



In-Band OSNR Measurements on 40 G Polarization-Multiplexed QPSK Signals Using a Field-Deployable, High-Resolution OSA

We describe a non-intrusive measurement method for determining the in-band optical signal-to-noise ratio (OSNR) of polarization-multiplexed 43 G QPSK signals from a high-resolution spectral analysis. Using a high-resolution JDSU optical spectrum analyzer (OSA-610), we demonstrate in-band OSNR measurements up to 25 dB with less than 0.25 dB measurement error. In contrast to other spectral analysis techniques, our method does not require calibration of the instrument on a noise-free signal at the transmitter and is tolerant to optical filtering in ROADMs with 50 GHz channel spacing.

Background

OSNR measurements are standard procedure in long-distance fiber-optic communication systems to characterize the quality of transmitted signals after installation or during normal operation. The OSNR is defined as the ratio of the total optical power of the (noise-free) optical signal to the spectral power density of the optical noise, usually the noise power in 0.1 nm bandwidth. Hence, the OSNR is an excellent measure of signal degradations caused by amplified stimulated emission (ASE) noise added in the optical amplifiers along the transmission link. Traditionally, OSNR measurements are performed while the communication system is in service (in-service measurements) without interrupting transmission of the digital payload.

In cases where the communication systems carries only a few and widely-spaced wavelength-multiplexed signals, the OSNR of a particular signal can be readily determined by a spectral analysis of the signal power and the optical noise floor on either side of the signal spectrum [1], as shown schematically in Figure 1.

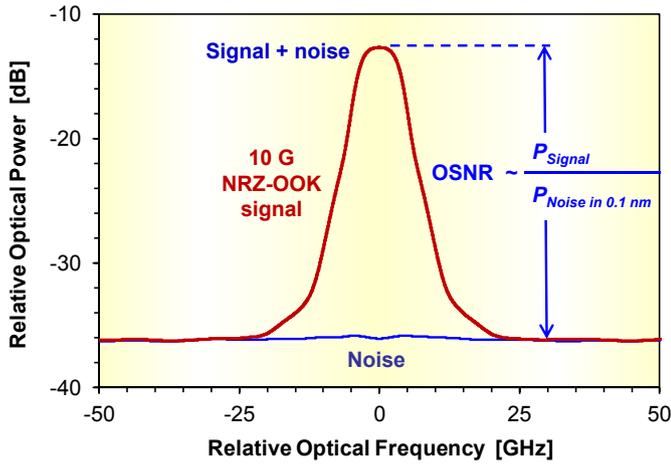


Figure 1. OSNR determined from out-of-band noise floor measurements

This simple spectral analysis can usually be performed with a conventional grating-based OSA as shown in Figure 2. Moreover, the OSA often can be connected to a monitoring tap along the transmission link, such as at an optical amplifier site, so that the OSNR measurement can be performed without interrupting or otherwise affecting data transmission.

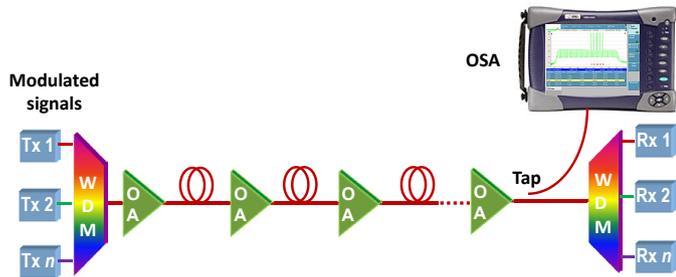


Figure 2. Typical setup for in-service OSNR measurements with an OSA

However, most long-distance fiber optic communication systems employ dense wavelength-division multiplexing (DWDM), where various transmitted optical signals are closely spaced in frequency. Often, these signals are transmitted through 50 GHz-wide WDM channels, which renders it very difficult, if not impossible, to measure the optical noise floor on either side of the signal spectrum. The situation is further aggravated when signals are passed through reconfigurable optical add-drop multiplexers (ROADMs), as shown in Figure 3, because ROADMs usually attenuate the optical noise level in the narrow guard bands between the signals [2]. Figure 4 shows an example of the effects of ROADM filtering on the noise and signal spectra.

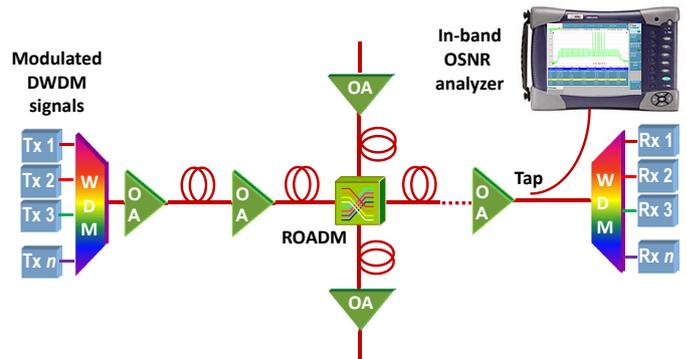


Figure 3. In-service OSNR measurements in ROADM networks require an in-band OSNR analyzer.

