GOSNR Characterization by Optical Spectrum Analysis

Gang He[1], Steven Searcy[2], Daniel Gariépy[1], and Sorin Tibuleac[2]
(1) EXFO, 400 Godin Ave., Quebec City, Quebec, G1M 2K2 Canada, gang.he@exfo.com
(2) ADVA Optical Networking, 5755 Peachtree Industrial Blvd, Norcross, GA 30092, USA

Abstract: We introduce a GOSNR measurement based on optical spectrum analysis and experimentally validate the method using multiple coherent signal types (34 and 69 Gbd, QPSK and 16QAM) over 8 and 12 spans LEAF transmission.

1. Introduction

As network operators increasingly adopt practices of disaggregation, separating the terminal equipment (transceivers) from the optical line system (including amplifiers and ROADMs), it has become increasingly important to identify straightforward methods to monitor optical system performance. Increased use of coherent receivers operating without optical dispersion compensation has led to the widespread application of models based on the fact that highly dispersed signals take on Gaussian-noise-like character, and generate nonlinear "noise", which can typically be treated as additive, white, and Gaussian [1]. This has led to the concept of Generalized Optical Signal to Noise Ratio (GOSNR), in which the traditional $OSNR_{ASE}$, due to ASE noise from optical amplifiers, and the "nonlinear" $OSNR_{NL}$, due to nonlinear distortions, can be combined in a single metric, GOSNR, quantifying the linear and nonlinear noise accrued by a signal while passing through a line system consisting of fiber spans and amplifiers. This GOSNR metric is particularly useful in "open" or disaggregated systems, where it is desirable to quantify the line system performance independent of the terminal equipment, which may come from multiple vendors or have different intrinsic properties.

However, despite the growing acceptance of GOSNR as a performance metric, to date there has not been a method to directly measure GOSNR of a link, independent of performance metrics from the transceiver DSP. Many traditional approaches for measuring $OSNR_{ASE}$ have relied on optical spectrum analysis, which has several advantages, including the ability to measure all WDM channels at the same time and the lack of requirement to access the coherent DSP for each channel. In this work, we apply the optical spectrum analysis method to the task of measuring GOSNR and find that it can be used to accurately measure GOSNR without dependence on the coherent modem. We describe the method and demonstrate its effectiveness on a link operating in the linear and nonlinear transmission regimes, with a mix of signals of varying modulation formats (QPSK and 16QAM) and symbol rates (34 and 69 GBaud).

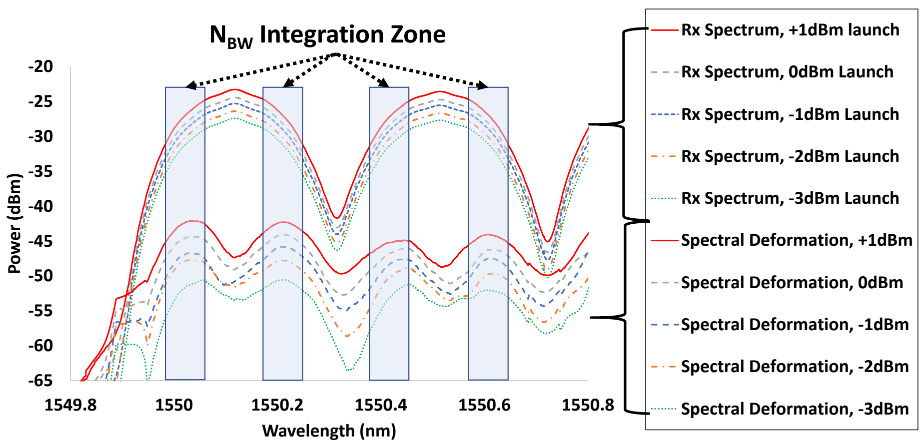

Fig. 1: Spectral deformation after 8 spans obtained by subtracting the reference spectrum from the received spectrum. The strength of the non-linearity increases with launch power. The vertical bars indicate the integration zone N_{BW} used for calculating N_{SD}.

2. Principle of operation

As it propagates along the link through spans of fiber, amplifiers, and other network elements, the modulated power spectral density profile of transmitted optical signal is subject to gain, loss and nonlinear-induced spectral deformation [2] and it gradually accumulates ASE. We have previously demonstrated a spectrum-based OSNR measurement technique where performing a fine spectral analysis of the received signal and comparing it to a reference spectrum of the transmitted signal without ASE noise allowed the measurement of $OSNR_{ASE}$ despite the presence of important nonlinear effects [3]. We observed that stronger nonlinear effects led to larger spectral deformations and leveraged the measured amplitude of the deformations with an empirical correction to determine $OSNR_{ASE}$. Here, we investigate the relation between $OSNR_{SD}$, determined by spectral deformation noise, and $OSNR_{NL}$ to use this relation in a spectrum-based GOSNR measurement. Fig. 1 shows how the spectral deformation noise amplitude $N_{SD}(\lambda)$ changes with the strength of the non-linearity. We integrate the non-spectrally uniform deformation noise $N_{SD}(\lambda)$ over a spectral region N_{BW} (in nm) determined by the relative power distribution of the signal peak and normalize it to 0.1 nm to obtain $N_{SD} = \frac{0.1}{N_{BW}} \int_{\lambda_{-10dBpk}}^{\lambda_{-3dBpk}} N_{SD}(\lambda)\, d\lambda$ and we calculate $OSNR_{SD}$ as the relation between the total power and N_{SD}.

