MB4 (Invited)
2:30 pm – 3:00 pm

Revisiting Nonlinear Interactions Between Signal and Noise in Presence of FEC

A. Bononi, P. Serena, J.-C. Antona and S. Bigo

Abstract

We review the system implications of the nonlinear interaction between signal and noise in 10 Gb/s OOK-NRZ long-haul systems working at low signal-to-noise ratios and employing FECs.

I. INTRODUCTION

Amplified spontaneous emission (ASE) noise and transmitted signal propagating into an optical fiber interact through a four wave mixing process, which leads to a power transfer between signal and noise that degrades the received optical signal-to-noise ratio (OSNR). This process is known as parametric gain (PG) [1].

The standard model to analyze PG effects on communication systems starts from a continuous wave (CW) signal to which a zero-mean white Gaussian ASE process is added at each optical amplifier, and linearizes the nonlinear Schrödinger propagation equation (NLSE) in the assumption of a large OSNR (i.e. a CW power much larger than the ASE power), thereby obtaining the power spectral density (PSD) of the received in-phase and quadrature ASE components [2]–[4]. In the absence of dispersion management, propagation in the anomalous regime leads to modulation instability [1] and thus an enhancement of the in-phase ASE, while in the normal regime the in-phase component gets depressed [2] (ASE squeezing) with potential improvement in system performance when the signal-in-phase beat noise is the dominant noise source at the receiver [2], [5]. The quadrature component, instead, gets always strongly enhanced, being a consequence of the nonlinear phase noise [3]. Such an enhancement/depression is limited to specific frequency bands, and in general the ASE becomes a colored (frequency-dependent) stochastic process, with correlated in-phase and quadrature components.

With dispersion mapping, things may change considerably. The in-phase component may be enhanced or depressed according to the dispersion map, both in the (average) normal and in the (average) anomalous regime [6]. Moreover, the post-dispersion compensating fiber usually added at the receiver to further improve the received signal waveform has the deleterious effect of coupling the in-phase and quadrature ASE from the line onto the received in-phase ASE, thereby vanishing the potential performance gain stemming from in-phase squeezing observed at large OSNR.

Some have conjectured that the failure of the linearized PG model in predicting system performance may be due to signal depletion operated by the ASE [7]. Others have shown that part of the trouble with the linearized PG model is due to the failure of the standard Gaussian approximation for bit error rate (BER) evaluation in the presence of PG-correlated ASE with unequal in-phase and quadrature components, and a more sophisticated BER estimation for quadratic detectors in Gaussian noise is necessary [8]. Intuitively, the trouble stems from the fact that the Gaussian approximation would predict a worsening of performance when the quadrature component is increased, while actually such an increase (think of it as phase noise) can never degrade performance.

While the above causes of failure are certainly true, in this paper, building on the results in [9], [10], we will show that the main cause of failure in performance prediction of 10 Gb/s non return-to-zero on-off keying (NRZ-OOK) dispersion mapped systems working over transmission fibers with low dispersion and at the typical low OSNR values of long-haul systems operated with forward error correction codes (FEC) is the nonlinear beat of the ASE with itself during propagation, a feature that is not captured by the linearized NLSE. The key result is that such an ASE-ASE beat, after a specific power (i.e. nonlinear phase) threshold, causes the in-phase ASE to exhibit a large PSD inflation in the low-frequency band, well above the prediction of the small-signal model, which leads to large penalties, making PG the main nonlinear impairment. Instances of such an inflation can be found in [9], and also in [6], Fig. 5. A useful formula for the PG power threshold is reported in [9].

A. Bononi and P. Serena are with the Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Parma, Viale delle Scienze 181A, 43100 Parma, Italy. Email: bononi@tlc.unipr.it.

J-C. Antona and S. Bigo are with Alcatel Research & Innovation, Route de Nozay, 91460 Marcoussis, France. Email: Jean-Christophe.Antona@alcatel.fr.

