In-Band OSNR Monitoring of PM-QPSK Using the Stokes Parameters

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Abstract: We discuss OSNR monitoring using low bandwidth Stokes parameter analysis. OSNR levels reaching 23 dB are experimentally estimated within ± 1 dB. Simulations show resilience to chromatic dispersion, corresponding to 1000 km of SMF for the experimental setup.
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1. Introduction

The optical signal-to-noise ratio (OSNR) is important to monitor as it is directly related to the bit error rate (BER) [1]. The traditional method uses linear interpolation to estimate the in-band noise from out-of-band measurements, which relies on the assumption that the noise between the wavelength-division multiplexing (WDM) channels is representative for the in-band noise. In modern systems, this is no longer valid as the noise levels may have been altered by reconfigurable optical add-drop multiplexers. Another challenge are WDM systems with high spectral efficiency. In particular, in Nyquist-WDM systems (where the channel separation is equal to the symbol rate) there is no guard band and this method cannot be used.

A number of monitoring methods have been proposed, including the polarization nulling method [2] and the reference based differential spectral response method [3]. The former relies on the assumption that the signal contains all its power in one polarization, while the amplified spontaneous emission (ASE) noise generally is unpolarized. This is not compatible with polarization multiplexing. The latter method requires that a detailed reference spectrum is obtained at or near the transmitter. A different approach is to monitor the OSNR using DSP in the receiver. In [4], a method using signal cyclostationarity is presented. The limitations of this method include that a narrow spectrum leads to estimation errors and in the Nyquist-WDM case, no OSNR estimation is possible. Another general issue of DSP-based methods is that while they can be integrated within the digital coherent receiver, they are less suitable for a stand-alone monitoring system, where inexpensive solutions are favored.

In this paper a method for in-band OSNR monitoring of polarization-multiplexed (PM) QPSK signals based on Stokes parameter analysis is presented and evaluated experimentally and numerically. A method using the Stokes parameters has been proposed previously [5], but required a detection bandwidth of the order of the signal symbol rate and a custom-fabricated integrated polarimeter. The method was also sensitive to chromatic dispersion (CD), which is a serious drawback as modern coherent systems often allow high amounts of uncompensated CD. Our method has been implemented using readily available optical components and relatively low-speed electronics (sampling rate is 50 MHz). It is shown using simulations that by applying low-pass filtering, the method can be used at large amounts of accumulated CD and that the method also works well for rectangular spectra in a Nyquist-WDM system.

2. Operation principle

Although PM signals have a time-averaged degree of polarization (DOP) that is zero, the DOP is non-zero if a sufficiently short measuring time is used. In the experimental part of this work, a measurement bandwidth of 10 MHz was used, but for clarity reasons in the theoretical discussion we assume a bandwidth higher than the symbol rate of the signal to make the instantaneous state of polarization (SOP) observable. It can be shown that a general PM complex modulated signal is bounded in Stokes space by two paraboloidal surfaces, forming a disc shape [6]. In the special case of phase shift-keying (PSK), the data symbols are mapped onto the S_2–S_3-plane in Stokes space. If the amplitude stays constant during the transitions, S_1 will remain zero. In Fig. 1a the Stokes representation of a PM-QPSK signal is shown. Note that the sixteen symbols are mapped onto four points and that S_1 is nonzero in the transitions.

If a high-speed polarimeter is used, ASE noise has a random SOP, effectively tracing out a sphere in Stokes space. When ASE is added to a signal, it increases the thickness of the disc. For PSK signals, the constant amplitude of the data symbols causes the thickness to be highly dependent on the noise power while it is less sensitive to the signal power. The disc thickness can therefore be used as a measure of the OSNR [5]. Since the diameter of the disc is related