In ROADM networks, therefore, the optical power level on either side of the signal spectrum is no longer representative of the noise floor within the signal bandwidth. In this situation, one has no other choice but to measure the optical noise floor within the optical spectrum of the signal (in-band noise measurement). OSNR measurements based on in-band noise power levels are often referred to as in-band OSNR measurements.

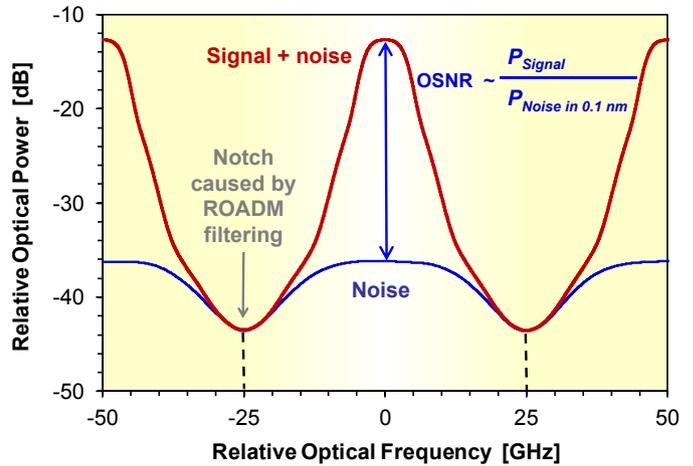


Figure 4. OSNR determined from in-band noise floor measurements.

It is well known that the in-band noise floor of conventional single-polarized optical signals (for example, of 2.5 or 10 G NRZ on-off-keyed signals) can be measured by blocking the highly polarized optical signal with a properly oriented polarization filter, as shown schematically in Figure 5. Since ASE noise generally is depolarized, the polarization filter passes 50% of the optical noise power, which can then be used to measure the in-band noise floor [3]. This in-band noise measurement technique is known as the polarization extinction or the “polarization-nulling” method.

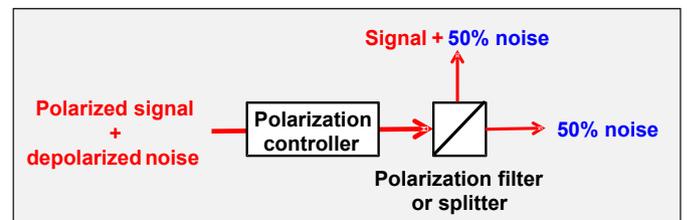


Figure 5. Polarization-extinction method for measuring in-band noise in polarized signals.

However, modern optical communication systems operating at line rates above 10 G often transmit polarization-multiplexed (PM) optical signals to increase the spectral efficiency of the WDM channels (and hence the transmission capacity of the fiber). Polarization multiplexing is frequently employed to transmit 40 G and 100 G QPSK signals over 50-GHz wide WDM channels [4]. Since these signals are composed of two orthogonally polarized but independently modulated optical signals at the same carrier frequency, it is impossible to block the two orthogonally polarized signals simultaneously with polarization filters without also extinguishing the entire optical noise, as shown in the example of Figure 6. Therefore, the polarization-extinction method described above cannot be used to measure in-band noise in polarization-multiplexed signals.

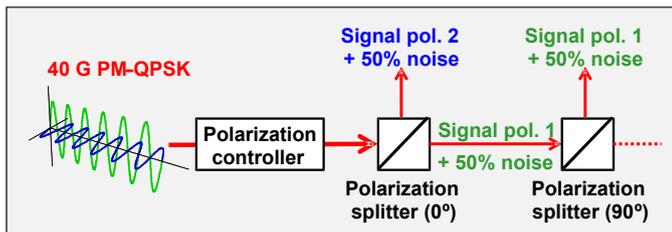


Figure 6. Polarization-extinction method fails for polarization-multiplexed signals.

Unfortunately, there is no other physical parameter available that would allow one to distinguish a polarization-multiplexed signal from random optical noise, because all optical parameters are employed for encoding digital information into the signal such as optical amplitude, phase, frequency, and polarization state. Nevertheless, there exists a particular feature in the spectrum of 40 G PM NRZ-QPSK signals that can be exploited to measure in-band noise floors in these signals.

This in-band noise measurement method requires a high-resolution spectral analysis of the signal, as explained below in more detail, which cannot be performed with standard, grating-based OSAs. However, the field-deployable, high-resolution JDSU OSA-610 is well suited to measure OSNRs up to at least 25 dB in 40 G PM NRZ-QPSK signals with a maximal error of 0.25 dB.

In-Band Noise Measurements on 40 G PM NRZ-QPSK Signals

It is well known that the optical spectrum of an unfiltered 40 G PM-QPSK signal comprises deep but fairly narrow minima (holes) [4], which can be clearly seen in the high-resolution optical spectrum displayed in Figure 7.

