OSA / OFC/NFOEC 2010

OWE5.pdf

Impact of PMD and Nonlinear Phase Noise on the Global Optimization of DPSK and DQPSK Systems

L.D. Coelho[1], O. Gaete[1], E.-D. Schmidt[2], B. Spinnler[2], N. Hanik[1]

1: Technische Universität München, Institute for Communications Engineering, D-80290 Munich, Germany
2: Nokia Siemens Networks GmbH & Co. KG, St. Martin Strasse 76, D-80240 Munich, Germany
leonardo.coelho@tum.de

Abstract: Using a global optimization algorithm, we maximize the reach of DPSK and DQPSK systems including PMD and nonlinear phase noise at data rates ranging from $5\,\mathrm{Gbit/s}$ to $230\,\mathrm{Gbit/s}$.

OCIS codes: (060.4510) Optical communications; (060.5060) Phase modulation; (060.4370) Nonlinear optics, fibers

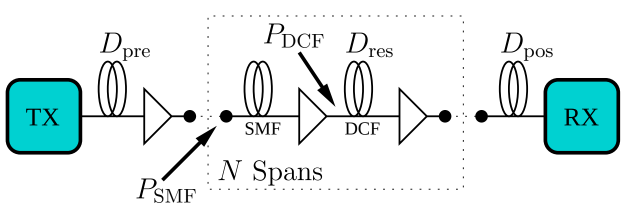
1. Introduction

In optical communication systems, the main source of performance degradation are the accumulated amplified spontaneous emission (ASE) noise, polarization-mode dispersion (PMD) and fiber dispersion and nonlinearity [1]. The bit-error rate (BER) for systems containing all these impairments and their interactions with the signal can be calculated using the standard Monte Carlo method. However, if the BER has to be computed several times, the overall computational effort is so large that it becomes prohibitive for system optimization. In this case, the BER can be calculated very fast and accurate by using linearization techniques of the Nonlinear Schrödinger Equation (NLSE) together with Karhunen-Loéve series expansion [2].

Even using these semi-analytical methods for calculating the BER, the optimization procedure can still be very time-consuming if, for example, grid search algorithms are employed. Several fast optimization methods have been investigated, but all of them use simplified models for nonlinear signal propagation and, therefore, are only valid for a certain range of parameters or modulation formats [3–6]. In this context, global optimization algorithms [7] can be employed to guide the search over the large set of parameters in order to find the best solution in the minimum simulation time. After the optimization procedure, simplified models [4] may be used to include PMD, which would require a large computational effort at each iteration of the optimization algorithm.

In this paper, we use a global optimization algorithm [7] together with an extended Karhunen-Loéve method [2] and the nonlinear phase-shift criterion [4] to find the maximum reach of single-channel DPSK and DQPSK systems including PMD and nonlinear phase noise, induced by the interaction between the signal and ASE noise. We extend the results presented in [7] and also show the impact of both effects on the maximum reach for data rates ranging from $5\,\mathrm{Gbit/s}$ to $230\,\mathrm{Gbit/s}$.

2. System and Simulation Set-Up



	SMF	DCF
Attenuation α [dB/km]	0.23	0.50
Dispersion D [ps/nm]	16.6	-103.4
Slope S [ps/nm^2]	0.058	-0.2
NL Par. γ [$1/(\mathrm{W}\cdot\mathrm{km})$]	1.52	5.27
PMD Coeff. τ [$\mathrm{ps}/\sqrt{\mathrm{km}}$]	0.05	0.1

Fig. 1. System set-up and fiber parameters.

Fig. 1 shows a typical long-haul optical communication system comprising N spans. The link is composed of a fiber for pre-compensation D_{pre}, standard single mode fiber (SMF) of length $L_{\mathrm{SMF}} = 80$ km, a dispersion compensating fiber (DCF) for in-line dispersion compensation, a fiber for post-compensation D_{pos} and optical amplifiers with equal noise figure $F_n = 6$ dB. P_{SMF} and P_{DCF} are the SMF and DCF fiber input powers, respectively. The nonlinearity of the pre– and post–compensation fibers is neglected, but their attenuations are taken into account. D_{pos} is set such that the accumulated dispersion at the receiver amounts to D_{acc}. The optical filter was modeled as a second-order

Gaussian filter and its bandwidth was optimized for each data rate in a back-to-back configuration. The electrical filter was modeled as a fifth-order Bessel filter with a bandwidth of $0.75 \cdot R_\mathrm{s}$, where R_s is the symbol rate.

