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Optical signal-to-noise ratio (OSNR) has always been a key performance parameter for each channel of a multiwavelength optical network.

In first-generation wavelength-division multiplexing (WDM) and dense wavelength-division multiplexing (DWDM) networks, OSNR was usually measured on channels of point-to-point trunk links, or ring-based metro networks, in which each of the multiplexed signal wavelengths generally followed the same optical path (including the same optical amplifiers). Under these conditions, the OSNR could be measured using a straightforward optical spectrum analyzer-based method, known as the interpolation method (standardized in IEC 61280-2-9), which provides a single spectral measurement for all the DWDM channels.

However, as the deployment of reconfigurable optical add-drop multiplexers (ROADMs) and mesh-like network architectures becomes more prevalent, it is frequently the case that any given DWDM signal wavelength may have passed through a different combination of intermediate nodes (each node generally with its own ROADM and optical amplifier) than an adjacent channel (see figure 1). Under these circumstances, the interpolation method can no longer be used since the underlying noise level of a particular channel is not necessarily related to the noise level of a neighboring channel.

Also, when the channel density is high, the interpolation method often cannot even be used in amplified point-to-point links, with different channels traveling along the same fiber path. This is the case with recent systems transmitting 40 Gbaud signals on a 50 GHz-spaced channel plan, since the underlying amplified spontaneous emission (ASE) noise is hidden by the wings of the channels.

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Figure 1. In a mesh network with ROADM nodes, the accumulated noise can be different in separate DWDM channels. Also, the narrow channel bandwidths substantially cut the ASE noise, making application of the traditional interpolation method infeasible.
In order to overcome these limitations, alternative measurement approaches have been developed. In these techniques, the information needed to determine the OSNR for any given channel can be obtained only from an in-channel measurement, independent (at least ideally) from the behavior of adjacent channels. Most of these methods are based on the different polarization properties of the signal portion and the noise portion of light in a channel. Specifically, they assume that the underlying channel noise is essentially unpolarized, whereas the signal light is highly polarized.

In its simplest form (see figure 2), the channel light is analyzed using a combination of a polarization controller (PC), a linear polarizer (POL) and an optical detector (DET). The PC is first adjusted until the detected optical power is a minimum $P_{\text{min}}$. This power is then proportional to $\frac{1}{2} P_N$, where $P_N$ is the (unpolarized) noise power. Next, the PC is adjusted until the detected power is a maximum $P_{\text{max}}$. This power is then proportional to $P_{\text{sig}} + \frac{1}{2} P_N$. These two measurements are then sufficient to determine the OSNR, whose value is generally given in decibels:

$$\text{OSNR (dB)} = 10 \log_{10} \left( \frac{P_{\text{max}} - P_{\text{min}}}{2P_{\text{min}}} \right)$$

In many realistic optical network measurement scenarios, however, this simplest version of the polarization-nulling method is not reliable. One of its most serious drawbacks is its sensitivity to polarization mode dispersion (PMD), a fiber phenomenon that may cause the state of polarization (SOP) of the signal to vary significantly over its spectral width, leading to an apparent partial depolarization of the signal portion of the light within the channel under-test. As a result, the noise power, which is assumed to be proportional to the detected unpolarized light, can be significantly overestimated, leading to an OSNR result that is too low. As an example, for an effective channel width of approximately 25 to 30 GHz (typical of a 50 GHz-spaced DWDM network with cascaded filtering from multiple ROADMs along the signal path) a PMD of 1 ps can lead to a signal depolarization of up to 10%, preventing a reliable OSNR measurement, when this value is much lower/higher than 10 dB.

In addition, at very high transmission rates (e.g., >20 Gbaud), second-order PMD can be a significant source of additional depolarization.

