_N value in the measured channel, the real accumulated noise will be estimated incorrectly. The resulting OSNR value will be overestimated;
- inability to detect noise in systems with signals whose speeds, when using software-defined forward error correction (SD FEC), are comparable to the bandwidth of the occupied channel. The frequency spectrum of the optical channel signals 100G/200G/400G/800G (B100G) is generally much wider than the frequency spectrum of the optical channel signal 10G. This means that the midpoint between the channels in this case no longer consists solely of noise, but rather of signal plus noise. Thus, the IEC 61280-2-9 method applied to such channels will overestimate the noise level. The resulting OSNR value will be underestimated.

In reality, the IEC 61280-2-9 method gives only an estimate of the noise in the channel, not a direct measurement. For this reason, it is applicable only to narrowband systems operating in linear mode, where it is sufficient to determine ASE to obtain OSNR. Practically this method is applicable for networks with optical channels with throughput up to 10 Gb/s and without ROADM.

B. Out-of-band OSNR Method with Functional Interpolation

The method proposed by ANRITSU [11] differs from IEC 61280-2-9 in that a linear interpolation is replaced by a point-to-point interpolation method with approximation of noise fitting interpolation of a specified noise area (Figure 2). The SNR in dB is calculated by:

$$SNR = 10\log\left(\frac{L_{S,Lin}}{N(\lambda_{sig})}\right) \qquad (3)$$

where:

$L_{S,Lin}$ – linear value (W) of level at signal at optical signal wavelength;

$N(\lambda_{sig})$ – linear value (W) of noise level at optical signal wavelength.

The optical signal level is calculated by:

$$L_{S,Lin} = \sum_{i=1}^{n}\left\{P(i) - N(\lambda_{sig})\right\} * \frac{Span}{Sampl - 1} * \frac{\alpha}{ActRes(i)} \qquad (4)$$

where:

n – data count in the range of the signal span/bandwidth;

Span – signal span/bandwidth (nm);

Sample – sampling point;

P(i) – power (W) of i-th data point;

ActRes(i) – the actual resolution of the i-th data point;

α – equipment dependent power correction coefficient.

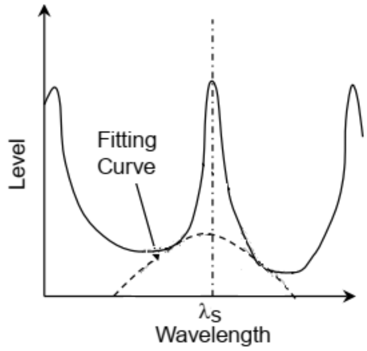

Fig. 2. Noise level estimation by point-to-point interpolation with approximation of noise characteristic in the optical channel frequency bandwidth

C. Practical implementation of out-of-band measurement methods

The optical spectrum analyzer (OSA) ANRITSU MS9740B [11] implements both out-of-band methods. It should be noted that out-of-band OSNR measurement methods allow obtaining not the true, but only the calculated optical power level in the optical channel frequency spectrum. They cannot be used in the presence of devices in the optical transmission systems that change the shape of the channel spectrum and suppress noise between channels, for example, ROADM. As it was depicted below an in-band OSNR measurement provides the true value of the OSNR in the channel.

IV. In-band OSNR Measurement Methods With Channel Disabling

The channel disabling provides very accurate OSNR measurements. In this case, using OSA, the power levels of the channels at the receiver with all channels on are first measured, and then the measurements are made consequently (step-by-step) per each channel in disabling status. Such measurements require $m + 1$ curves, where m is the number of optical channels (wavelengths).

Obviously, this method cannot be used in real traffic conditions, where even with second time duration channel disabling is fraught with huge losses for the operator. For this reason, methods are being developed for in-band measurement of OSNR without disconnecting the optical channel, that is, without channel disabling.

V. In-band OSNR Measurement Methods Without Channel Disabling

In-band OSNR measurement task without channel disabling is also complicated due to the fact that for 100G and B100G channels:

- the modulation formats are used with polarization multiplexing (Pol-Mux);
- the spectrum bandwidth of high-speed channels is equal to or greater than the standard frequency grid spacing of optical channels of 50 GHz or 100 GHz.

The following in-band methods for measuring OSNR without channel disabling have been proposed:

- optical polarization splitting (OPS) - offered by Viavi Solutions Inc. (JDSU) [12, 13];
- spectral correlation method (SCorM) - proposed by Viavi Solutions Inc. [14].

A. In-band OPS method of OSNR measurement

The OPS method allows to measure the true OSNR value of all optical channels under any conditions, regardless of the data rate and modulation format [15]. It is based on the fact that the optical signal of the channel consists of polarized light, while the ASE noise consists only of non-polarized light. The measurement method involves separating the signal by polarization and simultaneously measuring the power level of both states of polarization (SOP) using a two-port OSA.

The following measurement results by OSA are used to evaluate OSNR:

- the signal with a certain polarization is suppressed, and only the noise component of the signal is transmitted to the input of the OSA;
- a signal with a certain polarization is not suppressed, and a signal with a certain polarization together with a noise component is transmitted to the input of the OSA.

