Compensation of nonlinear phase noise impairments through optical phase conjugation in long-haul transmission systems

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Differential-quadrature phase-shift-keying (DQPSK) can, unlike on-off-keying (OOK), be impaired by nonlinear phase noise (NPN). It has been shown that optical phase conjugation (OPC) is an effective compensation scheme for NPN resulting from the ASE of EDFAs (ASE-NPN). In this paper we discuss the influence of NPN resulting from modulator imperfections (MI-NPN). We show that MI-NPN can be compensated for through OPC, though shifts the optimum location of the OPC towards the middle of the transmission link.

Introduction

Recently significant research interest has been dedicated to return-to-zero differential quadrature phase-shift-keying (RZ-DQPSK) modulation format [1-3]. RZ-DQPSK has a favorable spectral width making it robust against narrow band filtering. Furthermore RZ-DQPSK has a higher polarization mode dispersion (PMD) and chromatic dispersion tolerance at the same effective data rate as binary modulation [4, 5], which could possibly ease deployment of 40Gbit/s transmission over legacy fiber. A concern is, however, that RZ-DQPSK can unlike OOK be impaired by nonlinear phase noise (NPN). Conventional NPN, which we will refer to as ASE-NPN, results from power fluctuations originating from amplified spontaneous emission (ASE) noise that are converted into phase fluctuations of the signal through the Kerr effect [6-7]. As will be discussed in this paper, a second source of NPN exists through modulator imperfections (MI). MI lead to amplitude fluctuations, which through the Kerr effect result in NPN after transmission (MI-NPN).

It has been shown both theoretically [8, 10] as well as experimentally [11-12] that optical phase conjugation (OPC) can be employed to compensate for ASE-NPN. In this paper we study the influence of impairments through MI-NPN with and without OPC in a transmission line. We show that modulator imperfections are compensated for through OPC, but will shift the optimum location of the OPC towards the middle of the transmission link.

Nonlinear phase noise without MI

We consider a long haul transmission link with a system length much longer than the dispersion length. In such a system, the soliton condition is maintained adiabatically and the growth of the soliton power and phase perturbations can be approximated using the correlation equations as studied in [13]. Assuming a loss-less, dispersion-less transmission system, these result in the following set of formulas [10]:

$$\left\langle p^2 \right\rangle = \left\langle p^2 \right\rangle_0 + \sigma_p z \quad (1)$$

$$\left\langle p\phi \right\rangle = \left\langle p\phi \right\rangle_0 + \left\langle p^2 \right\rangle_0 \bar{\gamma} z + \sigma_p \bar{\gamma} z^2 / 2 \quad (2)$$

$$\left\langle \phi^2 \right\rangle = \left\langle \phi^2 \right\rangle_0 + 2\left\langle p\phi \right\rangle_0 \bar{\gamma} z + \left\langle p^2 \right\rangle_0 \bar{\gamma}^2 z^2 + \sigma_\phi z + \sigma_p \bar{\gamma}^2 z^3 / 3 \quad (3)$$

where z represents the transmission distance with the initial position at $z = 0$. $\bar{\gamma}$ is the effective nonlinear coefficient and <> denotes an ensemble average. σ_p and $\sigma_\phi \approx \sigma_p / 4$ represent the strength of the power-induced and the noise-induced phase kicks, respectively. Assuming an ideal modulator, the average noise amplitude power at the transmitter is set to zero ($<p^2>_0 = 0$). When an OPC is placed in a transmission link, the sign of $<p_\phi>$ is inverted at the OPC whereas the signs of the quadratic terms ($<p^2>$ and $<\phi^2>$) are unaffected. Fig. 1 shows the ASE-NPN represented by the phase variance ($<\phi^2>$) as a function of the transmission distance. In this plot, both transmission distance and phase variance are normalized so that without OPC 100% of phase variance is obtained after 100% transmission. Without OPC, the phase variance increases with $z^3/3$. When the OPC is placed in the middle (at 50%) of the transmission line, the phase variance is reduced to 25% after transmission. NPN, resulting from noise introduced after OPC cannot be compensated for. As a result, the optimal location to compensate ASE-NPN is at 66% [10] where the phase variance after transmission is reduced to 11.1%.

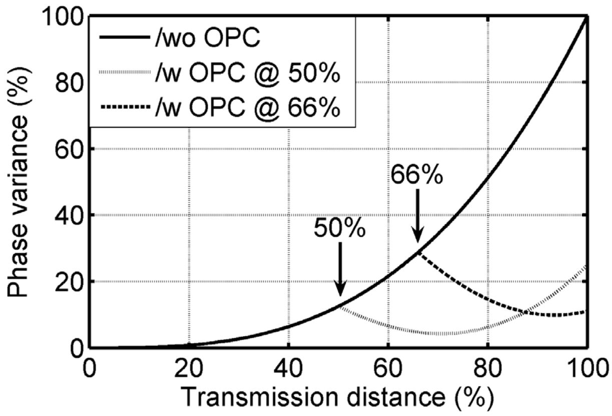

Fig. 1: Normalized phase variance due to ASE-NPN as a function of the transmission distance with (/w) and without (/wo) OPC.