![Figure 2. Principle of the polarization-nulling approach: measurements are taken with a polarization controller PC adjusted to as to maximize the signal and then adjusted so as to effectively extinguish the signal. The signal is assumed fully polarized and the depolarizing effect of PMD across the signal bandwidth is assumed negligible.](image)
Incorrect results can also be obtained if the optical noise is not completely unpolarized, as can be the case if the polarization-dependent loss (PDL) of the optical link (including the filter edges) is significant.

Although a number of different approaches based on the polarization-nulling principle have been proposed (using laser heterodyne analysis for instance), approaches based on a conventional optical spectrum analyzer (OSA) design are the most attractive for network operators, since these OSAs are general-purpose instruments that can also be used for many other field applications.

One test equipment vendor offers an OSA-based approach that can somewhat reduce the effect of PMD-induced depolarization [4]. The basic idea is to measure the noise power within a narrow spectral slice to minimize the depolarization effect. The width of this typical spectral slice is approximately 7 GHz, corresponding to the resolution bandwidth (RBW) of a standard OSA, versus the approximately 25 to 30 GHz effective width typically resulting from multiple cascaded ROADM filters. In this way, for the same OSNR accuracy, the maximum tolerable PMD can be enhanced by approximately a factor of four. In addition, some additional PMD tolerance can be achieved by performing an off-center measurement of this spectral slice; the apparent signal contribution is significantly lower than at the peak, so that PMD-induced depolarization of this signal contribution will have a proportionally lower contribution to the measured noise.

Nevertheless, this approach, like all the other polarization-nulling variants, is still fundamentally predicated upon the assumption that the optical signal (or that portion of it being measured) is fully polarized and that the noise is unpolarized. It is thus still significantly hindered by moderately high PMD values, particularly for new-generation high-bit-rate signals transmitted through narrow DWDM channels. In addition, an accurate measurement requires that the true minimum (and, somewhat less critically, the true maximum) measured power be found for each channel, a constraint that can significantly increase the measurement time.

EXFO recently introduced a new OSA-based in-channel OSNR measurement method—the polarization-resolved optical spectrum OSNR (PROS OSNR) method—which largely overcomes many of the aforementioned difficulties. It is based on the assumption that the noise $N(\lambda)$ and actual signal $S(\lambda)$ have different polarization properties, but does not require that the noise be completely unpolarized or that the signal be completely polarized. $S(\lambda)$ is presumed to have a substantial degree of polarization (DOP), for example >50%, but certainly does not need to be 100%. The noise component is assumed to be significantly depolarized; i.e., with a DOP less than that of $S(\lambda)$, and it is assumed not to vary significantly with wavelength beneath the $S(\lambda)$ curve.

This fundamentally different approach to measuring in-channel OSNR has recently materialized with EXFO’s FTBx-5245/5255 Optical Spectrum Analyzer.

Figure 3 shows a simplified optical schematic of the FTBx-5245/5255. The optical input to be measured is decomposed into orthogonal (parallel and perpendicular) linear polarization components, as follows:

$$P_{\text{input}} = P_{//} + P_{\perp} \quad (1)$$

The optical spectrum of each of these two components is measured with independent detectors sharing the same synchronized (diffraction grating-based) filter.
Figure 3. A polarization diversity OSA comprises two channels, each measuring one of orthogonal polarization components of the incoming light. Conveniently, these two components correspond to orthogonal linear polarization components.

This polarization-resolved optical spectrum OSNR (PROS OSNR) method, introduced by EXFO, makes use of the same components as a polarization diversity OSA. However, it includes an additional refinement since it combines two independent approaches—one based upon a different behavior of the in-channel signal and noise with respect to polarization and the other based on the different behavior of the in-channel signal and noise with respect to the resolution bandwidth of the spectral measurement. Before the method is examined, it is important to understand its two basic underlying approaches; i.e., differential polarization response or D-Pol, and differential RBW response or D-RBW.