GOSNR is obtained by performing a typical commissioning characterization procedure, where it is possible to turn off transceivers for measuring the received $OSNR_{ASE}$ and to vary the launched power level in a controlled manner. The measurement can be done entirely in the optical domain with a commercial OSA and the correlation with GOSNR is obtained by leveraging the $1/P^2$ dependence of the nonlinear signal-to-noise ratio SNR_{NL} (and thus of $OSNR_{NL}$) in agreement with the Gaussian noise model for uncompensated links [1]. Based on our previous observations [3] that $1/OSNR_{NL} \propto 1/OSNR_{SD}$, we postulated that $\frac{1}{OSNR_{NL}} = \left[F \cdot \frac{1}{OSNR_{SD}}\right]^n$ where F is a noise shape factor intended for taking into account the impact of the power range choice for the integration region N_{BW} on a spectrally non-uniform distribution of $N_{SD}(\lambda)$. Since we have not established if $OSNR_{SD}$ also has $1/P^2$ dependence, exponent n is intended to allow adjustment of the relation for different nonlinear conditions associated with different system configurations (e.g. fiber types, chromatic dispersion and span lengths). We show below how to obtain n through relative optical spectrum measurements at commissioning. Since it acts as a normalization factor that should depend only on our above definition of $OSNR_{SD}$, we expect the noise shape factor F will be independent of the system configuration and that an initial calibration procedure on any system with known GOSNR conditions (e.g. the relation between $OSNR_{NL}$ and $OSNR_{ASE}$ can be deduced from the Gaussian noise model for a system operating at BER optimized conditions). Once F and n have been determined, we can obtain GOSNR as $\frac{1}{OSNR_G} = \frac{1}{OSNR_{ASE}} + \left[F \cdot \frac{1}{OSNR_{SD}}\right]^n$.

3. Experimental setup and methodology

The optical spectrum measurement of GOSNR was validated in an experimental transmission link consisting of 12 spans LEAF (G.655) fiber with average span length of 73 km (879 km total). EDFAs were used for per-span amplification and ROADMs were used to equalize channel powers at the beginning of the link and after 4 and 8 spans (without applying any per-channel optical filtering). The WDM spectrum consisted of fourteen commercial coherent transceivers spread across 850 GHz (including two empty 50 GHz slots for ASE noise level reference). All channels operated at ~30-34 GBaud on the 50 GHz grid, except for the central two channels operated at 69 GBaud with 75 GHz channel spacing. Channel powers were set to equal power spectral density, with high baud rate signals set to 1.76 dB higher power relative to the low baud-rate signals, normalizing for the difference in slot width (75 vs 50 GHz). The central six channels were used for measurement and analysis, comprised of the following signal types: 2x100G QPSK (34GBd), 2x200G 16QAM (34GBd), 1x200G QPSK (69GBd), and 1x400G 16QAM (69GBd), all with root-raised-cosine pulse shaping (roll-off factor 0.2). Various performance metrics from the coherent DSP were recorded for all six test channels, including pre-FEC BER and Q factor. The optical spectrum was measured at the beginning and end of the link using a commercial grating-based optical spectrum analyzer with ~35 pm resolution.

Launch power per span was scanned over a 6 dB range covering at least ± 2 dB relative to the optimum launch power, to test the GOSNR measurement in the linear and nonlinear regimes. Optical spectrum measurements and coherent receiver metrics were taken after 8 and 12 spans transmission at each launch power. Back-to-back measurements with ASE noise loading were also performed to derive a calibrated curve of Q vs GOSNR (with GOSNR = $OSNR_{ASE}$), which was used to compute the GOSNR from the measured Q per channel on the transmission link. This receiver-based GOSNR data served as reference for validating the accuracy of the optical spectrum-based GOSNR measurement.

4. Results and discussion

We started by measuring $OSNR_{SD}$ for two 30 GBd QPSK channels (without spectral shaping) while varying the per-channel launch power P of the system from -4 dBm to +1 dBm in 1 dB steps and performed On/Off measurements to obtain the ASE level ($OSNR_{ASE}$). We assumed a 2 dB/dB ($\Delta OSNR_{NL}$ vs ΔP) variation [1] to determine the value of exponent n for the 8 spans configuration described above and found that n=1 provided a good fit for the four ΔP data points (e.g. -4 dBm to -3 dBm, and so on). To validate the GOSNR measurement, and determine the value of F, we applied the n=1 value obtained on the two unshaped QPSK channels to six test channels with different symbol rates and spectral shaping (thus different noise integration widths N_{BW}) and with different modulation formats for the two system configurations. It is worth noting that $OSNR_{SD}$ is a relative measurement of the incremental deformation in the signal compared to that of the reference. If $OSNR_{NL}$ of the reference is known or if the reference has negligible deformation due to nonlinearity (e.g. near the transmitter site or when a low launch power signal is used as reference at the receive site), $OSNR_{NL}$ and not just its incremental contribution, can be related directly to $OSNR_{SD}$. In our configuration the low launch power conditions reference had measurable nonlinear noise and we obtained its $OSNR_{SD}$ by comparison with the transmit spectrum measured at the beginning of the link. We were then able to determine $OSNR_{NL}$ the "absolute" $OSNR_{SD}$ for all other conditions using the lowest launch power received signal as a reference.

