All-Optical GOSNR Estimation on an Open Line System Using Polarization-Resolved Optical Spectrum Analysis

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

Abstract: We introduce an all-optical method for estimating linear and nonlinear noise using an unmodulated laser source and varied state of polarization optical spectrum analyzer, then experimentally validate the technique against the conventional transceiver-based GOSNR approach.

1. Introduction

In recent years, the optical networking industry has seen a significant shift towards deployment of disaggregated systems, with terminal equipment (transceivers) and line system (optical amplifiers, ROADMs/filters, etc.) being supplied by different vendors [1]. The many benefits of disaggregated systems have led to their adoption by many operators across the optical networking industry, from data-center interconnect to ultra-long-haul subsea links [2]. However, some practical aspects remain challenging for operators of disaggregated systems, including performance optimization and troubleshooting network issues. To aid operators in deployment and maintenance, it is very beneficial to have methods for simple and accurate characterization of the disparate pieces of the network. Transceivers can be characterized independently in a laboratory environment, but the line system is more difficult to characterize fully since it includes the deployed fiber optic cable. While the $OSNR_{ASE}$ can be directly measured on a line system in various ways, it is more challenging to measure the ratio of signal power to combined linear and nonlinear noise, typically referred to as generalized optical signal-to-noise ratio, GOSNR (or GSNR). The most widely used conventional method for characterizing an "open cable" (fiber + WDM line system) uses coherent transceivers to "probe" the system and estimate the link G(O)SNR [2]. Despite excellent efforts to clarify and unify such approaches, they still rely on a test transceiver calibrated with some offline back-to-back characterization.

In this work, we propose a novel method for measuring GOSNR of an open line system without using any transceivers. Instead, the all-optical method relies on an unmodulated laser source along with a commercial polarization-diverse optical spectrum analyzer (OSA) to characterize linear and nonlinear noise contributions. The method uses both polarization and optical spectrum differential properties of the test signal (polarized laser) to measure nonlinear-induced signal depolarization. In a line system with broadband ASE loading, it is possible to measure the GOSNR including full-load nonlinear effects, before any traffic is added to the link. This enables open line system characterization independent of any transceivers which may be used, and validation of GOSNR immediately after line system installation. The method could in principle be applied to subsea open cables as well as terrestrial open line systems. In this work we focus on measurements with a terrestrial system.

First, we describe the principle of the new all-optical technique for measuring linear and nonlinear noise. Next, we validate the method using an 8-span SSMF link with all-EDFA amplification, comparing the novel GOSNR technique with the conventional GOSNR method using a calibrated test transceiver, and show good agreement between the two approaches.

2. Measurement Principle

The novel GOSNR measurement concept is based on using a polarized test source and a varied state of polarization OSA (VSOP-OSA), as illustrated in Fig. 1(a) [3-4]. An advantage of the VSOP-OSA is its relative insensitivity to environmentally-induced SOP variations and the high accuracy that may be obtained via power-related polarization spectrum analysis. While the test signal is initially fully polarized, the ASE noise contribution is unpolarized, and the test signal experiences depolarization induced by nonlinear effects in the transmission fiber [5]. The depolarization arises from the Kerr effect ("nonlinear birefringence"), giving rise to rapid change in SOP of the polarized test signal, which leads to time-dependent polarization "scrambling," or a signal depolarization effect in a low-speed detection system. This nonlinear-induced temporal signal depolarization can be used to estimate the nonlinear noise component of the GOSNR.