Nonlinear phase noise with MI

So far, an ideally modulated signal is assumed ($<p^2>_0 = 0$). In practice however, the bandwidth of the Mach-Zehnder modulator limits the quality of the signal e.g. extinction ratio, rise/fall time, etc. This becomes a problem when either low-quality modulators or an advanced modulation format such as RZ-DQPSK is employed. In this paper, we focus on the RZ-DQPSK modulation format. A conventional way to generate DQPSK is by using an integrated DQPSK modulator with two parallel MZMs within a super Mach-Zehnder structure as shown in Fig. 2. For the generation of DQPSK, the required amplitude of the driver voltages is $2xV_{pi}$. At data rates of 20Gbit/s and more, the broadband amplification of a driver signal is not trivial. Fig. 2 shows the eye diagram of a

42.8Gbit/s RZ-DQPSK signal. In this figure, the MI of the parallel DQPSK modulator result in the broadening of the '1' rail (amplitude fluctuations) of the RZ-DQPSK signal. Similar to ASE-NPN, these amplitude fluctuations cause NPN through the Kerr effect.

Fig. 2: Super Mach-Zehnder structure with the eye diagram of a 42.8Gbit/s RZ-DQPSK signal

The influence of MI is assessed by increasing the average noise amplitude power at the transmitter ($<p^2>_0 > 0$). ASE-NPN is excluded by assuming ideal amplifiers and hence setting the strength of the power-induced and the noise-induced phase kicks to zero ($\sigma_p = \sigma_\phi = 0$). Fig. 3 depicts the phase variance due to MI-NPN as a function of the transmission distance. Similar to Fig. 1, both transmission distance and phase variance are normalized so that without OPC 100% of phase variance is obtained after 100% transmission. Without OPC, the phase variance increases with z^2. The optimal OPC location where the phase variance due to MI-NPN is completely compensated is mid-link (50%). With the OPC placed at 66% of the transmission line, the phase variance after transmission is 10% of the variance without OPC. For ASE-NPN (Fig. 1), the optimal location for OPC is at 66% of the transmission line. Hence the compensation of MI-NPN and ASE-NPN require a different OPC location for optimal NPN compensation. An explanation for this is that the source of the amplitude fluctuations with MI-NPN originates solely from the transmitter, whereas with ASE-NPN amplitude fluctuations (ASE-noise) are added along the transmission line.

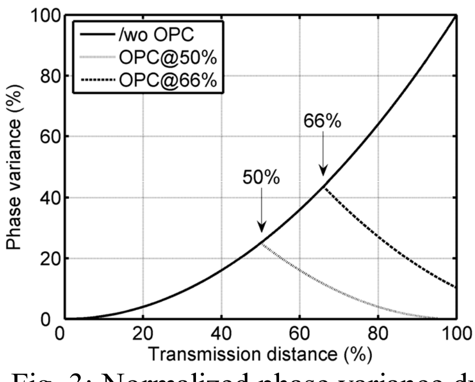

Fig. 3: Normalized phase variance due to MI-NPN as a function of the transmission distance.

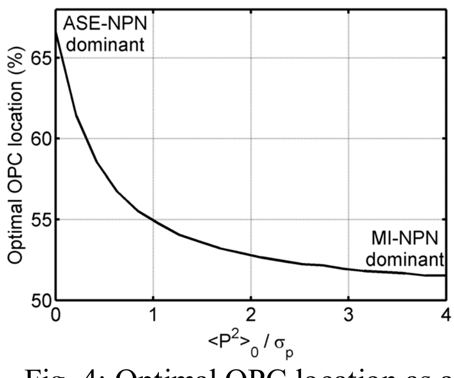

Fig. 4: Optimal OPC location as a function of the MI to ASE ratio ($<p^2>_0/\sigma_p$)

In a real transmission system both MI-NPN and ASE-NPN are present, hence the optimum OPC location is dependent on which NPN source is dominant. In Eq. 1-3 the MI are represented by the average noise amplitude power at the transmitter ($<p^2>_0$). The ASE is represented by the strength of the noise-induced power (σ_ϕ) and phase (σ_p) kicks. We consider both sources of NPN by the ratio of MI to ASE ($<p^2>_0/\sigma_p$). Note that

$\sigma_\phi \approx \sigma_p / 4$ relates the noise-induced phase kicks to the noise-induced power kicks. When $<p^2>_0/\sigma_p = 0$, no MI are present in the system and ASE-NPN is the dominating impairment. Increasing the ratio $<p^2>_0/\sigma_p > 0$ will increase the influence of MI-NPN on the transmission system. Fig. 4 shows the optimal OPC location as a function of the MI to ASE ratio ($<p^2>_0/\sigma_p$). As expected, the optimum location of the OPC is 66% when no MI are present ($<p^2>_0/\sigma_p = 0$) and shifts towards the middle of the transmission line with increasing MI.

Conclusion

Amplitude fluctuations, resulting from modulator imperfections can significantly increase nonlinear phase noise (NPN) build-up in long-haul transmission systems. OPC compensates NPN resulting from both modulator imperfections as well as ASE-noise. When impairments due to ASE-NPN are dominant, the optimum OPC location is at 66% of the transmission line, whereas the optimum location shifts towards the middle of the transmission link when MI-NPN is dominant.

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