Nonlinear Phase Noise Mitigation by Polarization Mode Dispersion in Dispersion Managed coherent PDM-QPSK Systems

Paolo Serena and Alberto Bononi
Università degli Studi di Parma, dept. Ingegneria dell'Informazione, v.le G. Usberti 181/A, 43100 Parma (Italy),
email: serena@tlc.unipr.it

Abstract *We show by simulation that PMD helps reduce nonlinear phase noise in single-channel coherent PDM-QPSK systems at both 43 and 112 Gbit/s, with improved resilience at 112 Gbit/s.*

Introduction

Coherent detection is considered as a key technology to upgrade optical network rates to 40 and 100 Gbit/s, in particular with polarization division multiplexed (PDM) quadrature phase shift keying (QPSK) modulation.[1]

Many problems in coherent detection have been solved by the use of digital signal processing (DSP) which is capable to almost fully compensate linear fiber impairments like group velocity dispersion and polarization mode dispersion (PMD).

However, the DSP performance worsens in the nonlinear regime. One source of penalty comes from nonlinear phase noise (NLPN) induced by the interaction between the amplified spontaneous emission noise (ASE) and the information signal. So far, studies of NLPN in coherent and non-coherent QPSK systems have been carried out in absence of polarization effects.[2–4] However the interaction between Kerr effects and PMD may introduce an extra penalty.[5]

In this work we investigate, for the first time to our knowledge, the interaction between NLPN and PMD in single-channel 43 Gbit/s and 112 Gbit/s PDM-QPSK systems and provide insights into the interaction. When linear distortions are fully compensated, we show that PMD reduces NLPN, more effectively at larger symbol rates.

Results and discussion

We first simulated a single channel 43Gbit/s (10.7 Gbaud) non-return to zero PDM-QPSK system propagated in a dispersion managed 20×100 km link based on transmission fibers with dispersion D=4 ps/nm/km, attenuation $\alpha = 0.2$ dB/km, nonlinear index $\gamma = 1.5$ 1/(W·km). The two polarizations of the QPSK signal were differentially encoded to avoid phase ambiguity, and modulated with different quaternary de Bruijn sequences of 4^4 symbols. The transmission fibers in the link were modeled with the coupled nonlinear Schrödinger equation (CNLSE) using 50 random waveplates per span. The CNLSE was then solved with the vectorial split-step Fourier method,[6] thus accounting for birefringence and PMD. Dispersion management was achieved with a pre-compensation of -87 ps/nm, full in-line compensation and zero total cumulated dispersion. PMD was also ideally fully compensated before reception by inverting the Jones matrix of the line. The DSP-based receiver was a standard one with carrier phase estimation based on the Viterbi algorithm with 7 taps.[1]

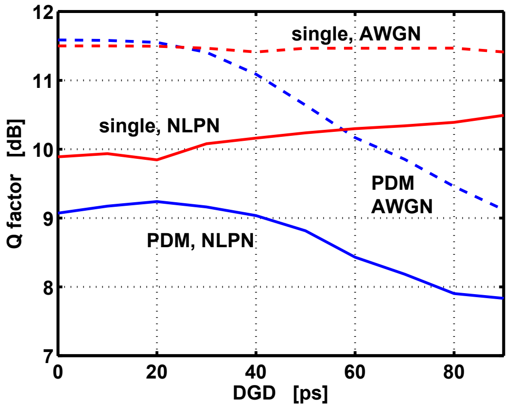

Fig. 1: Q factor vs. DGD for PDM-QPSK @ 43 Gbit/s. "single": single polarization. AWGN: white noise. NLPN: nonlinear phase noise. D=4 ps/nm/km.

The performance was measured in terms of the Q factor obtained by inverting the bit error rate, estimated from Monte Carlo simulations stopped when the relative accuracy was 0.1 at confidence 68%, corresponding to at least 100 error counts.In Fig. 1 we show the Q factor vs. average differential group delay (DGD) in different setups. The Q factor is the average among ten simulations with different PMD random seeds. Since linear PMD was compensated at the receiver, the residual contribution of PMD to the penalty comes from the coupling of nonlinearity and PMD. The AWGN case corresponds to noiseless propagation and an equivalent ASE source added before the receiver. In this case noise and signal do not experience nonlinear interaction. If X and Y represent our arbitrary reference system in the Jones space, in the single polarization case we just transmitted zero power on the Y polarization leaving the noise unchanged. The optical signal to noise ratio (OSNR) was fixed to 13 dB in 0.1 nm while the X+Y average power was 1.6 dBm, yielding a total nonlinear phase along the link of 0.3π.

