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Monitoring of Generalized Optical Signal-to-Noise Ratio using In-Band Spectral Correlation Method

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Abstract *We propose and experimentally demonstrate low-cost correlation methods for monitoring the generalized optical signal-to-noise ratio in the middle of link. For the first time, self-phase modulation noise can be directly monitored. ©2022 The Author(s)*

Introduction

Generalized optical signal-to-noise ratio (gOSNR) has recently been used as a performance indicator, which includes both the amplified spontaneous emission (ASE) and the nonlinear interference [1]. The gOSNR is a suitable signal quality indicator, however determining this parameter is not trivial in the middle of a transmission link. As modern optical networks are evolving towards rate adaptive, operated at low margin, and disaggregated/open, the capability of monitoring gOSNR in the middle of links is critical.

A spectral correlation method [2,3] has been reported to monitor gOSNR which uses the property of the clocked signal: the baud-rate separated spectral components are completely correlated signals, while the noises are completely uncorrelated. This method can estimate signal's gOSNR, but it requires expensive hardware: two relatively low speed (GHz) coherent receivers, operated with their local oscillator (LO) frequencies separated by baud rate. In addition, a gOSNR is monitored only for signal spectral component at half baud rate frequency from the carrier. In the case of Nyquist signal with strong optical filtering, the monitored gOSNR may not be representative of the entire signal.

In this paper, we propose two novel correlation methods that can monitor a signal's gOSNR by only one coherent receiver. The correlation can be performed on any spectral component, therefore it can avoid the error under strong optical filtering. Moreover, it is able to obtain a gOSNR spectrum by sweeping the spectral component which is useful in case the noise has non-flat spectrum. Besides, for the first time, self-phase modulation (SPM) noise can be directly monitored.

Basic Concept of Correlation Method

In order to determine the gOSNR based on correlation method, it is required to have two waveforms which have correlated signals but uncorrelated noises. One way to get such set of waveforms is to take spectral slices separated by exactly baud rate [2]. However, taking two different spectral components essentially requires two coherent receivers which is hardware expensive. However, it is possible to obtain such waveform set with only one low-speed coherent receiver by taking waveforms of a repeated signal at different timing or a non-repeated signal at different monitoring location, instead of taking two spectral components. Moreover, from current trend to deploy a coherent OPM in the middle of transmission links to provide better spectral resolution, the proposed method can be deployed in the real network without additional cost by adding a function to the OPM.

The two waveforms can be captured by using repeated signal block (RSB) which is identical signal blocks repeatedly transmitted at Tx. Each RSB accumulates noises during propagation, and resulting completely correlated signals but uncorrelated noises at the receiver. This is straight forward way to capture a set of waveforms but it has limited use in offline (debugging) mode due to the use of specially designed signal.

Another way is to capture a reference signal at different monitoring location for example a waveform at Tx or another monitoring location close to the Tx. There may require further signal processing to the reference waveform to match dispersion, timing, and frequency offset, but this method can be used for online (in-service) mode operation.

Repeated Signal Block Method

The basic concept of the repeated signal block (RSB) method is shown in Fig. 1. At Tx, a signal $E_s(t)$ is generated and repeatedly transmitted into the transmission link (Fig. 1(a)), and the signal is received at desired gOSNR monitoring locations in the middle of a link, for example the Monitor2 shown in Fig. 1(c). The RSBs accumulate uncorrelated noises during signal propagation, resulting completely correlated signals but uncorrelated noises. Therefore,

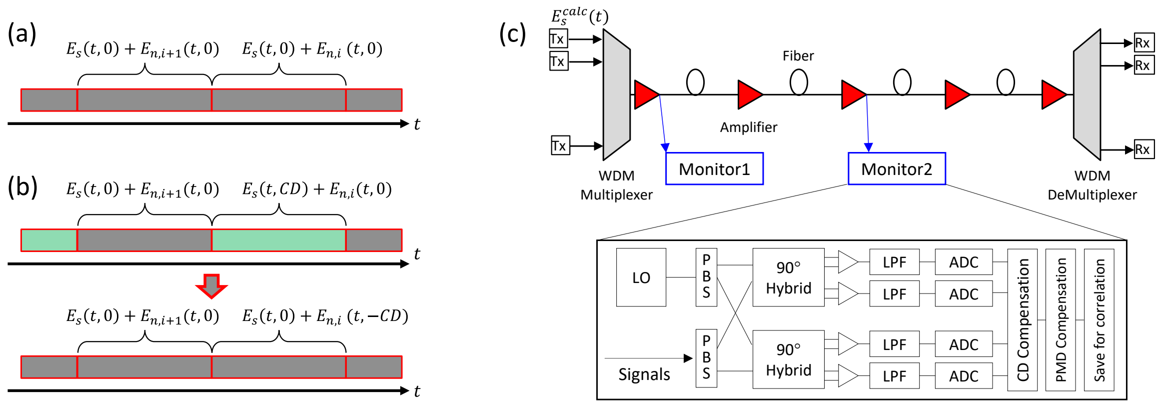

Fig. 1: (a) Schematic diagram of a repeated signal blocks. (b) Signal blocks with different preCD at the receiver (top) and the received signal blocks after preCD compensation (bottom) (c) Schematic illustration of a typical DWDM transmission link consisting several gOSNR monitoring locations enabled with existing low speed coherent receiver

