Implications of Nonlinear Interaction of Signal and Noise in Low-OSNR Transmission Systems with FEC

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Abstract: We review the performance degradation due to noise parametric gain in long-haul single-channel NRZ terrestrial systems working at low OSNR and its implications on system design in the presence of forward error correction.

OCIS Codes: (060.2360) Fiber optics links and subsystems

1. Introduction

Parametric gain (PG) is a well studied nonlinear effect in optical fibers, which may lead to a significant power transfer between signal and amplified spontaneous emission (ASE) noise [1]. For well-designed non-return-to-zero (NRZ) on-off keying (OOK) systems working without forward-error correction (FEC), the optical signal to noise ratio (OSNR) is usually large (e.g. > 23 dB/0.1 nm), and an accurate linearized PG model exists to estimate the power spectral density (PSD) of both the in-phase and quadrature components of the received Gaussian ASE on marks [2]. Such PSDs can then be used to accurately estimate the system bit error rate (BER) using an appropriate BER evaluation tool for quadratic detectors in Gaussian noise [3]. In [3] it is pointed out that the standard Gaussian approximation grossly over-estimate the BER when the variances of the in-phase and quadrature ASE components largely differ. The use of dispersion management (DM) in long-haul systems may substantially affect the received ASE PSDs [4]. Thus DM, which is often optimized through simulation for minimum noiseless signal distortion (minimization of self-phase modulation (SPM) and chromatic dispersion (CD) effects), may worsen the PG effects, and an optimal DM map which simultaneously accounts for PG and SPM/CD is desirable [5]. In this paper we wish to highlight the effect of DM on both the ASE spectra and BER for 10Gb/s long-haul terrestrial systems working at very low OSNR and thus requiring FEC. We will do so by an illustrative case study.

2. Case Study

The configuration of the simulated system is shown in Fig. 1. In the transmitter, a single NRZ OOK channel at 10 Gbit/s is generated using a 32 bit pseudo-random bit-sequence, with an extinction ratio of 13 dB. The link consists of N=20 spans, of 100 km of transmission fiber each, with nonlinear coefficient γ=1.7 km^{-1} W^{-1} and attenuation 0.2dB/km. All spans are equally compensated at their end by a linear in-line dispersion compensator. Pre-compensation and post-compensation (an addition to the compensation of the last span) may also be used in the system to further improve performance. Dispersion slope is assumed to be perfectly compensated at the end of each span.

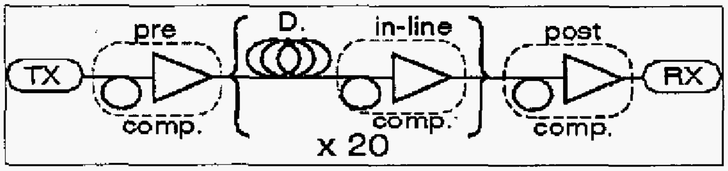


Fig. 1. Configuration of the simulated link

At the end of the link, the receiver is modeled by an optical filter of Gaussian shape with 3-dB bandwidth of two times the bit rate, and a PIN photodiode followed by an electrical Bessel filter of bandwidth 0.65 times the bit rate. PMD is neglected in the simulations.

3. ASE spectra

We first checked the impact of the sign of the transmission fiber dispersion and of the in-line cumulated dispersion (dispersion cumulated within the curly brackets in Fig. 1) on the spectra of the in-phase and quadrature ASE before post-compensation (pre-compensation does not influence ASE spectra). The spectra are measured on a very long string of consecutive marks. Fig. 2 shows the ASE in-phase and quadrature PSDs, normalized to their value in absence of PG, vs. frequency (normalized to the bit rate), obtained by direct Monte Carlo simulation with 2^{19} time samples. The OSNR in linear propagation was 11 dB/0.1 nm. Dashed lines refer to a transmission fiber with CD D=+8 ps/nm/km, while solid lines to D=-8 ps/nm/km. In Figs. 2(a),(b) the signal average power P was chosen to cumulate a nonlinear phase rotation $\phi_{NL}=\gamma P L_{eff} N= 0.3\pi$ along the link, being L_{eff} the fiber effective length, and $\phi_{NL}=0.7\pi$ in Figs. 2(c),(d). The in-line cumulated dispersion was $D_{in}=-2000$ ps/nm in Fig 2(a),(c) and $D_{in}=+2000$ ps/nm in Fig. 2(b),(d). We note that while the quadrature noise PSD is always increased by PG, at moderate nonlinearity (Figs 2(a),(b)) the in-phase PSD experiences an increase or a squeezing depending on the sign of the in-line cumulated dispersion. Such shapes can be predicted by the linear PG model [2],[4]. At large nonlinearity (Figs 2(c),(d)) the in-phase ASE gets enhanced at low frequencies no matter what the sign of the in-line cumulated dispersion. We verified that such an enhancement is due to the ASE-ASE beating during propagation [6], which is neglected in the linear PG model [2]. In all cases, the sign of local dispersion D does not appreciably influence the PG spectra. It is only at very small in-line cumulated dispersions that the sign of D actually matters.