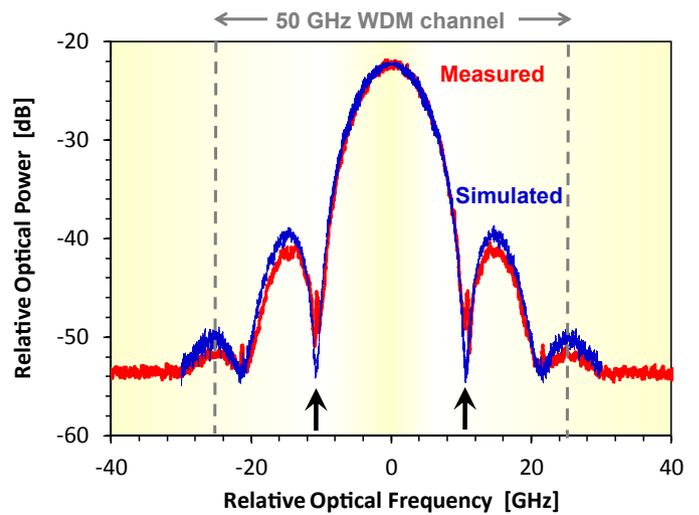


Figure 7. High-resolution spectrum of a 43 G PM NRZ-QPSK signal with 30 dB OSNR; the red curve is an actual measurement (with 300 MHz spectral resolution) and the blue curve is a numerical simulation of a corresponding measurement with an ideal signal

The two minima of interest (marked by arrows in Figure 7) occur at optical frequencies $f_0 \pm f_c$ where f_0 is the center frequency of the signal, and f_c is the clock frequency of the digital modulation. For a 40 G PM NRZ-QPSK signal with 7% FEC overhead, we find $f_c \approx 10.7$ GHz. Since these two minima are located within the center half of a 50-GHz wide wavelength channel, they are not significantly attenuated by optical filtering in wavelength multiplexers or ROADMs.

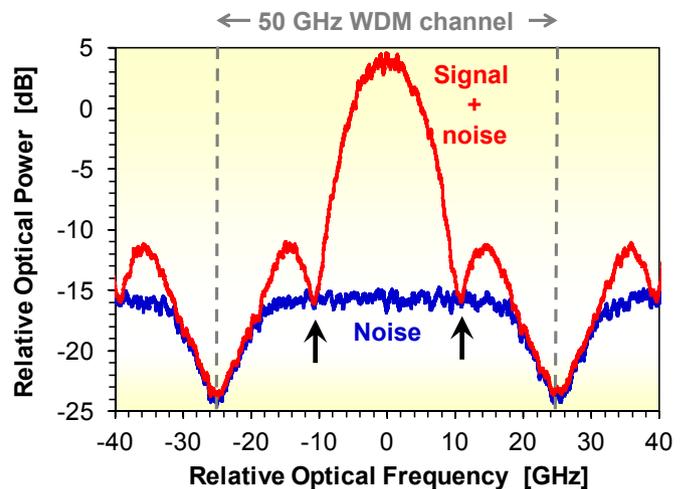


Figure 8. Simulated high-resolution spectrum of a 40 G PM NRZ-QPSK signal with 20 dB OSNR after transmission through four cascaded ROADMs (300 MHz spectral resolution)

It can be shown that an ideal noise-free 40 G PM NRZ-QPSK signal does not exhibit significant optical power in the center of these minima [4]. However, when broadband optical noise is added to the signal (for example, by optical amplifiers), the optical power density at $f_0 \pm f_c$ increases to the same level as the in-band noise floor within the signal bandwidth (see Figure 8). Hence, the optical power density measured at these two frequencies is equal to the noise power density of the in-band ASE noise. Therefore, the in-band noise of an ideal 40 G PM NRZ-QPSK signal may be determined from a high-resolution spectral analysis of the optical power densities at $f_0 \pm f_c$. It thus follows that the OSNR of a 40 G PM-QPSK signal can be determined from a high-resolution measurement of the power spectral density of the noisy signal, $P_{S+N}(f)$, using the following formula:

$$OSNR = \frac{\int_{-B/2}^{B/2} [P_{S+N}(f) - P_{S+N}(f_0 \pm f_c)] df}{P_{S+N}(f_0 \pm f_c) B_{0.1 nm} / B_{res}} \quad (1)$$

wherein B denotes the total bandwidth of the signal and B_{res} the spectral resolution of the OSA. It should be noted that the above described in-band OSNR measurement does neither require a prior reference measurement on a noise-free signal nor training on signals with known OSNR, in contrast to the spectral analysis technique described in [5].

In practice, however, the power density in the center of the minima at $f_0 \pm f_c$ is always larger than zero, even in a noise-free 40 G PM NRZ-QPSK signal, because of limited spectral resolution and/or non-ideal signal generation in the optical transmitter. Such undesired power density "offsets" in the two minima can severely limit the accuracy of the noise floor measurement, in particular when the OSNR is large.

