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Regular Articles

Nonlinearity-tolerant OSNR estimation method based on correlation function and statistical moments

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ABSTRACT

We propose a fiber nonlinearity-tolerant optical signal-to-noise ratio (OSNR) estimation method for high speed long haul coherent optical fiber transmission system. The correlation function of the amplitude noise and a calibration factor ξ are utilized to correct nonlinearity-induced distortions for the first time when the statistical moments-based method (SMB method) is applied. ξ depends on not only transmission distances but also launch powers. Besides, we put forward a fitting formula for optimal ξ and OSNR estimation results still keep valid regardless of transmission distances and launch powers. Compared with current existing OSNR estimation methods, the proposed method functions well in highly nonlinear systems and is demonstrated to be feasible and more accurate. OSNR estimation errors are below 0.94 dB after calibration over a wide OSNR range from 10 dB to 28 dB in a 112-Gb/s polarization-multiplexed quadrature phase shift keying (PM-QPSK) system when the launch power is up to 8 dBm and the transmission distance is as long as 2000 km.

1. Introduction

The ever-increasing demand for bandwidth and higher data rates forces better spectral efficiency and more flexible light path assignment for future optical network. Exploring new OSNR estimation methods remains vital to manage a high capacity optical communication system. It is also an important factor to directly estimate the performance of the system. However, long-haul transmissions require large launch powers, which also lead to large nonlinearity-induced distortions. Nonlinearity compensation algorithms such as digital back propagation [1] and nonlinearity reduction using hybrid amplification technique [2] are too complex to be accomplished now, thus it is difficult to compensate or reduce nonlinearity-induced distortions. Besides, it is also a tough task to distinguish amplified spontaneous emission (ASE) noise from fiber nonlinearity-induced distortions by digital signal processing (DSP). In this case, OSNR would be largely underestimated due to the obvious nonlinearity-induced distortions caused by Kerr effects.

Some OSNR estimation methods in digital coherent receivers have already been proposed, such as error vector magnitude (EVM) method [3], the SMB method [4,5], periodic training sequence based technique [6], differential pilot aided technique [7], etc [8–16], all of which perform well in deployed weakly nonlinear regimes. In other words, there still lacks some effective methods in highly nonlinear regimes for long haul transmission systems. Hence a more effective fiber nonlinearity-tolerant OSNR estimation method for long-haul transmission systems is required.

Recently OSNR estimation methods based on the correlation function have been proposed. Intra-channel nonlinearity-induced distortions are separated from total noise by using the correlation function of amplitude noise and a calibration factor ξ to correct the error vector magnitude method (EVM-CF method) though the EVM method is affected by chromatic dispersion (CD) and polarization-mode dispersion (PMD) [10]. ξ here is only relative to transmission distances while optimal ξ can only be calculated and found in a look-up table [10]. Simulation results show a maximum OSNR estimation error of 1 dB with actual OSNR ranging from 10 dB to 24 dB when the longest transmission distance is 1600 km and the largest launch power is 2 dBm. Conversely, the SMB method, utilizing second-order and fourth-order moments to achieve the envelope of equalized signals, is suitable for both constant and non-constant modulus modulation formats and is not affected by CD and PMD, because OSNR estimation process is done after the adaptive filtering [17]. And the maximum OSNR estimation error is over 1 dB when launch power is more than 4 dBm with actual OSNR ranging from 7 dB to 22 dB [17]. However, transmission

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distances and launch powers applied here are not enough to support long haul transmission systems in highly nonlinear regimes.

In this paper, a more accurate OSNR estimation method is proposed. We aim to test the feasibility of the proposed method in a highly nonlinear regimes. The proposed OSNR estimation method combines the correlation function of amplitude noise of received symbols with a calibration factor ξ for the first time to correct the SMB method in presence of strong nonlinearities. ξ here depends not only on transmission distances but also on launch powers. Besides, a fitting formula for optimal ξ is also developed and validated to be feasible and accurate regardless of transmission distances and launch powers. Compared with the SMB method and the EVM-CF method, the proposed method can estimate OSNR with a good accuracy of 0.94 dB in a wider OSNR range of 10–28 dB when the launch power is up to 8 dBm and the transmission distance is as long as 2000 km.

The organization of our paper is set as follows: Section 2 defines the theoretical principle of the proposed OSNR estimation method. Section 3 describes the simulation setup and parameter settings of the proposed method. Section 4 discusses simulation results and corresponding analyses of the proposed method, in which Section 4.1 introduces the simulation results after calibration while Section 4.2 derives the formula for optimal ξ and validates its feasibility. Finally, Section 5 concludes our paper.

It should be noted that the SMB method and the EVM-CF method are chosen as contrast terms because they suit coherent communication system well and need no more hardware devices.

2. Theoretical principle

2.1. OSNR estimation by the SMB method

In a long-haul transmission system, fiber loss can be overcome by increasing the launch power of fibers, which will also lead to large fiber nonlinearity-induced distortions. Thus OSNR will be underestimated since the accumulated noise in transmission links includes not only ASE noise but also nonlinearity-induced distortions.