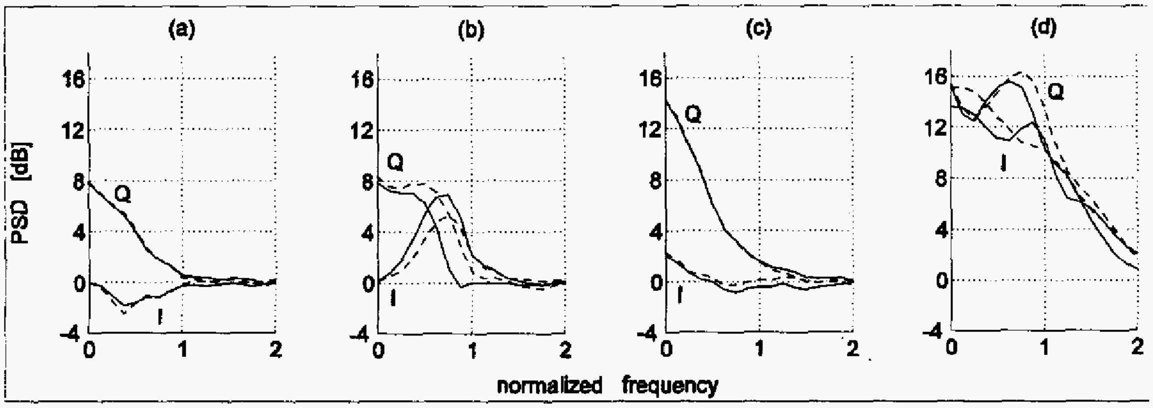


Figure 2 : Normalized in-phase (I) and quadrature (Q) ASE PSD vs. normalized frequency for 20x100 km 10Gbit/s NRZ system at OSNR = 11 dB/0.1 nm, with (dashed) D=+8 and (solid) D=-8 ps/nm/km. In-line cumulated dispersion: -2000 ps/nm ((a),(c)), and +2000 ps/nm ((b),(d)). Cumulated nonlinear phase: 0.3π ((a),(b)), and 0.7π ((c),(d)).

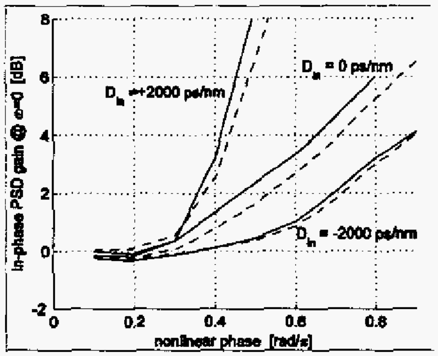
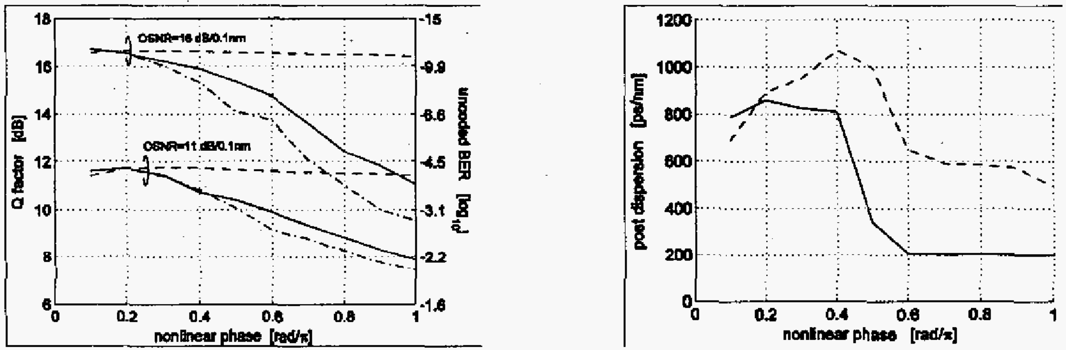