**Differential polarization response approach (D-Pol)**

For the sake of simplicity, this approach is explained considering a case in which PMD on the optical path can be neglected, and it can be assumed that the noise component is completely depolarized, such as is normally the case for ASE noise, when PDL in the successive components of the link is reasonably low. Figure 4 shows schematically the measured power spectrum corresponding to an optical input signal \[ P_{\text{sum}}(\lambda) = P_{\text{input}}(\lambda) \] (2), which is the sum of the pure (i.e., noise-free) signal \( S(\lambda) \) and the noise component \( N(\lambda) \); i.e.,

\[
P_{\text{sum}}(\lambda) = S(\lambda) + N(\lambda)
\]

One or the other of the two detected decomposed powers will generally be larger than the other, except when the input SOP is such that \( P_{/\!/} = P_{\perp} \). In this case, the SOP of the input light can be changed (e.g., with a simple polarization controller) and the measurement repeated. Hence,

\[
P_{\text{sum}}(\lambda) = P_{/>}(\lambda) + P_{<}(\lambda)
\]

where \( P_{/>}(\lambda), P_{<}(\lambda) \) are, respectively, the higher and lower of the two detected powers. (Note that these are not in general the absolute maximum and minimum powers, as required in the polarization-nulling approach.)
Figure 4. The polarization-resolved optical spectrum OSNR approach permits the noise to be calculated knowing only the total detected power and the difference between the orthogonal polarization components (neither of which needs to be a true minimum or maximum). The large error in the assumed noise near the peak wavelength can be substantially eliminated using an iterative process.

It is convenient to introduce the fraction $k$ representing the portion of the signal $S(\lambda)$ that is measured in $P_>(\lambda)$. Using this, the equation can be written as

$$ P_>(\lambda) = kS(\lambda) + 0.5N(\lambda) \quad (4a) $$

and, by extension

$$ P_<(\lambda) = [1 – k] S(\lambda) + 0.5N(\lambda) \quad (4b) $$

Assuming little or no link PMD, $k$ is constant with wavelengths within the bandwidth of the signal (e.g., approximately 40 GHz for a 40 Gbaud signal). With these expressions, the polarization-resolved optical spectrum OSNR $S'(\lambda)$ of the spectrum can now be readily calculated from the measured data as follows:

$$ S'(\lambda) = P_> – P_< = (2k – 1) S(\lambda) \quad (5) $$

Now, if assuming that, at the wavelength $\lambda_p$ corresponding to the peak of the signal, $S(\lambda_p) \gg N$, then the following can be approximated:

$$ k \approx k_a = P_>(\lambda_p) / P_{\text{sum}}(\lambda_p) \quad (6) $$

By inserting equation 6 into 5 one obtains:

$$ S(\lambda) – S_a = S'(\lambda) / (2k_a – 1) \quad (7) $$

And combining equation 7 with equation 2 then yields:

$$ N = N_a = P_{\text{sum}}(\lambda) – S'(\lambda)/(2k_a – 1) \quad (8) $$

From equation 8, it is clear that the noise value calculated near the signal peak $\lambda_p$ is likely to be unreliable, since $k_a$, the first-order approximation for $k$ in equation 6, forces the noise $N(\lambda_p)$ to be zero. However, at wavelengths significantly different than the peak, this error is generally minimal, as shown in figure 4.
For instance, at the cross-over wavelength, \( \lambda_c \), where \( N_a(\lambda_c) = S_a(\lambda_c) \), equation 8 can be rearranged to give:

\[
S'(\lambda_c) = P_{\text{sum}}(\lambda_c) \times (2k - 1)/2 \tag{9}
\]

From the acquired data, it is known that the curves for \( P_{\text{sum}}(\lambda) \) and \( S'(\lambda) \); hence, \( \lambda_c \) can be readily determined (generally two values \( \lambda_{c1,2} \), one on each side of the signal peak). The noise level at \( \lambda_c \) is then simply given by equation 8.

As an example, for \( S(\lambda_p)/N(\lambda_p) \) of 100 (20 dB), the associated error on \( N(\lambda_{c1}) \) and \( N(\lambda_{c2}) \) is less than about 0.05 dB.