Numerical simulations with ideal 40 G PM-QPSK signals have shown that a spectral resolution of 300 MHz is more than sufficient to properly measure noise floors in signals with an OSNR of up to 30 dB (see the blue curve in Figure 7). Since the measured spectrum in Figure 7 was recorded with an OSA having 300 MHz resolution, we find that the power offsets at $f_0 \pm f_c$ are generated by the 40 G transmitter.

It is possible, of course, to measure the noise power density at other minima in the optical spectrum, for example at $f_0 \pm 2f_c$, where the transmitter-induced power offsets usually are smaller. However, these frequencies are much closer to the edges of a 50-GHz wavelength channel and, hence, are severely attenuated by optical filtering in wavelength multiplexers and/or ROADMs.

The effect of optical filtering in ROADMs is shown in Figure 8, which displays the simulated spectrum of a 43 G PM-QPSK signal after passing through four cascaded ROADMs with 50-GHz spaced WDM channels. It is clearly seen in this graph that the minima at frequencies $f_0 \pm 2f_c$ have completely disappeared from the spectrum, because of spectral clipping in the ROADMs. However, the two minima at $f_0 \pm f_c$ remain essentially unchanged and, thus, can be used to estimate the in-band noise level in the signal. Close inspection of the noise spectrum in Figure 8 reveals that the noise power density at the two minima is substantially identical to that near the center of the signal spectrum, so that the in-band noise measurements at $f_0 \pm f_c$ indeed yield the correct OSNR value.

It should be noted that a similar spectral analysis with a conventional grating-based OSA would lead to incorrect in-band noise power levels.

This is demonstrated in Figure 9, which shows a simulated measurement of the signal and noise spectra displayed in Figure 8 with a conventional OSA having a resolution of 5 GHz (or equivalently 40 pm). Even though this spectrum exhibits two minima near $f_0 \pm f_c$, the optical power density at both minima is substantially higher than the power density of the in-band noise. Thus, the in-band noise floor of the signal cannot be directly extracted from the spectrum shown in Figure 9 [5].

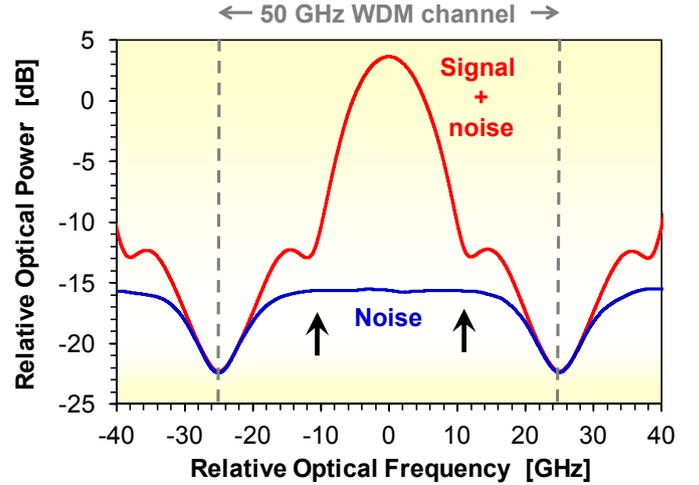


Figure 9. Simulation of a 43 G PM-QPSK signal spectrum measured with 5 GHz resolution

In principle, one could apply the above-described in-band noise measurement technique also to polarization-multiplexed 100 G QPSK signals, which exhibit similar minima at $f_0 \pm f_c$, as shown in the simulation of Figure 10 below. Unfortunately, these minima are located outside the bandwidth of a 50 GHz WDM channel and, hence, will be clipped off in wavelength multiplexers and/or ROADMs [4, 9], as demonstrated in Figure 10. Hence, they cannot be used to measure the in-band noise in 100 G PM-QPSK signals.

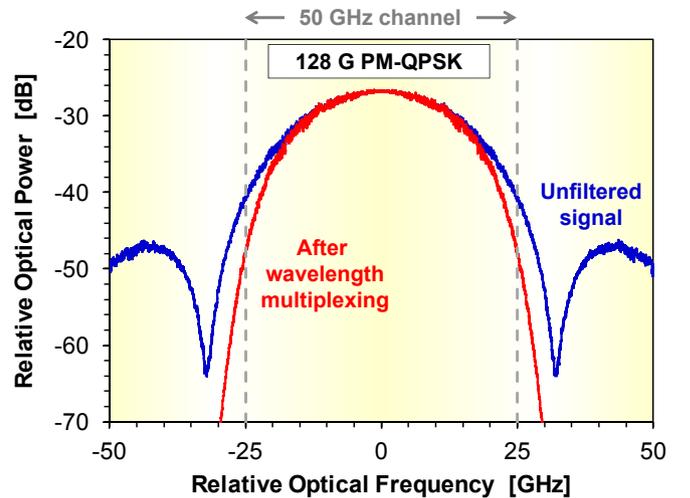


Figure 10. Spectrum of 128 G PM-QPSK signal before and after wavelength multiplexing.