If we take no account of nonlinearities, the k_{th} received signal after carrier-phase estimation block can be expressed as:

$$r_k = s_k + n_k, \quad k = 1,2,3,... \tag{1}$$

where s_k is the transmitted symbol and n_k shows the collective ASE noise generated by optical amplifiers [16].

According to the definition of OSNR, OSNR can be expressed as

$$OSNR = \frac{P_{sig}}{P_{ASE}} = \frac{E[|s_k|^2]}{E[|n_k|^2]} \tag{2}$$

where P_{sig} is the optical signal power, P_{ASE} is the ASE noise power within 0.1-nm measurement bandwidth and E[·] denotes expectation [15].

However, in a real transmission system, nonlinearity-induced distortions also impair system performance in addition to ASE noise,

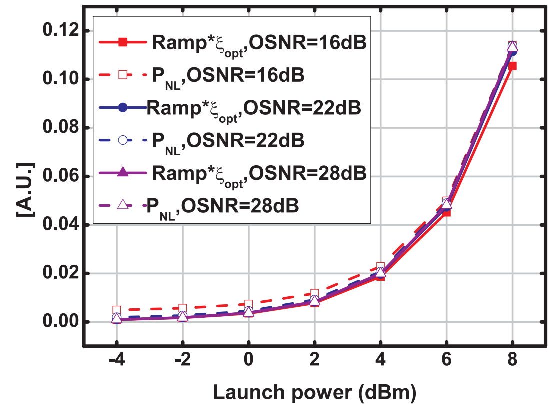


Fig. 2. $R_{amp}(1)\cdot\xi_{opt}$ and P_{NL} for different OSNR values and launch powers when the transmission distance is 800 km.

which cannot be easily compensated by DSP techniques. Considering nonlinearity-induced distortions modeled as additive Gaussian noise independent of ASE noise[16], Eq. (1) can be re-written as

$$r'_k = s_k + n'_k = s_k + n_k + v_k \tag{3}$$

where $n'_k = n_k + v_k$, consisting of ASE noise n_k and nonlinearity-induced distortions v_k. In order to accurately estimate the actual OSNR of the system, the optical signal to noise and distortion ratio (OSNDR) can be introduced as

$$OSNDR = \frac{E[|s_k|^2]}{E[|n'_k|^2]} = \frac{E[|s_k|^2]}{E[|n_k|^2] + E[|v_k|^2] + E[n_k v_k^*] + E[v_k n_k^*]} = \frac{P_{sig}}{P_{totalnoise}} = \frac{P_{sig}}{P_{ASE} + P_{NL}} \tag{4}$$

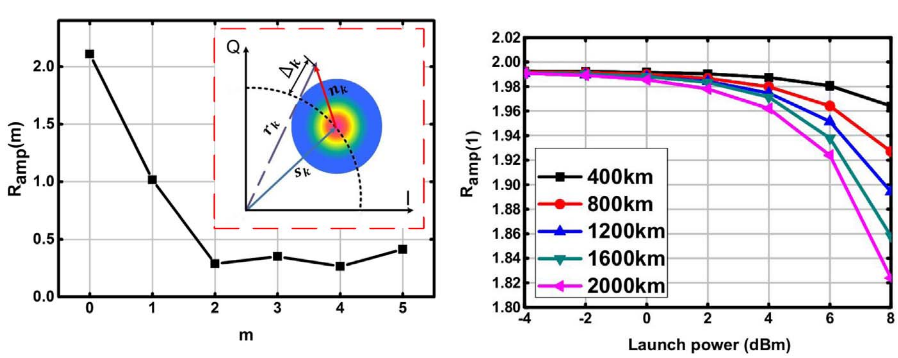
where $P_{NL} = E[|v_k|^2] + E[n_k v_k^*] + E[v_k n_k^*]$ represents nonlinearity-induced distortion power. We should estimate P_{NL} and subtract it from total noise power to attain the actual ASE noise power. It is known that OSNDR can be calculated by the SMB method [4,5].

$$OSNDR = \frac{P_{sig}}{P_{ASE} + P_{NL}} = \frac{\sqrt{2\{E(|r'_k|)^2\}^2 - E(|r'_k|)^4}}{E(|r'_k|)^2 - \sqrt{2\{E(|r'_k|)^2\}^2 - E(|r'_k|)^4}} \cdot \frac{R_s}{B_{ref}} \tag{5}$$

where R_s is the symbol rate, and the bandwidth B_{ref} is usually set as 12.5 GHz, which is equivalent to the 0.1 nm optical spectrum analyzer (OSA) resolution bandwidth [17].

In order to estimate OSNR more accurately in presence of large fiber nonlinearities, we should subtract P_{NL} from measured total noise power in Eq. (5) and obtain the proposed OSNR estimation method in Eq. (6) as follows:

$$OSNR_{est} = \frac{P_{sig}}{P_{ASE}} = \frac{P_{sig}}{P_{totalnoise} - P_{NL}} = \frac{1}{1/OSNDR - P_{NL}/P_{sig}} \tag{6}$$



(a) (b)

Fig. 1. Measured correlation function between two symbols of the receiver signals as a function of (a) time index m over 1000 km transmission; (b) signal launch powers for various transmission distances (when $m = 1$).