Measuring $N_{SD}(\lambda)$ requires challenging power resolution especially for large $OSNR_{SD}$ and shaped signals. To make the measurement more robust, we treated adjacent channels as pairs with the assumption that the nonlinear conditions should be similar for immediate neighbor channels on the same path, and we averaged their results. Figure 2 shows the experimental deviation results for GOSNR measured optically via $OSNR_{SD}$ (with F=1 and n=1) and GOSNR determined from the Rx Q measurements. Note that at the highest launch power for the 12 spans configuration, the GOSNR was too low to obtain a valid Q for some channels.

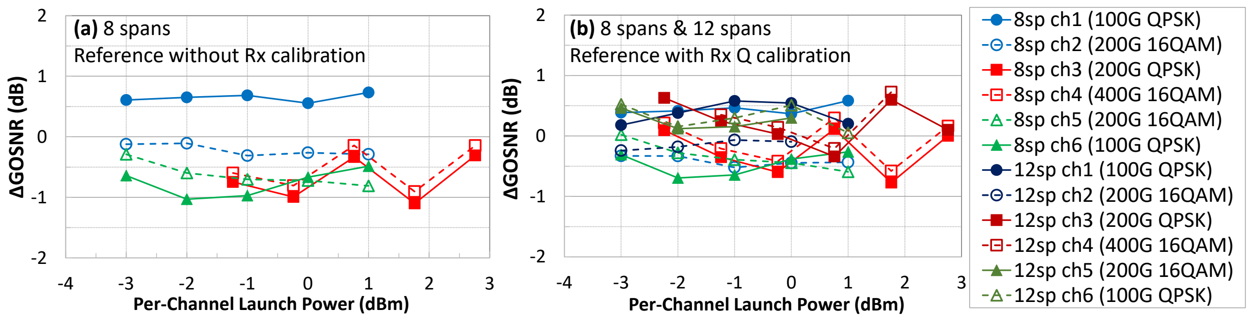

Fig. 2: GOSNR measured by spectral analysis compared to actual GOSNR (computed from Rx Q), over a range of launch powers, for (a) 8 spans and (b) 8 and 12 spans LEAF transmission. For Fig. 2(a), the -4 dBm reference signal $OSNR_{NL}$ contribution was determined by measuring $OSNR_{SD}$ from the spectral traces while for Fig. 2(b) it was derived from the receiver Q.

The spectrum-based GOSNR is typically accurate within 1 dB for all test channels, with the default parameters of F=1 and n=1. Results for Fig. 2(a) were obtained entirely through optical spectrum analysis, including the contribution of the reference determined from $OSNR_{SD}$ of the two 30 GBd QPSK channels. Alternatively we can obtain $OSNR_{SD}$ for the -4 dBm launch reference signal. This is presented for both the 8 spans and 12 spans configuration on Fig. 2(b) where all measurements were done optically but the known $OSNR_{NL}$ reference contribution was added to the relative optical measurement. These are promising results and the fact that the same parameters apply to both distances despite different nonlinear conditions indicates that $OSNR_{SD}$ as we defined it results in $1/OSNR_{SD}$ displaying the same P^2 dependence as $1/OSNR_{NL}$. Our choice of integration zone, without further correction of factor F for the shape of $N_{SD}(\lambda)$, also allowed direct comparison with ASE noise.

The measurement of $N_{SD}(\lambda)$ by a subtraction of spectra requires high accuracy and repeatability in power measurement and despite the averaging of neighbor values, power inaccuracy is still an important cause of deviation which leads to the higher variability, especially for the more challenging spectrally shaped 69 GBd channels with 75 GHz spacing (test channels 3 & 4), where the integration region is actually smaller than for non-shaped signals.

5. Conclusion

We have demonstrated a GOSNR measurement that relies on optical spectrum analysis of the signals and determined the relation between the nonlinear-induced optical spectrum deformation measured with an OSA, and the nonlinear $OSNR_{NL}$, which can be combined with $OSNR_{ASE}$ to obtain GOSNR. We showed that with a deformation-free reference signal we could perform the GOSNR measurement with deviations mostly within 1 dB for a range of signal types and in two system configurations with different nonlinear conditions using a simple relation between the optically measured spectral deformation $OSNR_{SD}$ and the actual $OSNR_{NL}$. Future investigations of other nonlinear system conditions and configurations are required to determine if the same F and n parameters of the relation will apply and how precisely we can measure GOSNR for such systems.

6. References

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