In the following section, we shall briefly describe the new high-resolution JDSU OSA and then report exemplary OSNR measurements on noisy 40 G PM-QPSK signals.

High-Resolution JDSU Optical Spectrum Analyzer (OSA-610)

Although grating-based OSAs can be designed to exhibit spectral resolutions below 1 GHz, these instruments tend to be quite large and, hence, not suitable for field-test applications. As an alternative solution, JDSU has introduced a compact, field-deployable, high-resolution OSA which is based on coherent detection [6]. Coherent receivers are known to be highly frequency selective and, hence, can be designed to serve as optical spectrum analyzers with very high spectral resolution [7]. Figure 11 shows a schematic block diagram of the OSA-610, in which the signal to be analyzed is first mixed with the continuous-wave output light of a local oscillator (LO) laser and then detected by a pair of carefully balanced, low-speed photo receivers to obtain high rejection of undesired direct-detection products [8]. Polarization-independent detection of arbitrarily polarized signals is accomplished by employing two parallel coherent mixers in a polarization-diversity arrangement [8]. The frequency resolution of this homodyne receiver is equal to two times the electrical bandwidth of the receiver circuit and, hence, can be precisely adjusted by means of electrical low-pass filters (LPF), as shown below in Figure 11.

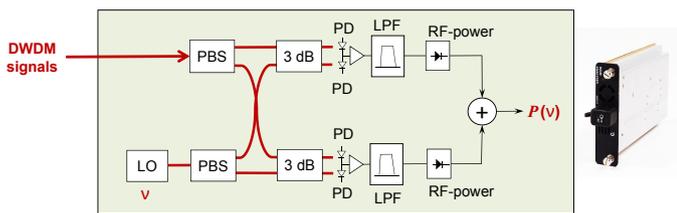


Figure 11. Schematic diagram (left) and actual implementation (right) of the high-resolution OSA-610, which employs a coherent receiver with scanning local oscillator laser:
 v = optical frequency; LO = local oscillator laser; PBS = polarization beam splitter; PD = photo diode; LPF = electrical low-pass filter

The OSA-610 is designed to have a spectral resolution of only 300 MHz (or equivalently 2.4 pm), which is more than 15 times higher than that of grating-based field-test instruments. This is shown in Figure 12, where we have compared the transmission function of the OSA-610 to that of the high-performance grating-based JDSU OSA-500.

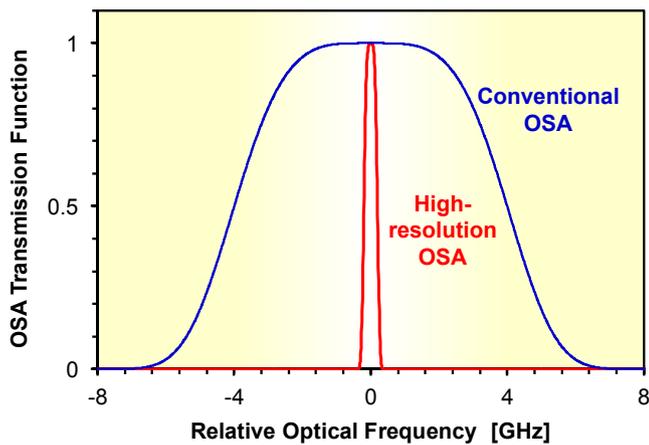


Figure 12. Transmission function of the high-resolution OSA-610 (red curve) compared with that of a high-performance, grating-based OSA (for example, OSA-500, blue curve)

Thus, when the frequency of the LO laser is tuned across the optical bandwidth of a modulated signal, the OSA-610 measures its optical power spectrum with a resolution of only 300 MHz. The instrument employs a stepwise continuously tunable, narrow-linewidth LO laser with proprietary frequency control, which allows spectral analysis with an absolute accuracy of ± 370 MHz (or ± 3 pm).

Exemplary In-Band OSNR Measurements

We have evaluated the accuracy of our in-band OSNR measurement technique using a commercial 43 G PM-NRZ-QPSK transmitter as the signal source. In a first series of tests, we have measured in-band noise on an unfiltered signal, obtained directly from the output of the transmitter, to which we have added variable amounts of broadband ASE noise from an erbium-doped fiber amplifier.

To facilitate automatic in-band OSNR measurements, we have implemented a new software algorithm in the OSA-610, which automatically searches for the two minima at $f_0 \pm f_c$ (without requiring prior knowledge of the exact value of f_c) and then directly calculates the in-band OSNR of the signal from Equation (1).

