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Novel OSA-Based Method for In-Band OSNR Measurement

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Abstract: A new approach for in-band OSNR measurements in narrow DWDM channels is described, which is robust to PMD and enables rapid measurement of accurate OSNR values of >20 dB without need for polarization extinction.

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Introduction

Optical signal-to-noise ratio (OSNR) is a key performance parameter of signal quality for optical telecommunication signals. In DWDM networks, particularly where different channels are routed through different paths via ROADMs, the polarization-nulling (PN) method and its many reported variants [1-3], employing an optical spectrum analyzer (OSA) or similar field-suitable instrumentation, are often used. They are predicated on the assumption that the underlying noise is unpolarized (e.g. amplified spontaneous emission – ASE) and that the signal, or at least that the portion of the signal measured within the resolution bandwidth (RBW) of the OSA, is fully polarized. When the signal-under-test (SUT) is maximally extinguished by an analyzer, corresponding to the minimum detected power when randomly scrambling the state-of-polarization (SOP), the OSNR at that wavelength can be estimated.

Accurate measurement of OSNR (to within 0.5 dB) requires the capability to measure an extinction ratio (of a hypothetical noise-free signal) approximately 10 dB greater than the OSNR value to be measured, necessitating excellent SOP coverage and considerable measurement time for large OSNR values (e.g. >15 dB). Although this high-extinction constraint can be relaxed if the channel bandwidth is at least somewhat larger than the bandwidth of the SUT, allowing the underlying noise in the signal wings to be estimated where the signal (and hence the "local" OSNR) is lower, this is not the case in most 40Gb/s and 100Gb/s DWDM applications, where the signals fully fill or even "overfill" the channel bandwidth. In addition, polarization mode dispersion (PMD) in the fiber link can partially depolarize the SUT even within a narrow OSA RBW (e.g. 4 ps of PMD leads to ~1 % depolarization in a RBW of 50 pm), resulting in an underestimated value for high OSNR. This PMD-induced error can be partially mitigated by averaging over several wavelengths within the channel [4,5], but nevertheless remains problematic.

Here, we demonstrate a novel "Hybrid Differential Spectral Response" (H-DSR) OSNR measurement approach that largely overcomes many of the aforementioned problems. The method relies partially on the polarization properties of the signal, but also takes advantage of the differential spectral (i.e. resolution-bandwidth-dependent) characteristics of the signal and optical noise.

Hybrid Differential Spectral Response (H-DSR) Method

The Differential Spectral Response (DSR) method, which, like PN, is based on the assumption that signal and superposed noise components of the detected light have different polarization behavior, differs from PN in that total or near-total extinction of the signal is not required for OSNR determination. This is a major advantage, since it significantly relaxes the constraints on SOP coverage, quality of the polarization optics, and measurement time.

Concretely, the DSR method can be implemented in a polarization-diverse OSA [6] with an input polarization scrambler (PS in Fig. 1), by detecting the "spectral curves" corresponding to orthogonally-analyzed light components, assuming that the SOP of the input light is such that these two "spectral curves" are different in magnitude (in practice at least >3 dB, preferably more for the measurement of large OSNR). To ensure this difference, measurements are generally acquired with randomly-selected input SOPs. From the acquired data, the "signal-only" spectral curve can be reconstructed, and this curve subtracted from the initial light signal to determine the (unpolarized) noise component.

Figure 2 shows schematically the measured DWDM-channel power spectrum, corresponding to a measured optical input, $P_{sum}(\lambda) = P_{//}(\lambda) + P_{\perp}(\lambda) = P_{input}(\lambda) * f(\lambda)$, where $P_{input}(\lambda)$ is the actual input spectrum, $P_{//}(\lambda)$ and $P_{\perp}(\lambda)$ are the orthogonal measured powers, $f(\lambda)$ is the OSA filter function, and "*" denotes a convolution operation.

This measured optical input is the sum of the to-be-determined data-carrying signal spectrum $S(\lambda)$ and noise spectral curve $N(\lambda)$ (both convoluted with the OSA filter function), and hence

$$P_{sum}(\lambda) = P_{>}(\lambda) + P_{<}(\lambda) = S(\lambda) + N(\lambda) \qquad (1)$$

where $P_{>}(\lambda)$, $P_{<}(\lambda)$ are, respectively, the higher and lower of the two detected powers $P_{//}(\lambda)$ and $P_{\perp}(\lambda)$.

