# Optical Signal-to-Noise Ratio Monitoring Using Uncorrelated Beat Noise

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***Abstract*—We propose and experimentally demonstrate a new technique for monitoring optical signal-to-noise ratio (OSNR). The noisy signal to be measured is split into two paths. With offset optical bandpass filters and balanced radio-frequency subtraction after detection, the signal is separated from the beat noise. OSNR can then be monitored by analyzing this beat noise. An experiment for a 10-Gb/s system shows that for OSNR in the range of 10–30 dB, the proposed OSNR monitoring scheme produces errors of less than 0.5 dB.**

***Index Terms*—Amplified spontaneous emission (ASE) noise, beat noise, optical signal-to-noise ratio (OSNR) monitoring, wavelength-division multiplexing (WDM).**

## I. Introduction

OPTICAL signal-to-noise ratio (OSNR) is one important quantity to monitor for managing both current and future optical networks. A number of OSNR monitoring techniques have been developed. The traditional optical spectrum analyzer (OSA)-based OSNR estimation [1] relies on interpolation of the amplified spontaneous emission (ASE) levels adjacent to the channel of interest to obtain the approximate ASE level in the channel. As the interpolated ASE noise may not be the real ASE noise in the channels of interest, and overlap with adjacent signals may cause inaccurate ASE noise measurements between the channels, those conventional linear interpolation techniques may not monitor the OSNR accurately for a dynamically reconfigurable wavelength-division-multiplexed (WDM) network. The polarization nulling method [2] overcomes those problems by measuring the ASE at the carrier frequency, however, this method is susceptible to polarization-mode dispersion (PMD) [3]. Another OSNR monitoring approach uses beat noise measurement at the frequencies where no signal is present [4], but the method is dependent on pattern length. In-band OSNR monitoring using nonlinear detection is reported in [5]. In this letter, we propose and demonstrate a novel OSNR monitoring method using uncorrelated beat noise. The method is independent of the pattern length and insensitive to PMD.

## II. Description of the Method

Fig. 1 shows the principle and experimental setup of the proposed OSNR monitoring method. Within the OSNR monitoring module, which performs OSNR estimation for each WDM channel, the modulated signal with ASE noise is split into two paths by a 50 : 50 coupler. Then the two parts pass through two optical tunable bandpass filters (BPF 1 and BPF 2). The bandwidth of both filters is the same and larger than the bandwidth of the signal and their center frequencies are located symmetrically about the signal frequency, as illustrated in the inset in Fig. 1. Thus, BPF 1 and BPF 2 both pass samples of the signal and select different ASE noise. A variable optical attenuator and a variable optical delay line are used to match the power and the delay of the two paths. The outputs of the two paths feed into a pair of balanced photodiodes, in which detection and radio-frequency (RF) subtraction are performed. An RF amplifier and RF spectrum analyzer (RFSA) are used to measure the uncorrelated beat noise.

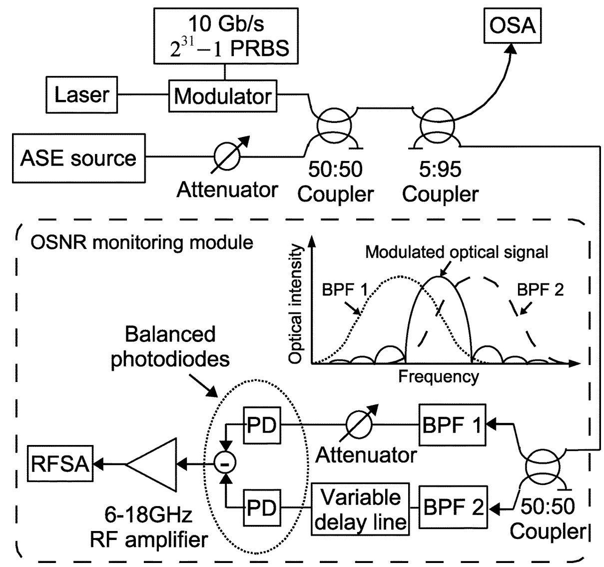


Fig. 1. Experimental setup. (BPF: Bandpass filter. PD: Photodiode.)