Figure 13 displays a series of the high-resolution spectra of the 43 PM-QPSK signal measured at various OSNR values between 9.5 dB and 34 dB. These spectra clearly show that the power spectral density at $f_0 \pm f_c$ is indeed representative of the in-band ASE noise in the signal, at least for OSNRs up to 20 dB. At OSNRs above 20 dB, we find that the accuracy of the in-band noise floor measurements is increasingly impaired by transmitter-generated offsets in the minima at $f_0 \pm f_c$.

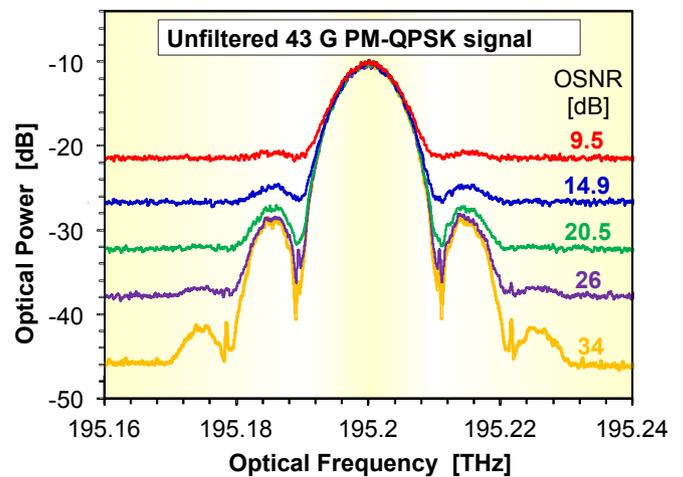


Figure 13. High-resolution spectra of an unfiltered 43 G PM-QPSK signal at various OSNRs

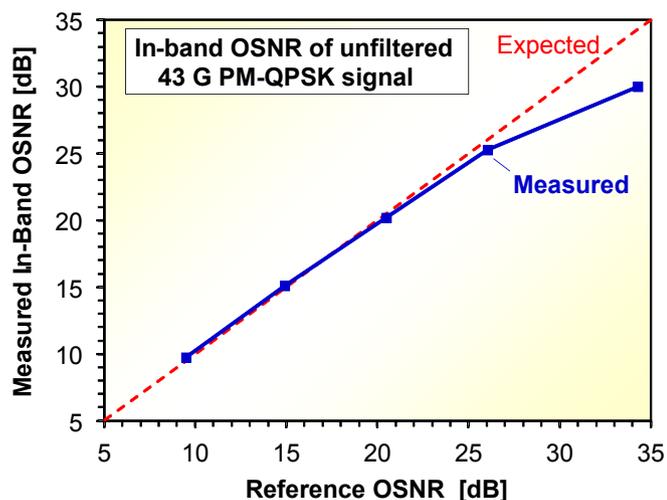


Figure 14. In-band versus out-of-band OSNR determined from the spectra of Figure 13.

In Figure 14, we have plotted the in-band OSNR calculated from these spectra as a function of the true (or reference) OSNR, which was obtained from out-of-band noise measurements (see Figure 1). As expected, we find the in-band measurements to be very accurate up to OSNRs of 20 dB, with measurements errors of less than ± 0.25 dB. At OSNRs between 20 and 25 dB, the accuracy is still acceptable, with measurement errors increasing to almost 0.75 dB. Beyond 25 dB, however, the measurement error grows rapidly, reaching more than 4 dB at the highest measured OSNR of 34 dB.

In another series of measurements, we have tested the in-band noise measurement method on a 43 G PM-QPSK signal that was spectrally filtered by two cascaded 50-GHz ROADMs. In these tests, broadband ASE noise was added after the first ROADM and subsequently filtered by the second ROADM before being analyzed by the OSA-610. Figure 15 displays the measured high-resolution spectra of the filtered noisy signal at various OSNR levels between 10 dB and 25 dB. Just as in Figure 13, the power spectral densities at $f_0 \pm f_c$ increase proportionally to the in-band ASE noise in the signal.

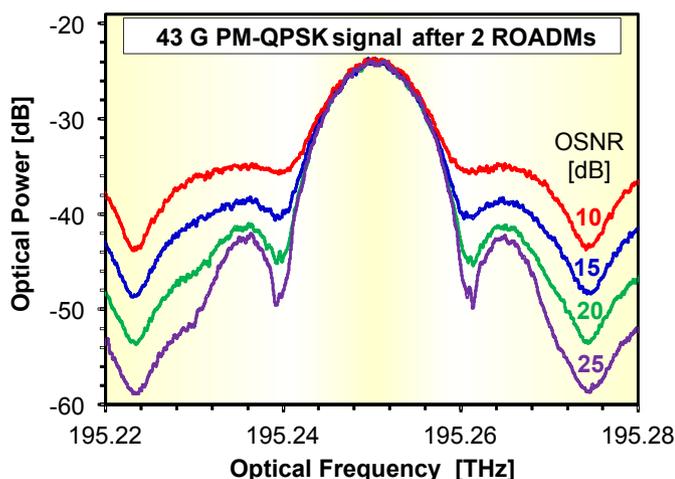


Figure 15. High-resolution spectra of a ROADM-filtered 43 G PM-QPSK signal at various OSNRs