The technique relies on the acquisition of multiple polarization-resolved optical spectra, each corresponding to a different orientation between the input light SOP and the two orthogonal polarization analyzers. Orthogonal polarization power spectra of the polarized probe are measured using a VSOP-OSA, with the aggregate spectrum,

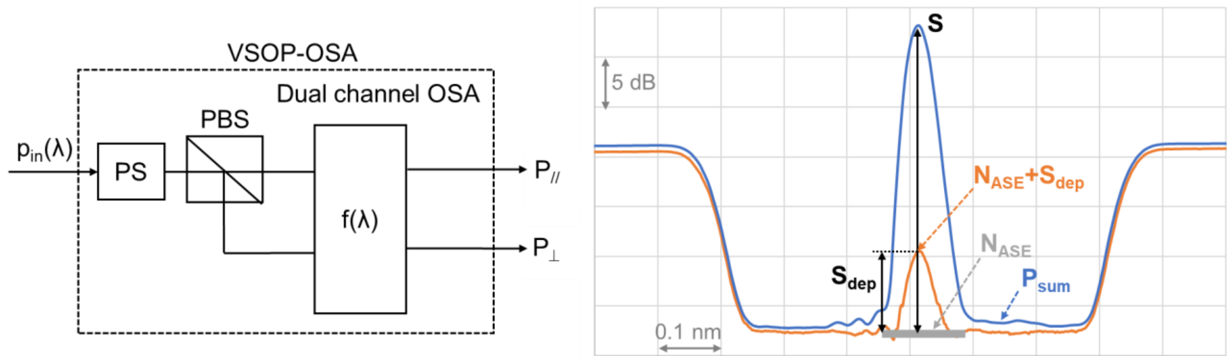

Fig. 1. (a) Schematic of VSOP-OSA (PS: polarization scrambler, PBS: pol. beam splitter), (b) Example spectrum of the measurement concept.

$P_{sum}(\lambda) = P_{//}(\lambda)+P_{\perp}(\lambda)$, corresponding to the sum of the polarized "pure" (i.e. noise-free) signal, $S(\lambda)$, and the ASE noise component, $N_{ASE}(\lambda)$, as follows:

$$P_{sum}(\lambda) = p_{in}(\lambda)*f(\lambda) = [s(\lambda) + n(\lambda)]*f(\lambda) = S(\lambda) + N_{ASE}(\lambda) \quad (1)$$

where * denotes the convolution operation and $f(\lambda)$ is the spectral filter response of the OSA.

For each of the n_{SOP} varied SOP analysis conditions generated by the polarization scrambler, n_{SOP} pairs of mutually-orthogonal polarization-analyzed traces are obtained. By taking the min/max values of the composite traces, we can construct minimum and maximum power spectral traces, $P_{min}(\lambda)$ and $P_{max}(\lambda)$, which effectively represent $P_{max}(\lambda)=\kappa S_{pol}(\lambda)+0.5\cdot S_{dep}(\lambda)+0.5\cdot N_{ASE}(\lambda)$ and $P_{min}(\lambda)=(1-\kappa)S_{pol}(\lambda)+0.5\cdot S_{dep}(\lambda)+0.5\cdot N_{ASE}(\lambda)$, where κ is the portion of the polarized test signal contribution that is measured in $P_{max}(\lambda)$, $N_{ASE}(\lambda)$ is the ASE noise, and $S_{pol}(\lambda)$ and $S_{dep}(\lambda)$ are the polarized and depolarized parts of the signal, respectively, with $S(\lambda) = S_{pol}(\lambda) + S_{dep}(\lambda)$. By subtracting these two equations, one obtains the differential polarization response:

$$\Delta P(\lambda) = P_{max}(\lambda) - P_{min}(\lambda) = (2\kappa-1)S_{pol}(\lambda). \quad (2)$$

The signal-only spectrum, $S(\lambda)$, can be constructed from the differential polarization-resolved spectra as:

$$S(\lambda) = K\,\Delta P(\lambda), \quad (3a)$$

where $K = [(2\kappa - 1)(1-C_{dep})]^{-1}$ and $C_{dep} = S_{dep}/S$ is a coefficient of signal depolarization.