In [6], we reported an OSNR monitoring method based on analysis of the uncorrelated signal-spontaneous beat noise under the condition of "ideal" optical filters with identical rectangular responses. In this letter, the actual shape of the optical filters is considered and the uncorrelated spontaneous-spontaneous beat noise is included to improve the monitoring accuracy and dynamic range. The principle of the uncorrelated beat noise method was explained in detail in [6] and is summarized here. The signal in each path is correlated while the nonoverlapping ASE noise (assumed in the analysis below to be additive white Gaussian [7]) in each path is uncorrelated because it is in different frequency bands. This means that the detected beat noise in each path arising from the nonoverlapping ASE spectra is also uncorrelated. On the other hand, the beat noise in each

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path arising from the overlapping ASE spectra is correlated. If we apply two identical filters with symmetrical shapes to cover symmetrically the optical signal spectrum, then in the electrical domain, after balanced RF subtraction, the signal components and the correlated beat noise are removed. With the signal removed, the remaining uncorrelated beat noise can be measured, and using a separate measurement of the total (signal + ASE) power, the OSNR can also be determined. The new technique is compatible with a variety of different modulation formats, while the parameters for OSNR calculation could depend on the modulation format.

Removal of the modulated signal enables us to measure the uncorrelated beat noise and obtain accurate OSNR estimates. Examples will be given in Section III to compare the performance of the new method and the measurement without removing the signal (i.e., using the output of just one photodiode).

According to the theory of beat noise [8], the uncorrelated beat noise power density ($N_{\text{beat}}$) including the signal-spontaneous beat noise power density ($N_{\text{sig-sp}}$) and the spontaneous-spontaneous beat noise power density ($N_{\text{sp-sp}}$) as measured at the RFSA is given by

$$N_{\text{beat}} = N_{\text{sig-sp}} + N_{\text{sp-sp}} = \frac{A \cdot P_{\text{sig}}^2}{\text{OSNR}} + \frac{B \cdot P_{\text{sig}}^2}{\text{OSNR}^2} \tag{1}$$

where $P_{\text{sig}}$ is the optical signal power, and $A$, $B$ are constants related to the shape of the optical filters, the responsivity of the photodiodes, and the RF amplifier gain.

The measured optical power level before the photodiodes consisting of the signal power and the ASE noise power is

$$P_m = \gamma \cdot P_{\text{sig}} \left(1 + \frac{C}{\text{OSNR}}\right) \tag{2}$$

where $\gamma$ and $C$ are constants related to the properties of the optical filters. By (1) and (2), the OSNR can be calculated by solving the following quadratic equation:

$$\left(C^2 - \frac{B \cdot P_m^2}{\gamma^2 \cdot N_{\text{beat}}}\right)\frac{1}{\text{OSNR}^2} + \left(2C - \frac{A \cdot P_m^2}{\gamma^2 \cdot N_{\text{beat}}}\right)\frac{1}{\text{OSNR}} + 1 = 0. \tag{3}$$

## III. Experimental Results

The proposed OSNR monitoring method was experimentally demonstrated in a 10-Gb/s system, as shown in Fig. 1. The signal source was a 1550.42-nm laser externally modulated at 10 Gb/s by a $LiNbO_3$ intensity modulator with a nonreturn-to-zero pseudorandom binary sequence (PRBS) of pattern length $2^{31} - 1$. The ASE source was obtained from an erbium-doped fiber amplifier. The variable optical attenuator following the ASE source was used to change the OSNR. The signal and ASE noise were coupled together by a 50 : 50 coupler. A 5 : 95 coupler was used to tap 5% of signal and ASE noise into an OSA for baselining the OSNR. The remaining 95% of the signal and ASE noise were sent to the OSNR monitoring module. As tunable optical filters were not available in our laboratory when the experiment was conducted, two arrayed waveguide gratings (AWGs), both with 0.3-nm 3-dB, bandwidth were employed as the two optical bandpass filters (BPF 1 and BPF 2). The center frequencies of the two AWGs were temperature tuned to 1550.27 and 1550.57 nm, respectively. A 6–18-GHz RF amplifier and an RFSA were used for the uncorrelated beat noise measurement.