It is convenient to introduce the fraction κ representing the portion of the data-carrying signal $S(\lambda)$ that is measured in $P_{>}(\lambda)$. Using this and with the assumption that the optical noise is depolarized, we can write:

$$P_{>}(\lambda) = \kappa\, S(\lambda) + 0.5N \quad (2a)$$

$$P_{<}(\lambda) = (1-\kappa)\, S(\lambda) + 0.5N \quad (2b)$$

If there is negligible link PMD (and negligible inter-channel crosstalk), κ is constant with wavelength within the bandwidth of the signal (e.g. approximately 40 GHz for a 40-Gbaud signal). If significant PMD is present, κ will vary with wavelength, primarily as a result of depolarization from 2^{nd}-order PMD [7], but this wavelength variation can be well compensated and removed using a larger number of SOPs via an averaging procedure. From (2a) and (2b), the signal contribution can be "reconstructed" from the differential polarization response $\Delta P(\lambda) = P_{>}(\lambda) - P_{<}(\lambda)$:

$$S(\lambda) = [1/(2\kappa - 1)]\, \Delta P(\lambda) \quad (3)$$

Now, using the reconstructed signal $S(\lambda)$ from (3), it is possible to isolate the respective spectral contributions of the signal and the noise using a differential spectral resolution (DSR) approach, and thereby obtain the integrated noise in a given optical BW, without knowing the actual value of κ, but only that it is uniform in wavelength. Relying on both the polarization properties, to reconstruct the signal shape, and the spectral properties of the constituent signal and noise components, the Hybrid-DSR (H-DSR) approach is now detailed.

The integrated powers of P_{sum} in BW_1 and BW_2 can be expressed as

$$P_{sum}(BW_j) = \int_{BWj} P_{sum}(\lambda) = \int_{BWj} S(\lambda)d\lambda + \int_{BWj} N(\lambda)d\lambda \quad (4)$$

where j represents 1 or 2, respectively, and where $BW_2 = BW_1 + \Delta BW > BW_1$ and $BW_2 < CBW$. From Eqs.(3) and (4), the integrated noise in BW_1, BW_2 or the variation of N from BW_1 to BW_2 can be found by

$$\int_{BW1} N(\lambda)d\lambda = [P_{sum}(BW2) - \alpha P_{sum}(BW1)] / (\beta - \alpha) \quad (5a)$$

$$\int_{BW2} N(\lambda)d\lambda = [P_{sum}(BW2) - \alpha P_{sum}(BW1)]\, [\beta/ (\beta - \alpha)] \quad (5b)$$

$$\int_{BW2} N(\lambda)d\lambda - \int_{BW1} N(\lambda)d\lambda = [P_{sum}(BW2) - \alpha P_{sum}(BW1)]\, [(\beta-1)/ (\beta - \alpha)] \quad (5c)$$

where

$$\alpha = \int_{BW2} S(\lambda)d\lambda \,/ \int_{BW1} S(\lambda)d\lambda = \int_{BW2} \Delta P(\lambda)d\lambda \,/ \int_{BW1} \Delta P(\lambda)d\lambda \quad (6a)$$

$$\beta = \int_{BW2} N(\lambda)d\lambda \,/ \int_{BW1} N(\lambda)d\lambda \quad (6b)$$

For the case where $N(\lambda)$ is constant across BW_2 and BW_1, Eq. (6b) simplifies to

$$\beta = (BW_2/BW_1)\ \int_{BW1} N(\lambda)d\lambda \,/ \int_{BW1} N(\lambda)d\lambda = BW_2/BW_1\ . \quad (7)$$

The OSNR in the channel (or in-band OSNR) can thus be cast as:

$$OSNR = \int_{CBW} S(\lambda)d\lambda \,/\, N_r = [\int_{CBW} P_{sum}(\lambda)d\lambda - \int_{CBW} N(\lambda)d\lambda]/N_r \quad (8)$$

where CBW is the effective channel optical bandwidth and N_r is the integrated noise, or equivalent integrated noise normalized to a reference 0.1-nm bandwidth. For a given arbitrary bandwidth (BW), N_r can be expressed as

$$N_r = (0.1/BW) \int_{BW} N(\lambda)d\lambda. \quad (9)$$

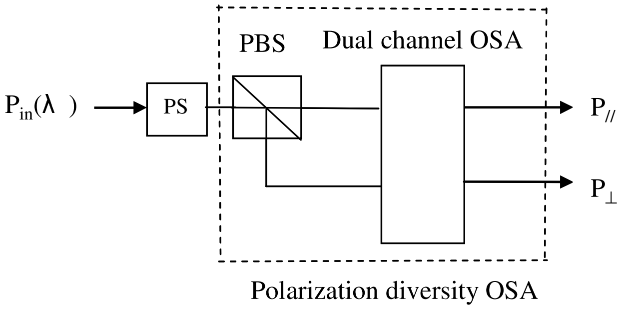

Fig. 1: Polarization-diversity optical spectrum analyzer.