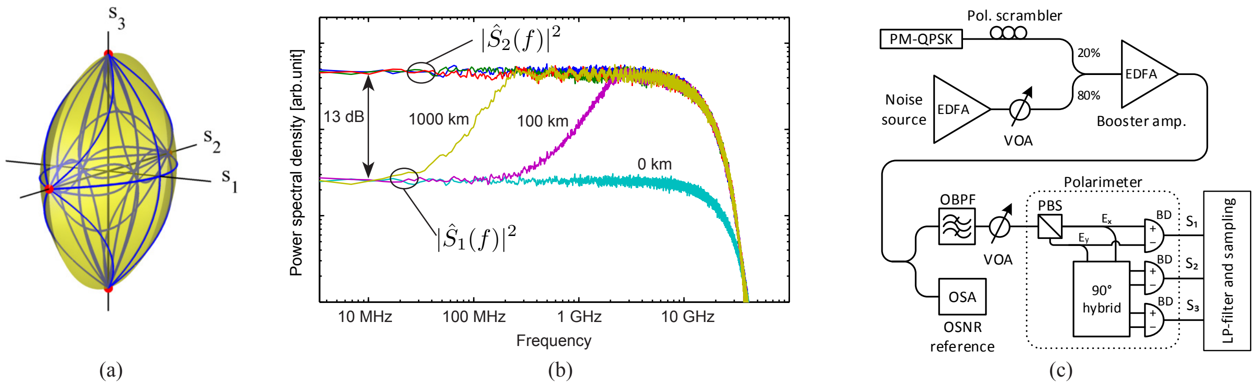

Fig. 1. (a) The Stokes representation of PM-QPSK. (b) The simulated spectrum of the Stokes parameters for different fiber lengths. (c) The experimental setup. VOA: Variable optical attenuator, OBPF: Optical band-pass filter, OSA: Optical spectrum analyzer, PBS: Polarization beam splitter, BD: Balanced detector, LP: Low-pass

to the signal power, we propose the ratio between the diameter and the thickness of the disc as a measure of the OSNR. This ratio, Γ, can be written in terms of the variances of the Stokes parameters [7],

$$\Gamma = \frac{\mathrm{Var}\,(S_2) + \mathrm{Var}\,(S_3)}{2\mathrm{Var}\,(S_1)} = \frac{k_{21}S^2 + k_1 SN + k_0 N^2}{k_{22}S^2 + k_1 SN + k_0 N^2} = \frac{k_{22}OSNR^2 + k_1 OSNR + k_0}{k_{21}OSNR^2 + k_1 OSNR + k_0}, \tag{1}$$

where S and N denote the signal and noise powers, respectively. This expression is valid for all PM signals, but the values of the coefficients depend on the modulation format. It should be noted that for higher order modulation formats where the amplitude of the symbols are different, e.g., 16-QAM, the assumption that the thickness represents the noise power no longer holds. A change of the signal polarization will cause a rotation of the disc in Stokes space. However, as long as the polarization stays constant during the variance averaging time, this rotation can be compensated for with a change of basis in Stokes space. Both the orientation and dimensions of the disc can be found using, e.g., singular value decomposition (SVD). We can then write $\Gamma = (\sigma_2^2 + \sigma_3^2)/(2\sigma_1^2)$, where σ_1, σ_2 and σ_3 are the singular values.

The Stokes parameters can be directly measured in several ways. We have used a setup based on a polarization beam splitter (PBS), a 90° hybrid and balanced detectors, similar to the kind that is used in a coherent receiver. The setup can be seen in Fig. 1c.

3. Numerical Simulations

In the simulations, a pseudo-random binary sequence of length $2^{15} - 1$ (PRBS15) was used to generate a 28 GBd PM-QPSK signal. The applicability of the method was verified for non return-to-zero (NRZ) and return-to-zero (RZ) signals as well as for sinc-based signals. The coefficients in (1) were found to depend on the pulse shape/spectrum of the signal.

The impact of CD was also investigated. In Fig. 1b the spectrum of the Stokes parameters are plotted for different lengths of standard single-mode fiber (SMF) with dispersion $D = 16\,\mathrm{ps/(nm\,km)}$. The separation between the two curves correspond directly to Γ. When the signal is affected by CD, the S_1 curve is raised to the same level as the S_2 curve at the high frequencies. This means that Γ is decreasing. However, if the Stokes parameters are low-pass filtered with sufficiently low bandwidth, the value of Γ is unchanged. These results show that while Γ is affected by the chromatic dispersion in a detrimental way, these effects can be mitigated by using a sufficiently low detector bandwidth. It can be seen in Fig. 1b that S_1 stays unaffected by dispersion corresponding to 1000 km SMF for frequencies below 10 MHz.

Simulations also showed that the method is insensitive to X/Y polarization time skew, but sensitive to polarization mode dispersion (PMD), as the accuracy of the OSNR estimation degrades for differential group delay (DGD) values above 10 % of the symbol time. The method is also sensitive to polarization dependent loss (PDL) which in the worst case gives an error in the Γ value of more than the power imbalance between the polarizations. Both PMD and PDL are possible to correct for; in the case of PMD, it requires a somewhat more complex setup with a second tunable filter, and for PDL by measuring also the DC component of the Stokes parameters. This is however beyond the scope of this work, and will be presented in a longer journal article.