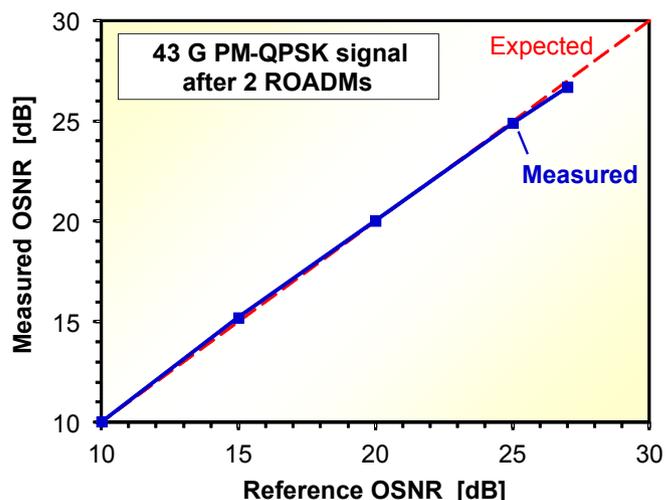


Figure 16. In-band OSNR versus reference OSNR calculated from the spectra of Figure 15

The in-band OSNRs determined from these spectra are plotted in Figure 16 as a function of the reference OSNR, which was measured here before the second ROADM using the out-of-band method. Again, we find the in-band measurements to be very accurate up to OSNRs of 25 dB, with measurements errors of less than 0.25 dB. However, just like in the case of the unfiltered signal, the measurement errors increase at OSNR values above 25 dB because of the transmitter-generated offsets at $f_0 \pm f_c$.

The exemplary measurements described above clearly demonstrate that in-band noise in 40-G PM-QPSK signals can be determined quite accurately through a high-resolution spectral analysis. Using the high-resolution OSA-610, we have measured in-band OSNRs up to 25 dB with an uncertainty of less than 0.25 dB. Again, it should be emphasized that these measurements did not require calibration of the instrument with the noise-free signal at the transmitter.

In-Band OSNR Measurements of Single-Polarized Signals

While it is also possible to use the above-described technique for in-band OSNR measurements on single-polarized signals, as shown in Figure 17 for the example of a 10 G NRZ-OOK signal, the measurement accuracy and OSNR range can be greatly enhanced by combining high-resolution spectral analysis with a simultaneous polarization analysis, for example by using the polarization-extinction method described earlier.

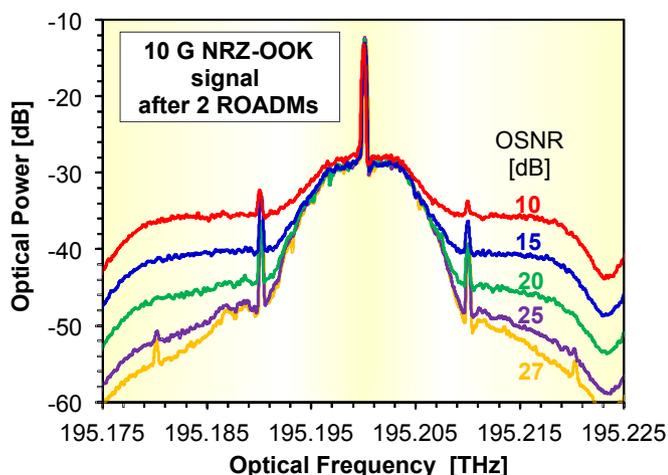


Figure 17. High-resolution spectra of a ROADM-filtered 43 G PM-QPSK signal at various OSNRs.

In fact, the polarization-extinction technique is the only known method for measuring in-band OSNR of single-polarized 40 G NRZ-DPSK or RZ-DQPSK signals, because the spectra of these signals do not exhibit any minima within the bandwidth of a 50 GHz-wide WDM channel [4]

When a variable optical polarization controller is added to the input of the OSA-610, as shown schematically in Figure 18, the amount of polarization extinction of the signal can be readily measured by the coherent receiver, because its polarization-diversity architecture allows simultaneous spectral analysis of two orthogonal polarization states (see $P_p(v)$ and $P_s(v)$ in Figure 18).

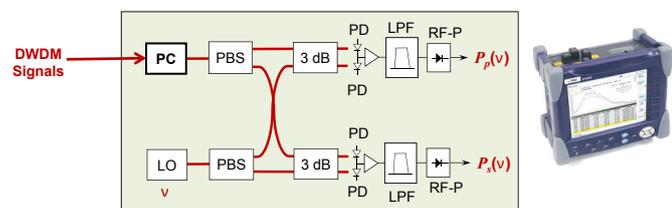


Figure 18. Schematic diagram of the in-service JDSU PMD analyzer (I-PMD™) employing a high-resolution OSA with input polarization controller (PC, left) and actual instrument (right)

The I-PMD, which employs the same high-resolution coherent receiver as the OSA-610 (see Figure 18), already includes such a variable input polarization controller and, in addition, features a software algorithm that automatically determines the in-band ASE noise floor in polarized optical signals via the polarization-extinction method. The built-in polarization analysis of this I-PMD/OSNR analyzer can also be used to determine whether a given signal is single-polarized (which is the case when the polarization extinction is large) or whether it is polarization-multiplexed (which can be assumed when there is no significant polarization extinction).