To divide the signal into two orthogonally polarized components Pol-X (P_1) and Pol-Y (P_2), the measurement scheme uses a polarization beam splitter (PBS) [16]. A tunable polarization controller (PC) is applied to determine the minimum and maximum optical signal power from both polarizations. The dual-port OSA connected to the output of the PBS measures both orthogonally polarized components P_1 and P_2 simultaneously (Figure 3), the sum of which indicates the sum of the levels of the useful polarized signal (P_S) and the non-polarized in-band noise (P_N). Further, both components P_1 and P_2 are measured simultaneously with the suppressed signals P_{S1} and P_{S2}, that is, the ASE noise level measurement.

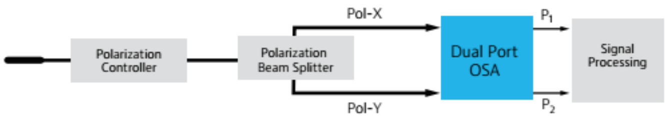

Fig. 3. Schematic diagram of the proposed OPS measurement technique

Measuring in-band OSNR will require several scans in the selected wavelength range with different PC settings to find the point of maximum suppression of the useful signal. The resulting minimum levels P_1 and P_2 indicate non-polarized in-band noise P_N [17]. At the end of the measurement, the in-band OSNR values of all channels are determined based on analytical relationships (Figure 4).

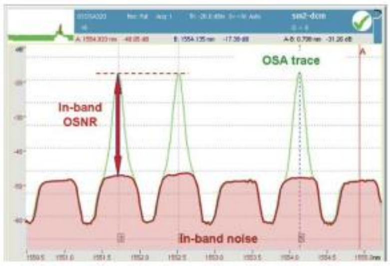

Fig. 4. Measurement result of Viavi OPS method

The advantages of the proposed method include simultaneous measurement of both SOPs together with adaptive narrowband filtering with offset from the center of the channel spectral range, which provides high resistance to PMD effects and measurement accuracy about 0.5 dB. In addition, all WDM optical channels can be measured simultaneously.

Unfortunately, such a method is not suitable for determining the in-band OSNR value in signals that are significantly distorted due to chromatic dispersion (CD) and PMD. Among other things, time domain measurement techniques require the use of high-speed photodetectors covering the entire bandwidth used to transmit data over an optical channel with a bandwidth of 100 Gbps or higher (B100G).

However, the OPS method can be used to evaluate the performance of an optical signal in the installation and maintenance of the optical transmission systems with ROADM.

B. In-band SCorM of OSNR measurement

Experience in the operation of the high-speed coherent optical transmission systems with ROADM has shown that it is problematic to use such familiar physical parameters as frequency, power, polarization state to separate the modulated signal from noise in order to subsequently measure the in-band OSNR. You need to select some other parameter that allows to select a signal against the background of noise.

To separate a useful optical signal from noise, it is proposed to use a correlation between measurements made inside the optical channel. Correlation analysis allows to statistically assess the relationship between two numerical variables - for example, the amplitude measurements results (power level) of the optical signal. The SCorM is based on the estimation of the correlation between signal components within the optical spectrum of the transmission channel and is based on the fact that the spectral components of the modulated signals are highly correlated, while there is no correlation for the spectral components of noise [14]. The method is applied in the frequency domain, therefore, to implement it, it is not necessary to use high-speed photodetectors and the clock and data recovery (CDR) function for correct synchronization and signal recognition.

SCorM is [18]:

- independent of modulation format and data rate;
- tolerant of large amounts of CD and PMD;

- tolerant to spectral filtering of the signal in ROADM.

The OSNR is calculated based on an estimation of correlation relationships between spectral components at predetermined pairs of spaced wavelengths. A certain difficulty is to analyze and compare with each other very narrow frequency intervals in the optical channel, taking into account that the components of the useful signal have a high-correlation, and the noise components have a zero-correlation level. The measurement bandwidth should be much smaller than the bandwidth used to transmit the useful signal.

To assess the correlation of spectral components, it is necessary to use two independently tunable detectors with ultra-high resolution and sensitivity. High resolution and sensitivity can be achieved only with the use of coherent detector circuits, according to the principles of operation similar to high-speed coherent detectors of the optical transmission systems.

V. Conclusions

The OSNR is the most important parameter characterizing the optical channel in DWDM systems. Measuring the OSNR of the optical channels, where not only DWDM technology but transmission with polarization multiplexing is used, is a difficult task.

This article summarizes and analyzes the methods for measuring OSNR in high-speed coherent channels of optical transmission systems. For optical 10G channels whose frequency spectrum is less than the frequency grid spacing of the optical channels of 50 GHz or 100 GHz, out-of-band OSNR measurement methods without channel disabling used. They cannot be applied in the presence of devices in the optical transmission systems that change the shape of the channel spectrum and suppress noise between channels, for example, ROADM. In this case there are in-band OSNR measurement methods with and without channel disabling. The features of these methods and the aspects of their application are considered.

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