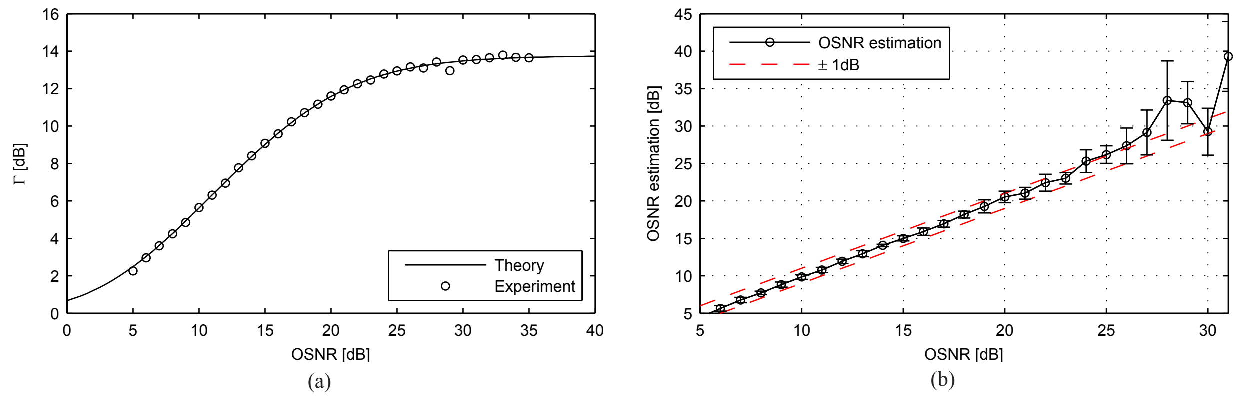

Fig. 2. (a) The theoretical curve for Γ together with experimental values. (b) OSNR estimation. The error bars represent the standard deviation of the dB-values of ten measurements.

4. Experimental Results

The polarimeter setup was implemented using discrete, fiber-coupled components, see Fig. 1c. External low-pass filters of bandwidth $\Delta f = 10\,\text{MHz}$ were used and a PRBS31 28 GBd PM-QPSK signal was noise-loaded with ASE from an erbium-doped fiber amplifier (EDFA) without input signal. An additional EDFA was used to boost the signal power. To make a reference measurement of the OSNR, the conventional optical spectrum analysis technique was used. The polarization was scrambled to emulate the random SOP of a real signal.

To estimate the OSNR the coefficients in (1) are needed. They were found by measuring Γ for a set of known OSNR-values and using least-squares fitting. The OSNR estimation was then done by taking a batch of samples of the Stokes parameters, after which Γ could be calculated, and inserted in the inverted (1). There was always a small variation between consecutive Γ values, so to get a more stable measurement, ten consecutive values were averaged. The measured Γ-values are plotted together with the theoretical curve in Fig. 2a. In Fig. 2b the estimated OSNR is plotted vs. the OSNR measured with the OSA. The estimated OSNR value keeps within ± 1 dB of the reference OSNR values up to 23 dB. This covers the typical range of OSNR values in practice.

5. Conclusion

In this paper, we have presented an in-band OSNR monitoring method for PM-QPSK using the Stokes parameters. With simulations we have shown that the methods' resilience to CD depends on the detector bandwidth, with a lower bandwidth tolerating more CD. We implemented the method with lumped components and experimentally estimated the OSNR of a 28 GBd PM-QPSK signal within ± 1 dB for OSNR values up to 23 dB. Simulations indicate that the implemented monitor with a detector bandwidth of 10 MHz should tolerate CD from more than 1000 km of SMF. The method needs calibration using knowledge of the pulse shape/spectrum of the signal.

6. Acknowledgements

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References

[1] "ITU-T recommendation G.697: Optical monitoring for DWDM systems," (2012).
[2] J. H. Lee *et al.*, "A review of the polarization-nulling technique for monitoring optical-signal-to-noise ratio in dynamic WDM networks," J. Lightw. Technol. **24**, 4162–4171 (2006).
[3] D. Gariépy *et al.*, "Non-intrusive measurement of in-band OSNR of high bitrate polarization-multiplexed signals," Opt. Fiber Technol. **17**, 518–522 (2011).
[4] M. V. Ionescu *et al.*, "In-band OSNR estimation for nyquist WDM superchannels," in "European Conference on Optical Communication (ECOC)," (2014), p. P.4.16.
[5] T. Saida *et al.*, "In-band OSNR monitor with high-speed integrated Stokes polarimeter for polarization division multiplexed signal," Opt. Express **20**, 165–170 (2012).
[6] B. Szafraniec *et al.*, "Performance monitoring and measurement techniques for coherent optical systems," J. Lightw. Technol. **31**, 648–663 (2013).
[7] L. Lundberg, "An in-band OSNR monitoring method for polarization multiplexed QPSK signals using Stokes parameters," Master's thesis, Chalmers University of Technology, http://publications.lib.chalmers.se/records/fulltext/188058/188058.pdf (2013).