Several observations can be made from the figure. First, NLPN introduces a significant penalty w.r.t. the AWGN case. Second, DGD introduces a nonlinear penalty, but it also relaxes the NLPN-signal interaction: this causes an initial improvement in Q and a merger of the AWGN and NLPN curves at large DGD. In the

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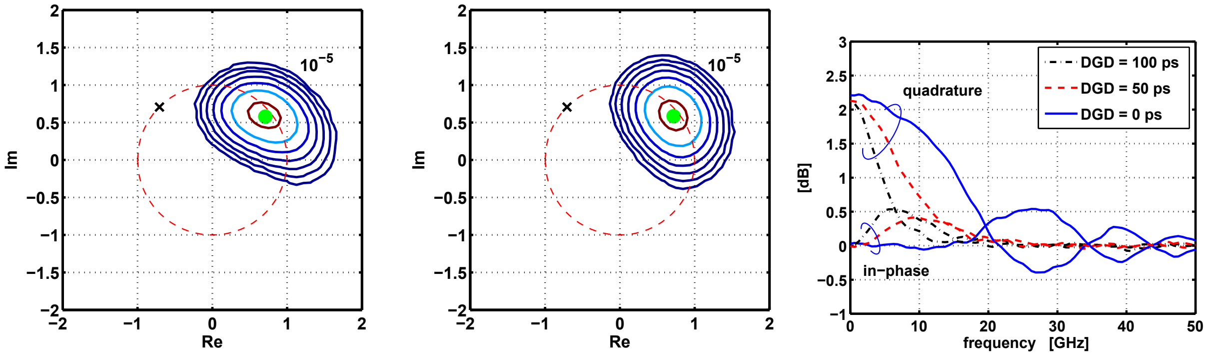

Fig. 3: *Electric field PDF with DGD=0 (left) and DGD=100 ps (center). Right: PSD normalized to the AWGN level.*

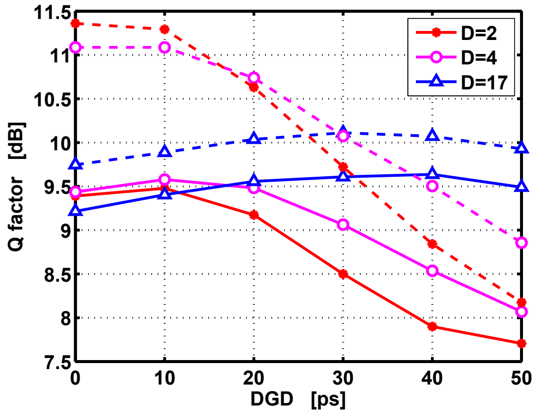

Fig. 2: *Impact of NLPN in different fibers @ 112 Gbit/s. Dashed: AWGN. Solid: NLPN.*

single-polarization case (which has half total power and thus smaller NLPN) only the Q improvement is observed on the shown DGD range.

Fig. 2 shows Q factor vs. DGD in a PDM-QPSK 112 Gbit/s (28 Gbaud) system with transmission fiber dispersions D=2, 4, 17 ps/nm/km, with (solid) and without (dashed) NLPN. Power is the same as in Fig. 1 and OSNR is 17.5 dB in 0.1 nm, which gives the same Q as in the 43 Gbit/s case in the linear regime. We observe that, at D=17 ps/nm/km, only the Q-improvement range is shown with peak around DGD=40 ps, while the peak is at DGD=10 ps when D=4 ps/nm/km. As expected, the NLPN penalty is larger for smaller dispersions.[4]

To understand the reason of the NLPN penalty reduction for increasing DGD, we measured the probability density function (PDF) of the complex electric field after the receiver optical filter, when a constant wave is transmitted on both X and Y on the same DM system as in Fig. 1. Such a PDF is shown in Fig. 3 down to 10^{-5} in absence (left) and presence (center) of PMD. The transmitted field is indicated by a cross; the received one is rotated on average and has a non-circular PDF, which appears to be almost elliptical[4] and inflated in the tangent direction. Comparing the PDFs we observe that DGD reduces the noise inflation and rotates the PDF yielding an ellipse with a main axis tangent to the unit circle. Such a condition better concentrates the PDF in a quadrant. Physically, DGD decorrelates the X and Y components so that if a noise spike is added at some instant, its X and Y components walk-off because of DGD, but since NLPN is proportional to the X+Y spike power the net effect is a smaller NLPN. The right plot of Fig. 3 shows the power spectral density (PSD) of the in-phase (radial) and quadrature (tangent) noise components in a reference system rotated by the average nonlinear phase. Since the quadrature component roughly coincides with NLPN, we observe that its PSD reduction for increasing DGD justifies the results in Figs. 1, 2. Going back to such figures, we note e.g. the following Q factors [dB] at D=4 ps/nm/km:

	DGD 0 ps	DGD 1 symbol
PDM 43G	9.1	7.3
PDM 112G	9.4	8.8

With a one symbol DGD, the nonlinear penalty is 1.5 dB smaller in the 112G PDM case: it is now clear that this is so, since the signal spectrum is broader and the inflated portion of NLPN (see Fig. 3(right)) is relatively smaller in the signal bandwidth.

Conclusions

PMD reduces NLPN, more at 112 Gbit/s giving larger tolerance than at 43 Gbit/s. Such effect is most noticeable with small dispersion fibers.

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