gOSNR can be obtained by a correlation between two RSBs at same spectral slice. Since the correlation is performed with waveforms at same spectral slice and monitoring location, it requires only one low-speed coherent receiver.

The electric field of the i^{th} block consists of signal as well as accumulated noises, $E_{n,i}(t)$, therefore $E_i(t)=E_s(t)+E_{n,i}(t)$, where the noise includes ASE, SPM, XPM noises, $E_{n,i}(\mathrm{t}) = E_{n,i,\mathrm{ASE}}+E_{n,i,\mathrm{SPM}}+E_{n,i,\mathrm{XPM}}$. The signal-to-noise ratio (SNR) can be obtained by the correlation of total electric field between two RSBs. However, unlike other noises, the SPM noises are correlated between RSBs with identical signals because the SPM noise is generated by the signal. Therefore, the SNR obtained in such correlation does not provide true gOSNR measurement.

In order to include the SPM noise into the SNR, one way is to apply different pre-added chromatic dispersion (preCD) in different RSBs to decorrelate the SPM noises. For example, as shown in top part of Fig. 1(b), a preCD can be applied to alternative blocks. After receiving this signal, the preCD of i^{th} block can be compensated as shown in the bottom of Fig. 1(b), thus it results correlated signal but uncorrelated SPM noises. Therefore, the correlation of total electric fields of two different-preCD RSBs becomes,

$$cor_D=\frac{\langle E_i(t)E_{i+1}(t)^*\rangle}{\sqrt{\langle|E_i(t)|^2\rangle\langle|E_{i+1}(t)|^2\rangle}}=\frac{P_s}{P_s+P_n}=\frac{1}{1+1/SNR_D} \quad (1)$$

where, $P_s=\langle|E_s(t)|^2\rangle$ is the signal power, $P_n=\langle|E_{n,i}(t)|^2\rangle=\langle|E_{n,i+1}(t)|^2\rangle$ is the noise power, and $SNR_D=P_s/P_n$ is the SNR obtained between different-preCD RSBs. Since the P_n includes all the noises, SNR_D can be directly converted to gOSNR. Similarly, the correlation between same-preCD RSBs gives another SNR which does not include the SPM noise as below,

$$cor_S=\frac{P_s+P_{n,\mathrm{SPM}}}{P_s+P_n}=\frac{1}{1+1/SNR_S} \quad (2)$$

where, $P_{n,\mathrm{SPM}}$ is the SPM noise power, and $SNR_S=P_s/(P_n-P_{n,\mathrm{SPM}})$ is the SNR between same-preCD RSBs. Since SNR_D includes SPM noise while SNR_S does not, the SPM noise power can be extracted from those two correlations as $1/SNR_{\mathrm{SPM}}=1/SNR_D-1/SNR_S$.

Reference waveform method

As mentioned earlier, the RSB method is only available in the offline (debugging) mode because it requires to transmit specially designed signals. In the online (in-service) mode, we can use reference waveforms captured at different monitoring locations instead of RSBs. There are two alternatives to capture the reference signal:

1. A spectral slice of transmitted signal, $E_s^{calc}(t)$, can be calculated at Tx and delivered to the desired monitoring location. The $E_s^{calc}(t)$ can be a narrow spectral slice such as 1 GHz or less, thus it can be delivered through other means such as digital communication network.
2. A captured waveform at another reference location can be delivered to the monitoring location. For example, a reference signal captured at Monitor1 shown in Fig. 1(c) can be delivered to Monitor2. The reference signal may be considered the same as $E_s^{calc}(t)$ when it is close enough to the Tx. However, the reference signal does not have to be close to Tx; the monitored gOSNR represents the signal quality degradation between the two locations.