The noise \( N \) between \( \lambda_{c1} \) and \( \lambda_{c2} \) (for example at \( \lambda_p \)) can be determined by:

- Interpolating a linear function between \( N_a(\lambda_{c1}) \) and \( N_a(\lambda_{c2}) \), thereby estimating \( N_a(\lambda_p) \)
- Using this interpolated approximate noise value in equations 2 and 6 to yield an improved second-order estimate \( k' \)
- Using this improved estimate to provide a more accurate value for \( N(\lambda_p) \)
- If necessary, repeating this iterative process until the noise value converges to a stable value (in practice, generally after one iteration)

In this way, the entire noise function \( N \) can be determined within the channel when PMD does not significantly influence the SOP as a function of \( \lambda \) within the signal bandwidth. (Hence, this condition is more easily satisfied with 10 Gbaud signals than with 40 Gbaud signals).

From equation 2, the signal level \( S(\lambda) \) is:

\[
S(\lambda) = P_{\text{sum}}(\lambda) - N \tag{10}
\]

Consequently, the signal-to-noise-ratio in the channel can be expressed as:

\[
\text{OSNR} = \frac{\int_{\text{CBW}} S(\lambda) \, d\lambda}{\int_{\text{CBW}} N(\lambda) \, d\lambda} \tag{11}
\]

where CBW is the effective channel optical bandwidth and \( N_r \) is the integrating noise in the standard 0.1 nm RBW at the channel center.

Alternatively, it may be more useful to provide the overall channel SNR; i.e., the actual ratio of signal to noise seen by a receiver in a transmission system after a channel demultiplexer. The OSNR\(_{ch}\) can be defined as:

\[
\text{OSNR}_{ch} = \frac{\int_{\text{CBW}} S(\lambda) \, d\lambda}{\int_{\text{CBW}} N(\lambda) \, d\lambda} \tag{12}
\]

For this case assuming that the noise is constant throughout the channel, this is given by:

\[
\frac{\int_{\text{CBW}} S(\lambda) \, d\lambda}{\left[ N_r \left( \text{CBW / 0.1nm} \right) \right]} \tag{13}
\]

When PMD-induced changes within the signal BW are not significant, generally only eight (8) or less, randomly chosen input-signal SOPs are needed to obtain good measurements for all present channels. If significant PMD is present, more SOPs, typically 40 to 60, are required to compensate for errors arising from the resulting wavelength dependence of \( k \). Nevertheless, when compared to the typically several hundred of SOPs required for the polarization nulling method, the D-Pol approach clearly has significant advantages; i.e., shorter measurement time and significantly reduced PMD and PDL sensitivity.
Differential RBW Discrimination Approach (D-RBW)

This alternative approach for determining the OSNR will now be reviewed in its simplest embodiment. The D-RBW method does not involve polarization-dependent measurements, hence, is insensitive to PMD. Furthermore, it can also (under certain conditions) be applied to polarization-multiplexed signals (such as those being considered for 100 Gbit/s transmission). Again, assuming that the underlying noise is spectrally flat.

It is also assumed, for this simplest case, that the available spectrum for the measurement (e.g., the channel bandwidth) is larger than the signal. (Under such circumstances, the interpolation method could also be applied. As it will be seen shortly, the full benefit of the the D-RBW discrimination approach is achieved when it is combined with the D-Pol approach.)