Hence, a single instrument, like the I-PMD analyzer, is capable of measuring in-band OSNR of single-polarized 2.5, 10, or 40 G signals as well as that of polarization-multiplexed 40 G NRZ-QPSK signals. This convenient feature is especially important when measuring OSNR of mixed signals in a hybrid communication system.

Moreover, the high spectral resolution of this instrument allows its user to unambiguously distinguish 2.5 G NRZ-OOK signals from 10 G NRZ-OOK signals and 40 G PM-QPSK signals as well as from broadband 40 G NRZ-DPSK signals, as shown in the example of Figure 19.

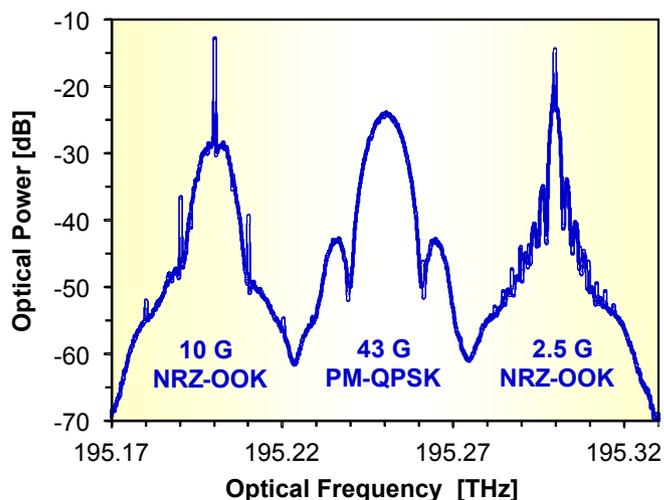


Figure 19. High-resolution spectra of 2.5 G NRZ-OOK, 10 G NRZ-OOK and 40 G PM-QPSK signals in a hybrid communication system

In addition, the built-in polarization analysis allows the user to distinguish between polarization-multiplexed 100 G PM-QPSK signals and single-polarized 40 G NRZ-DPSK or RZ-DQPSK signals, which otherwise exhibit similar spectral shapes. Therefore, within certain limits, the I-PMD/OSNR analyzer allows identification of the modulation format of the transmitted signals.

Conclusions

We have described a novel method for in-service OSNR measurements of 40 G PM-QPSK signals that is based on high-resolution spectral analysis. We have further shown that the high-resolution JDSU OSA-610 is capable of automatically measuring in-band OSNR up to 25 dB with high accuracy.

Moreover, since this method can also be used with the JDSU I-PMD/OSNR analyzer, one needs only a single instrument to measure in-band OSNR of polarization-multiplexed 40 G signals and single-polarized 2.5, 10, and 40 G signals.

References

- [1] International Electrotechnical Commission Standards Document IEC 61280-2-9, "Digital systems – Optical signal-to-noise ratio measurements for dense wavelength-division multiplexed systems," 2009.
- [2] F. Heismann *et al.*, "Wavelength switching technologies and requirements for agile optical networks at line rates of 100 G and beyond," *Opt. Fiber Technol.* vol. 17, p. 503, 2011.
- [3] M. Rasztoivits-Wiech *et al.*, "Optical signal-to-noise ratio measurement in WDM networks using polarization extinction", *Tech. Proc. European Conference on Optical Communication (ECOC)*, 20-24 September 1998, Madrid, Spain, pp. 549-550.
- [4] P. J. Winzer and R. Essiambre, "Advanced optical modulation formats," *Proc. IEEE*, vol. 94, p. 952, 2006.
- [5] D. Gariépy *et al.*, "Non-intrusive measurement of in-band OSNR of high bit-rate polarization-multiplexed signals," *Opt. Fiber Technol.* vol. 17, p. 518, 2011.
- [6] V. Lecœuche *et al.*, "Non-intrusive in-service PMD measurements: A novel approach based on coherent detection," in *Tech. Proc. ECOC 2011*, Paper Th.12.LeCervin.2.
- [7] D. M. Baney, "Coherent Spectrum analyzer," *IEEE Photon. Technol. Lett.*, vol. 14, p. 355, 2002.
- [8] E. Ip *et al.*, "Coherent detection in optical fiber systems," *Opt. Express*, vol. 16, p. 753, 2008.
- [9] E. Pincemin *et al.*, "Challenges of 40/100 Gbps and higher-rate deployments over long-haul transport networks," *Opt. Fiber Technol.* vol. 17, p. 335, 2011.



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