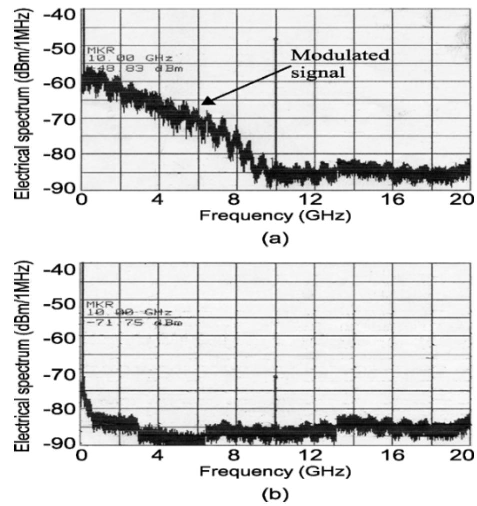


Fig. 2. RF spectra of the signal after (a) one photodiode and (b) balanced subtraction, with ASE source turned OFF and RF amplifier bypassed.

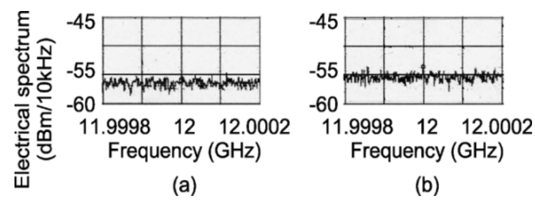


Fig. 3. RF spectra of the signal and beat noise after (a) one photodiode and (b) balanced subtraction, OSNR = 16 dB, PRBS pattern length = $2^{31} - 1$, with RF amplifier ON.

Fig. 2 shows the RF spectra of the signal after one photodiode [Fig. 2(a)] and after balanced subtraction [Fig. 2(b)], with ASE source turned OFF and RF amplifier bypassed in order to obtain a 20-GHz span. We can see that after the balanced subtraction, the modulated signal is removed.

Fig. 3 shows higher resolution RF spectra after one photodiode [Fig. 3(a)] and after balanced subtraction [Fig. 3(b)], at 16-dB OSNR in a 400-kHz span around 12 GHz with the RF amplifier ON. The power spectral density of Fig. 3(b) is larger than the power spectral density of Fig. 3(a) because the uncorrelated beat noise in each path adds on each other after the balanced subtraction.

As pointed out in Section II, it is important to remove the modulated signal so that it does not mask the beat noise. When we measured the beat noise at 8 GHz for 16-dB OSNR using the output of just one photodiode, a spectral density of −50.5 dBm/10 kHz was obtained, which included both the signal and beat noise. Using this signal and beat noise spectral density to calculate OSNR, a −5-dB OSNR monitoring error (i.e., the difference between the OSNR obtained by beat noise measurement and by the OSA) was produced. Applying the new method, we removed the signal by balanced subtraction and obtained an uncorrelated beat noise spectral density of −54.8 dBm/10 kHz, which gave a monitoring error of only −0.25 dB.

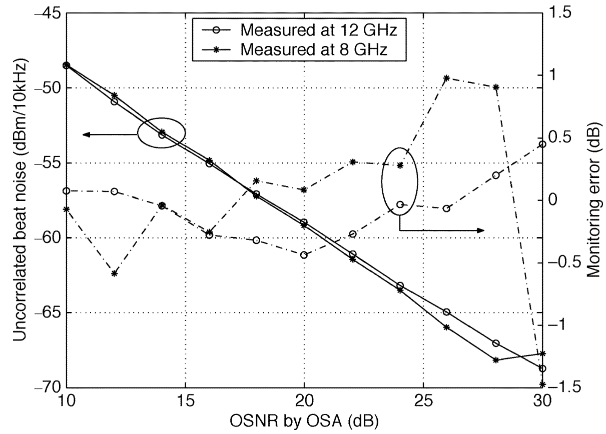


Fig. 4. Measured uncorrelated beat noise power density and the monitoring error versus the OSNR measured by the OSA.