Assuming ASE noise is approximately constant within the signal bandwidth, K and N_{ASE} can be evaluated by solving the equation $P_{sum} = K\,\Delta P(\lambda) + N_{ASE}$ at two or more wavelengths within the signal spectrum. The polarized signal-only spectrum $S_{pol}(\lambda)$ can be constructed from $\Delta P(\lambda)$ as $S_{pol}(\lambda) = \Delta P(\lambda)/(2\kappa-1)$. An *ab initio* statistical approach can be used to derive an estimated value of κ from the probability density function, as a function of the number and distribution of SOP on the Poincaré sphere (n_{SOP}). For independent and uniformly distributed SOP, the expectation value μ of the calculated PDF yields the following estimate for κ as a function of n_{SOP}:

$$\kappa = 0.5\,[(2n_{SOP}+1)/(n_{SOP}+1)]. \quad (4)$$

With the estimated κ, one can then obtain $S_{dep}(\lambda)$ or C_{dep}. In general, S_{dep} consists of depolarization contributions induced by fiber nonlinearity and DGD. In this case with CW laser as test signal, the DGD component is zero and the nonlinear depolarization is the only component of C_{dep}. We observe a very clear correlation between the measured nonlinear-induced signal depolarization and link nonlinear noise (obtained via the transponder-based method), and thus we can estimate $OSNR_{NL} = \alpha/C_{dep}$, where α is a constant scaling factor. We choose α based on the measured data at the optimum launch power, such that the nonlinear noise is equal to half of the linear ASE noise, as expected by the GN model theory. GOSNR can thus be estimated by $1/GOSNR = 1/OSNR_{ASE} + (1/\alpha)C_{dep}$.

3. Experimental Validation

We sought to validate the method using an experimental link consisting of 8 spans of standard SMF (70 km each), with extra variable attenuation placed at the end of each span in order to tune the span loss to 22 dB. The C-band spectrum (4.8 THz) was filled with broadband ASE noise, with the exception of the central 75-GHz slot centered at 193.6 THz, allocated to the test signal. Multiple ports of a flexible-grid ROADM were used to multiplex the test signal and ASE loading. For the conventional transceiver-based GOSNR estimation, a 60 GBd 16QAM signal was used from a commercial transceiver. 16QAM was used in order to avoid the saturation regime, due to the relatively high (G)OSNR on the link [2]. The polarization-spectrum analysis utilized an unmodulated laser source from an

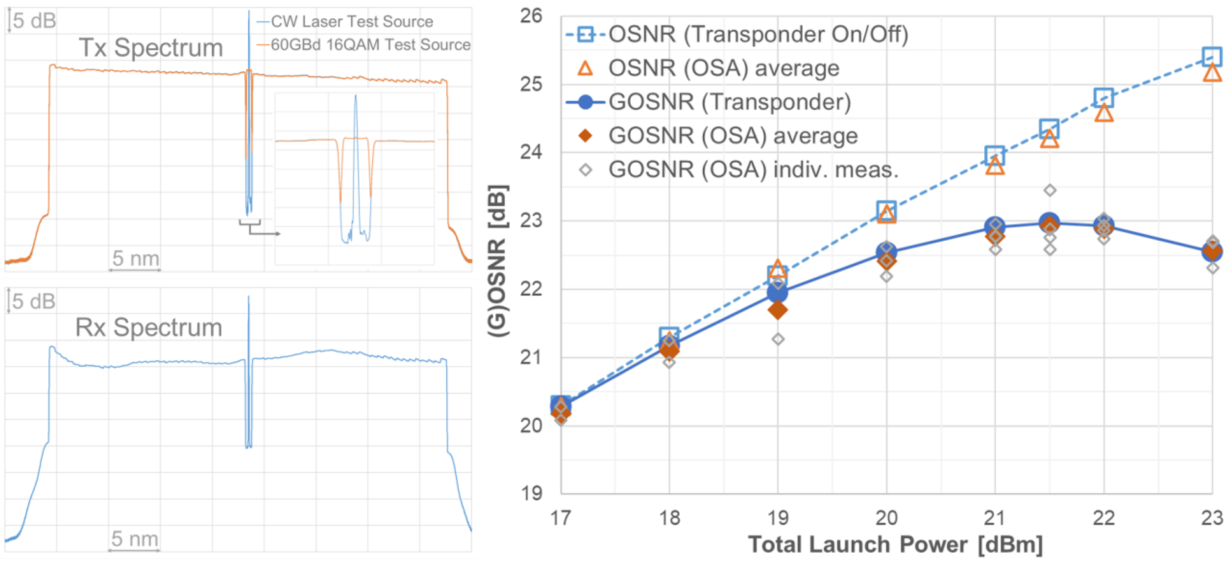

Fig. 2. (a) Measured Tx and Rx Spectra (at optimum launch power), (b) Experimental OSNR and GOSNR results from the link.