As illustrated in figure 5, it is assumed that the bandwidths \(BW_1\) and \(BW_2\) are both larger than the signal bandwidth (defined in this case as the point where \(S(\lambda)\) falls below the noise or the desired measurement sensitivity), and that \(BW_2 > BW_1\). Then, using equation 2, this can be expressed as follows:

\[
\begin{align*}
P_{\text{sum}}(BW_1) &= \int_{BW_1} P_{\text{sum}}(\lambda) = \int_{BW_1} S(\lambda) d\lambda + \int_{BW_1} N(\lambda) d\lambda \\
P_{\text{sum}}(BW_2) &= \int_{BW_2} P_{\text{sum}}(\lambda) = \int_{BW_2} S(\lambda) d\lambda + \int_{BW_2} N(\lambda) d\lambda
\end{align*}
\]

(14a)
(14b)

Since both \(RBW_1\) and \(RBW_2\) are assumed to be wider than the \(BW\) of \(S(\lambda)\):

\[
\int_{BW_1} S(\lambda) d\lambda = \int_{BW_2} S(\lambda) d\lambda
\]

(15)

From equations 14a, 14b and 15, the variation of \(N\) from \(RBW_1\) to \(RBW_2\) can be found by:

\[
\int_{BW_2} N(\lambda) d\lambda - \int_{BW_1} N(\lambda) d\lambda = P_{\text{sum}}(BW_2) - P_{\text{sum}}(BW_1)
\]

(16)

If \(N\) is assumed constant across \(RBW_2\), equation 16 can simplified to yield (see Figure 5) the following:

\[
N(\lambda_p) = \frac{[P_{\text{sum}}(BW_2) \mid_{\lambda_p} - P_{\text{sum}}(BW_1) \mid_{\lambda_p}]}{(BW_2 - BW_1)}
\]

(17)

Figure 5. As long as the condition of complete integration of the signal component can be achieved before the filtered noise edges, the differential RBW method permits the noise to be accurately estimated even in the presence of strong PMD or when polarization-multiplexed signals are used.
Polarization-resolved optical spectrum OSNR (pros OSNR)

In many practical in-channel measurement applications, the condition of equation 15 does not hold. However, by making use of the additional information provided by the differential polarization signal $S'(\lambda)$ (see equation 5), the in-band noise can still be determined even if $RBW_1$ and $RBW_2$ are narrower than the signal bandwidth. Under these circumstances, equation 16 may be expressed as:

$$\int_{BW_2} N(\lambda) d\lambda - \int_{BW_1} N(\lambda) d\lambda = \left[ P_{sum}(BW_2) - \alpha P_{sum}(BW_1) \right] \cdot \left[ (\beta - 1) / (\beta - \alpha) \right]$$  \hspace{1cm} (18)

where

$$\alpha = \int_{BW_2} S'(\lambda) d\lambda / \int_{BW_1} S'(\lambda) d\lambda$$  \hspace{1cm} (19)

$$\beta = \int_{BW_2} N(\lambda) d\lambda / \int_{BW_1} N(\lambda) d\lambda$$  \hspace{1cm} (20)

For the case that $N(\lambda)$ is constant across $BW_2$ and $BW_1$, Equation 20 simplifies to:

$$\beta = BW_2 / BW_1$$  \hspace{1cm} (21)

Compared with the D-Pol method, the main advantage of this PROS OSNR approach is that it does not depend upon the absolute values of $k$, and hence no iteration process is required.

Figure 6 shows a typical result using this PROS OSNR method.

![Figure 6. The polarization-resolved optical spectrum OSNR approach is a hybrid of the D-Pol and D-RBW methods, allowing accurate noise estimation even when the signal bandwidth takes up almost all of the channel bandwidth.](image)

**Conclusion**

The polarization-resolved optical spectrum OSNR measurement method, when used with a dual-channel, polarization-diverse optical spectrum analyzer, is a breakthrough approach that represents a powerful tool for the measurement of in-channel OSNR.

Compared to other methods, the polarization-resolved optical spectrum OSNR technique does not require the signal to be extinguished, leading to a tremendous advantage, in both measurement speed and overall precision for challenging high-baud-rate DWDM applications.

**References:**


5. The absolute value of the measured power as a function of wavelength of course depends upon the RBW of the OSA. By convention, the acquired values are generally normalized to a RBW of 0.1 nm in the data processing, even though the raw data generally corresponds to a narrower RBW (about 0.5 nm for the FTBx-5245/5255).