Figure 3 : Normalized in-phase PSD at zero frequency vs. nonlinear phase. (dashed): D=+8 ps/nm/km. (solid): D=-8 ps/nm/km.

Fig. 3 summarizes the growth of the in-phase PSD at zero (i.e. carrier) frequency for increasing nonlinearity at a fixed OSNR = 11 dB/0.1 nm for positive, zero and negative cumulated in-line dispersion. We note that increasing maps are much more affected by the ASE-ASE beating than are decreasing maps. Recall that the post-compensation fiber at the and of the link has the effect of mixing the in-phase and quadrature ASE components from the line [4], in most cases increasing the received in-phase ASE PSD. However, it has no effect on the PSDs at zero frequency.

4. System Performance

At large OSNR, it is the variance of the in-phase ASE that mostly determines the BER, since the signal-ASE beat is the dominant noise term. However, for accurate BER evaluation, a model for quadratic detectors in Gaussian noise, which correctly accounts also for the quadrature ASE is needed [3]. Things get more complicated at small OSNR, since the Gaussian injected ASE noise undergoes a nonlinear transformation which alters its initially Gaussian statistics. However, we verified by Monte Carlo simulations that even at small OSNR, but with a moderate amount of local CD, the BER can still be evaluated assuming Gaussian ASE statistics, provided that the correct PSDs (which can be obtained by off-line Monte-Carlo estimation, as we did in the previous section) are used. We applied this method to a 20x100 km system with D=+8 ps/nm/km, pre-compensation of -173 ps/nm, zero in-line cumulated dispersion (full span compensation), and optimized post-compensation. Fig. 4(a) shows the Q-factor, calculated by inverting the BER, versus average nonlinear phase, both at a moderate (linear) OSNR=16 dB/0.1nm and a very low OSNR=11 dB/0.1nm. The dashed lines refer to systems in which the post-compensation dispersion was optimized by minimizing the BER evaluated from the noiseless simulated received signal, adding to it analytically a white ASE noise, thus ignoring the PG coloring of the ASE. The shown Q-factor comes from such a BER which ignores PG. The dash-dotted lines show the Q-factor for the same systems with noiseless-optimized post-compensation, but now the BER is correctly evaluated by including PG. We note large penalties, in excess of 4 dB at $\phi_{NL}=\pi$, with respect to Q-factor evaluations that ignore PG. The solid lines refer instead to systems in which the post-compensation was optimized by minimizing the BER when jointly considering signal distortion and PG. We note that some limited improvement, up to 1 dB, is possible, and the optimal values of post-compensation are reported in Fig. 4(b). From Fig. 4(b) we learn that, when PG effects are comparable with noiseless signal distortion (SPM/CD) effects, less post-compensation is beneficial.



(a) (b)

Figure 4 : (a) Q-factor vs. nonlinear phase for linear OSNR=16 and 11 dB/0.1 nm. Pre-compensation: -173 ps/nm; full in-line compensation Dashed lines: post-compensation optimized based only on SPM/CD, BER evaluation ignores PG. Dash-dotted lines: post optimized for SPM/CD, PG included in BER calculation. Solid lines: post jointly optimized for SPM/CD+PG. PG included in BER calculation. (b) Post-compensation dispersion at OSNR=11 dB/0.1 nm optimized for (dashed) SPM/CD, and (solid) SPM/CD+PG.

5. Conclusion

We have shown that significant PG-induced ASE enhancement is present in DM systems operated at very low OSNRs, such as those envisaged when using FECs at 10Gbit/s. PG is thus responsible for a decrease of the expected Q-factor by several dBs. This implies that FECs with stronger coding gains are needed to counteract such an effect.

References

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