ITLA with specified linewidth <15 kHz (Novoptel LU1000). The launch power per span on the link was scanned over a range extending above and below the optimum launch power. For each condition, the receive spectrum was measured using a commercial grating-based VSOP-OSA with ~35 pm resolution (EXFO model FTBx-5255), to estimate GOSNR using the CW laser. OSA traces with 2000 scans were collected at each condition, to ensure sufficient variation in SOP over the measurement time. Additionally, the 16QAM test signal was inserted in place of the CW laser to measure the Q^2 factor and estimate the link GOSNR by fitting with a back-to-back calibration curve using the same transceiver bypassing the fiber link under test. A small transceiver-related transmission penalty of ~0.2 dB was observed, which was excluded from the GOSNR estimation (by subtracting $1/OSNR_i$ from $1/OSNR_{EXT}$ to obtain 1/GOSNR, as in Eq. (11) of [2]).

Example optical spectra are presented in Fig. 2(a-b), showing the CW laser source or 60 GBd 16QAM signal configured within the central 75-GHz slot and surrounded by broadband ASE loading. Fig. 2(c) shows the measured $OSNR_{ASE}$ and GOSNR using the calibrated test transceiver and using the OSA with CW laser. At least two repeated OSA measurements were taken for each test condition, and the individual OSA measurement points are shown in open grey markers, while the average across multiple traces is shown in solid orange markers. Some individual GOSNR measurements differed by up to 0.7 dB from the transceiver-based measurement, but the average estimated GOSNR using the OSA was within 0.3 dB of the transceiver result. With lower GOSNR and/or larger n_{SOP}, there is less uncertainty (less variation), and averaging is a good way to reduce the uncertainty. It is possible to reduce the uncertainty more efficiently by increasing n_{SOP}. The same type of measurements were also completed with two 60 GBd transceivers operating in the adjacent 75-GHz slots surrounding the test signal, and the GOSNR results using the transceiver and OSA methods were nearly identical in this configuration as well as the case with only ASE loading surrounding the test signal. Additional measurements were also performed with ~3 dB lower span loss, also showing similar agreement between the transceiver and OSA-based methods. Further work remains to validate the OSA-based technique across a broader range conditions, including different transmission distances and fiber types.

4. Conclusion

We have introduced a novel all-optical method for measuring the GOSNR of an open line system using only an unmodulated laser source and VSOP-OSA, which can be used to independently characterize a line system before any transceivers are deployed. By experimental validation using an 8-span link, we showed that the OSA-based method can achieve similar results to the conventional approach using a calibrated test transceiver.

5. References

[1] V. Kamalov, et al, "Lessons Learned from Open Line System Deployments," in *Proc. OFC*, Los Angeles, CA, March 2017, paper M2E.2.
[2] E. Rivera Hartling, et al., "Design, Acceptance and Capacity of Subsea Open Cables," *J. Lightwave Technol.* 39 (3), pp. 742-756, 2021.
[3] D. Gariepy, et al., "Novel OSA-based method for in-band OSNR measurement", in *Proc. OFC*, San Diego, CA, March 2010, paper JThA15.
[4] G. He, et al., "In-Band Optical Noise Measurement Using Differential Polarization Response" US Patent 8,364,034 B2 (2013).
[5] B. Collings and L. Boivin, "Nonlinear Polarization Evolution Induced by Cross-Phase Modulation and Its Impact on Transmission Systems," *IEEE Photon. Technol. Lett.* 12 (11), pp. 1582-1584 (2000).