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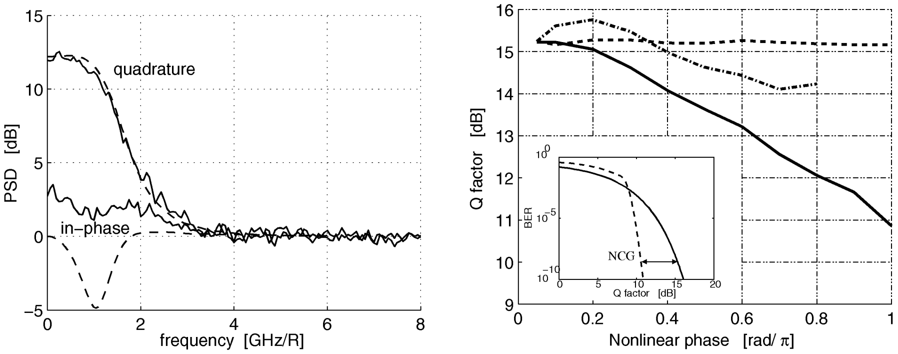

Fig. 1. (Left): In-phase and quadrature PSD versus normalized frequency after 2000 km of a fully-compensated 10 Gb/s system with OSNR=15 dB. (Right): Q-factor in absence (dashed) and in presence of Monte Carlo PG (solid) and small-signal PG (dash-dot), versus nonlinear phase.

II. CASE STUDY

Consider a 20 × 100 km OOK-NRZ single-channel system at $R = 10$ Gb/s, based on a D=2.9 ps/nm/km fiber fully compensated at each span, operating at an OSNR=15 dB in 0.1 nm, and with an average cumulated nonlinear phase of $\Phi_{NL} \triangleq \gamma P L_{eff} N = 0.6\pi$, being γ the nonlinear fiber coefficient, P the average signal power, L_{eff} the fiber effective length and $N = 20$ the number of spans. The system also has pre- and a post-dispersion compensating fibers for optimal noiseless signal reception. Fig. 1 (left, solid lines) shows the in-phase and quadrature ASE PSD at the end of the line, estimated by direct Monte Carlo solution of the NLSE, with a CW of power equal to the marks power, plus ASE. The PSDs are normalized to their value in absence of PG. The dashed lines refer to the PSDs obtained from the linearized NLSE, which incorrectly predicts a depletion of the in-phase ASE PSD in this zero average dispersion map. We calculated the BER with a model for quadratic detectors in Gaussian noise [8] that postulates Gaussian received ASE statistics, with a white PSD on spaces and a PG-colored PSD (obtained by off-line Monte-Carlo simulation) on marks. The signal was propagated by solving the noiseless NLSE. The system Q-factor was then inferred from the calculated BER. Fig. 1 (right) shows the Q-factor calculated without PG (dashed line), and with PG (solid line) versus the average cumulated nonlinear phase at OSNR=15 dB. The case with PG obtained from the linearized NLSE is also shown in dash-dotted line. The post-compensation fiber was optimized for each Φ_{NL}. We observe that while with white noise the Q-factor remains essentially equal to the back to back value (self-phase modulation plays no role in this system), the linearized NLSE PG model would incorrectly predict an initial enhancement of performance, and would largely underestimate the actual Q-factor penalty obtained by considering the ASE-ASE beat during propagation. The Q-penalty reduces the net coding gain (NCG) of the FEC planned for a system in which PG is ignored, as shown in the inset of Fig. 1, where the uncoded (solid line) and coded (dashed line) BER versus the Q factor are plotted for a standard RS$(255, 239)$ FEC.

In conclusion, we have shown that PG is a non-negligible factor in the design of long-haul dispersion-managed optical 10 Gb/s OOK-NRZ transmission systems operated at small OSNR, small dispersion of the transmission fiber, and substantial cumulated nonlinear phase, in which the ASE-ASE beating along the fiber cannot be neglected. The additional penalty introduced by PG requires the use of more powerful FECs than planned when ignoring PG.

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