Above mentioned reference waveforms are essentially noise free. In this case, Eq. (1) needs modification by substituting $E_{i+1}(t)$ with $E_s(t)$, and the SNR is linked to the correlation as,

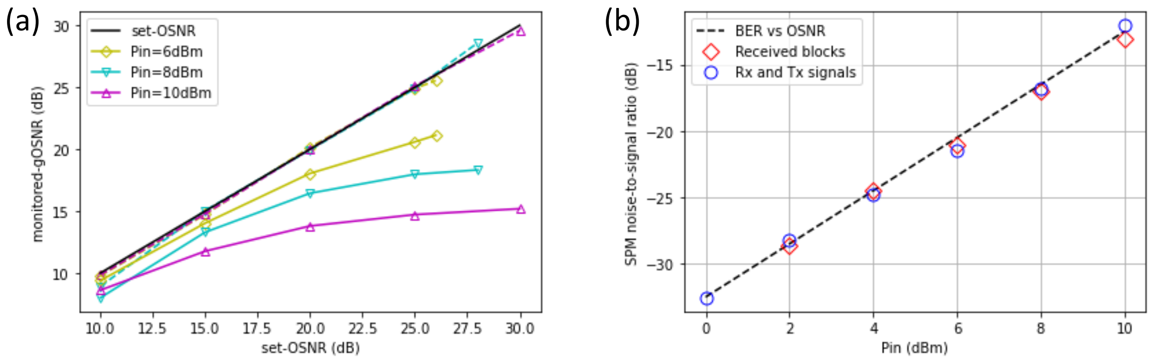

Fig. 2: (a) Monitored-OSNR based on correlation between same preCD (dashed) and different preCD (solid) RSBs at different launch power. (b) Monitored SPM noise-to-signal ratio and comparison with standard BER vs. OSNR method.

$$cor_D^2 = \frac{\langle E_i(t)E_s(t)^*\rangle^2}{\langle |E_i(t)|^2\rangle\langle |E_s(t)|^2\rangle} = \frac{1}{1+1/SNR_D}. \quad (3)$$

Note that the signal's power waveforms of the RSBs or the reference waveforms are also correlated but the noise power waveforms are not correlated [4]. Therefore, the gOSNR can also be obtained from the correlation between the power waveforms of RSBs. Power waveform correlation is not sensitive to signal's phase change, therefore it is beneficial to use the power waveforms if the phase change cannot be fully compensated.

Experimental Results and Discussion

We demonstrated the proposed gOSNR monitoring in 6x75km SSMF span, dispersion-uncompensated link. The signal under test is 34 Gbaud DP-QPSK. At Tx, a preCD of 1500 ps/nm is applied to alternative blocks. At receiver, dispersion (link CD, or preCD + link CD) is properly compensated for all RSBs. We used single channel signal to have only SPM as the nonlinear noise. This is for easier confirmation of the monitoring of uncorrelated noise by directly comparing with set-OSNR. Even though we considered only ASE and SPM noises in the experiments, but the XPM noise also can be monitored by the correlation method because it is one of the uncorrelated noises same as the ASE.

Monitored-OSNR as a function of the set-OSNR under different fibre launch power estimated by SNR_S is shown in Fig. 2(a) as dashed curves. It does not have input power dependency and well agreed with the set-OSNR (black solid line in Fig. 2(a)). It is because the SNR_S does not include SPM noise which means the monitored quantity is pure OSNR. This shows that the SNR_S can monitor the uncorrelated noises such as ASE and XPM. The monitored-OSNR is in good agreement with less than 0.5dB error that can be further improved by more averaging.

The gOSNR (including SPM noise) can be monitored with different-preCD RSBs because they generate uncorrelated SPM noises. Monitored-gOSNR is shown in Fig. 2(a) as solid curves under different launch power (Pin). As shown, the monitored-gOSNR becomes lower than the set-OSNR by increasing Pin, indicating that there exist noises other than ASE. To confirm that the extra noise is SPM noise, we extract the extra noise and plot it as a function of the Pin (red-diamond in Fig. 2(b)). The power of this extra noise is proportional to launch power squared as expected of SPM. For further confirmation, SPM noise is also measured by the standard BER vs. OSNR method, which is in good agreement with the proposed method (black dashed line in Fig. 2(b)).

For an experimental confirmation of the online mode operation (reference waveform method), we perform the monitoring with the Tx signal. The gOSNR is calculated by the Eq. (3), and the SPM noise is extracted similarly as before. The calculated SPM noise is plotted in Fig. 2(b) as blue-circle, and it is well agreed with the other estimations which confirms the online operation.

Conclusions

We proposed a gOSNR monitoring method based on the correlation method. Two waveforms can be prepared with single coherent receiver by capturing different blocks of RSBs or capturing reference waveform at different monitoring location. The proposed method is experimentally confirmed with excellent accuracy by monitoring OSNR and gOSNR. For the first time, SPM noise is directly monitored in the middle of the link.

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