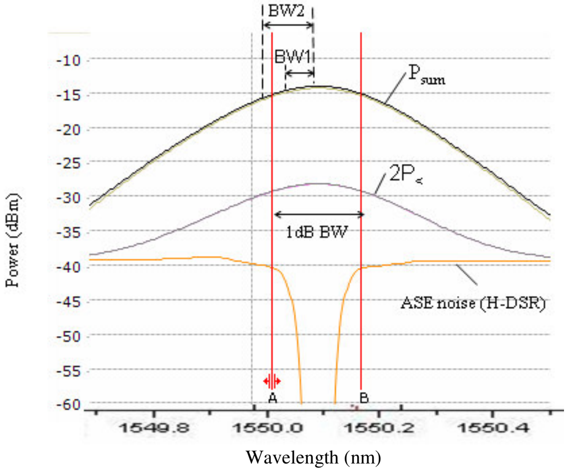

Fig. 2: Illustration of H-DSR method.

In contrast to PN-based methods, where the maximum measurable OSNR is directly limited by the achievable polarization extinction ratio ER ≈ $\kappa/(1-\kappa)$, the H-DSR method is fundamentally independent of κ or ER, so that it allows evaluation of OSNR values higher than the measured ER. As a result, a significantly reduced number of acquisitions (each at a different SOP) are required, resulting both in shorter measurement times and relaxed polarization-hardware (complexity and cost) requirements. As an example, a 16-SOP H-DSR result (Fig. 2) taken with an ER of only ~15 dB suffices to measure the OSNR of 25 dB to within ± 0.5 dB. In comparison, for this same OSNR value and uncertainty, the PN method requires an ER of ~35 dB, corresponding to 1500 SOPs.

Experimental results

To demonstrate the performance of the H-DSR method, a controlled test setup (Fig. 3) is used, where the OSNR can be set to known values, since the test-bed elements have been carefully pre-calibrated. Strong-mode-coupling PMD emulators (nominally 3, 5, 10 and 15 ps) are optionally inserted in the signal path and the SOP input into the respective emulator is adjusted to maximize the κ wavelength dependence. For each PMD emulator, the OSNR levels are varied from 15 to 30 dB (with respect to a 0.1-nm reference BW) and the deviation in H-DSR computed OSNR are recorded (Fig. 4). The source is a 40-Gb/s OOK-modulated transmitter. A series of 64 scans (i.e. 64 SOPs at the input of the polarization-diverse OSA) are performed using a non-uniform, low-cost "stepped" polarization scrambler. (When no emulator is used, the same results are achieved with only eight polarization input conditions.) Similar results are obtained in repeated tests with multiple PD-OSA units (EXFO FTB-5240S-P).

The H-DSR results fall well within 0.5 dB of the reference values for all emulated PMD conditions up to 25-dB OSNR and slightly exceed 0.5 dB for some emulated PMD conditions at 30-dB OSNR.

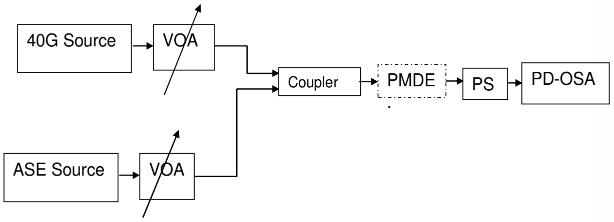

Fig.3 Schematic illustration of experimental set-up

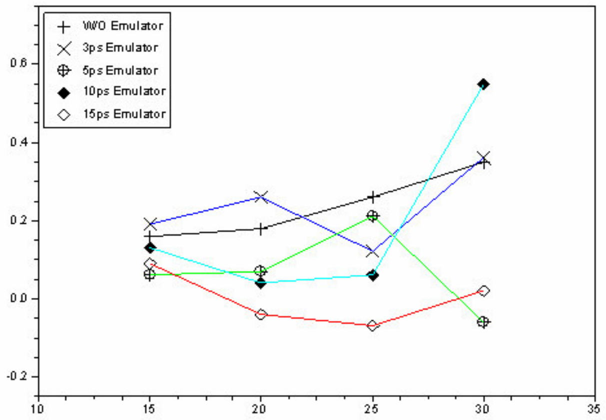

Fig. 4 Residuals of measured OSNR vs calibrated test-bed OSNR.

Conclusion

A novel polarization-diverse OSA-based method is demonstrated that allows for rapid and accurate in-band OSNR measurements for OSNR values up to 30 dB, even in the presence of strong emulated PMD. This H-DSR method relies on both differential polarization properties and spectral behavior of the signal with respect to the optical noise. Its application permits the determination of the OSNR well beyond the polarization-extinction-ratio limit of the hardware used, or, alternatively, allows for measurement of reasonably high OSNR using a limited number of input-polarization conditions.

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