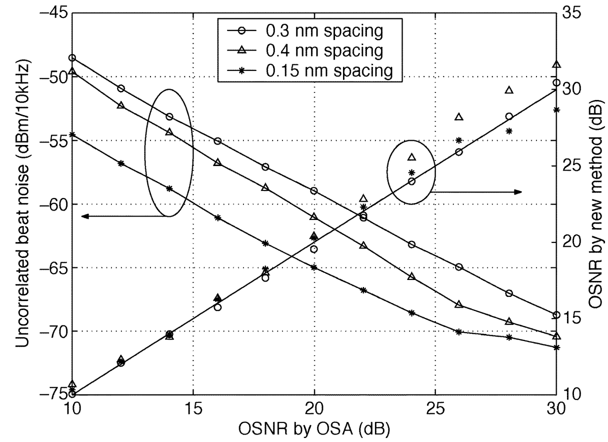


Fig. 5. Comparison of the measured uncorrelated beat noise power density and the measured OSNR by the proposed method at different spacings of the filters versus the OSNR measured by the OSA.

When $N_{\mathrm{beat}}$ was measured at 12 GHz, although the signal power was much less than the signal power at 8 GHz, simulation shows that without removal of the signal at 12 GHz, the monitoring error will be larger than 3 dB when the OSNR is above 20 dB. With the new method, experimental results below show that the monitoring error is less than 0.5 dB for OSNRs above 20 dB.

Fig. 4 shows the measured uncorrelated beat noise power density ($N_{\mathrm{beat}}$) and the monitoring error versus the OSNR measured by the OSA. $N_{\mathrm{beat}}$ was measured at both 8 and 12 GHz, then substituted into (3) to calculate OSNR. We can see that when measured at 12 GHz, the monitoring error is less than 0.5 dB in the OSNR range from 10 to 30 dB. When measured at 8 GHz, at larger OSNR (>25 dB), the monitoring errors become larger. This is because the subtraction is not perfect due to the limitations of the balanced photodiodes and the residual of the signal at 8 GHz is larger than the residual at 12 GHz. In order to obtain the true OSNR, it is necessary to measure the ASE at frequencies as close as possible to the optical carrier. To achieve this, the RF measurement frequency should be as low as possible. As shown above, we have used a measurement frequency down to 8 GHz. Measurement frequencies below 8 GHz are possible, but the measurement accuracy and the dynamic range of the OSNR measurement will be decreased.

As described above, the center frequencies of the optical filters were set 0.3 nm apart. We compared the measured OSNR with spacings of 0.15 and 0.4 nm. It was found that with 0.3-nm spacing, the monitor had better performance. Fig. 5 shows a comparison of the measured uncorrelated beat noise power density at 12 GHz and the measured OSNR by the new method versus the OSNR measured by the OSA at 0.3-, 0.4-, and 0.15-nm spacing. The solid line is the OSNR measured by the OSA for reference. We can see that at 0.4- and 0.15-nm spacing, the uncorrelated beat noise power densities are less than that obtained with 0.3-nm spacing. The reasons are as follows: at 0.4-nm spacing, the detected signal power is lower than that detected at 0.3-nm spacing; and at 0.15-nm spacing, the two filters overlap more which means more correlated ASE noise and less uncorrelated ASE noise. If the uncorrelated beat noise power density is close to the noise floor, it is hard to obtain the beat noise accurately. Consequently, the OSNR calculation will be affected. Therefore, at larger OSNR (>25 dB), the monitoring error is larger at 0.4- and 0.15-nm spacing than at 0.3-nm spacing.

In practice, frequency drift of the signal in relation to the filter center frequency may affect the accuracy of the proposed OSNR monitor. We experimentally tested the monitor at 20-dB OSNR and found that the monitoring error became larger than 1 dB when the carrier frequency drift was above 4 GHz. We also found through simulation that when the delay mismatch of the two paths was less than 3 ps, the OSNR monitoring error was within 1 dB.

## IV. Conclusion

We have proposed a novel OSNR monitoring method by analyzing the uncorrelated beat noise. A combination of optical and electronic signal processing was applied to remove the signal. The method is insensitive to PMD and compatible with a variety of different modulation formats. For OSNR in the range of 10–30 dB, the monitoring errors are less than 0.5 dB.

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