The performance of the system is measured in terms of the system reach. It is defined as the maximum number of spans N at which the BER is equal to or lower than 10^{-4}. The optimization problem is defined as $N = f(P_\mathrm{SMF}, P_\mathrm{DCF}, D_\mathrm{pre}, D_\mathrm{res}, D_\mathrm{acc})$, where $f(\cdot)$ is the objective function and $\{P_\mathrm{SMF}, P_\mathrm{DCF}, D_\mathrm{pre}, D_\mathrm{res}, D_\mathrm{acc}\}$ the 5-dimensional search space. For each data rate R_b, the algorithm tries to find iteratively the set of input parameters which maximizes the system reach, i.e. $N_\mathrm{max} = f(P_\mathrm{SMF}^\mathrm{opt}, P_\mathrm{DCF}^\mathrm{opt}, D_\mathrm{pre}^\mathrm{opt}, D_\mathrm{res}^\mathrm{opt}, D_\mathrm{acc}^\mathrm{opt})$.

The global optimization algorithm starts by simulating the 2^5 boundary points, then it divides the search space into a set of simplexes. For each simplex, the variable N is modeled as a Gaussian stochastic process and its mean and variance are used in order to find the next set of input parameters, which will most probably improve the currently best solution N_max^*. Based on the results of a previous work [7], the number of iterations was set to $N_i = 200$, which corresponds to approximately 0.01% simulations of an equivalent grid search. After N_i iterations the global optimization algorithm determines N_max and $\mathcal{S}_\mathrm{opt} = \{P_\mathrm{SMF}^\mathrm{opt}, P_\mathrm{DCF}^\mathrm{opt}, D_\mathrm{pre}^\mathrm{opt}, D_\mathrm{res}^\mathrm{opt}, D_\mathrm{acc}^\mathrm{opt}\}$ for each data rate R_b. The boundaries of the search space are given by P_SMF = $[-3, 4]$ dBm, P_DCF = $[-10, -4]$ dBm, D_pre = $[-450, 0]$ ps/nm, D_res = $[-40, 40]$ ps/nm and D_acc = $[-40, 40]$ ps/nm.

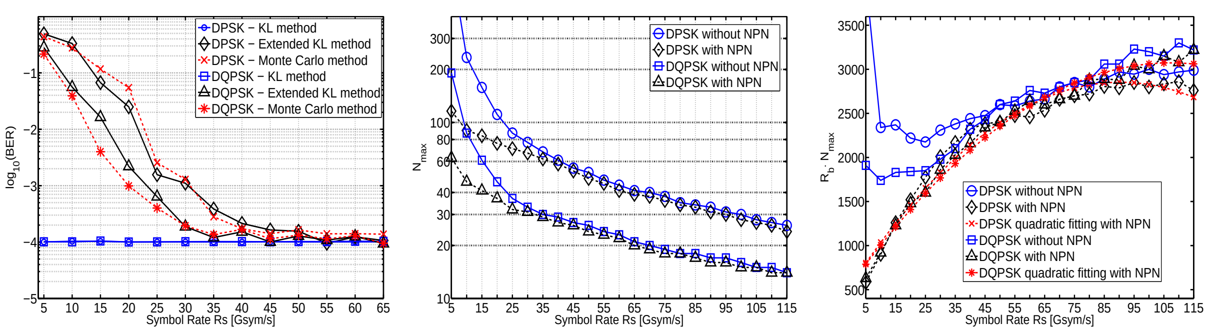
Simulations were carried out using non-return-to-zero (NRZ) pulse format and PRBS/PRQS sequences of length 4^5. The fibers were numerically simulated by solving the scalar NLSE (no PMD) or the coupled NLSE (with PMD) [8]. The coarse step method [9] was used to obtain the principal states of polarization (PSP) and the Maxwellian distribution of the differential group delay (DGD). PMD emulation was performed by using 320 birefringent sections per span and by dividing the signal equally between both principal states of polarization. In order to evaluate the average performance at large DGDs, ten different system realizations were simulated at a DGD 2 times larger than the average DGD, defined here as <DGD>, and another ten realizations were simulated at a DGD 3 times larger than <DGD>.

3. Results and Discussion

Considering the system in Fig. 1, the BER can be exactly evaluated using the Karhunen-Loéve (KL) method [1] only if the received optical noise is white and Gaussian. If fiber nonlinearities are of concern, linearization techniques of the NLSE can be applied together with KL method for BER evaluation in the presence of nonlinear phase noise (NPN) [2]. This method will be called here *Extended KL method*.

The global optimization algorithm was first applied to a system without PMD and NPN. In this case, the BER was evaluated using the KL method and it does not exceed 10^{-4} after N_max spans, as shown in Fig. 2(a). However, if the BER is evaluated using the Monte Carlo and Extended KL methods, then it changes considerably for symbol rates lower than $40\,\mathrm{Gsym/s}$. For symbol rates greater than $40\,\mathrm{Gsym/s}$, the penalty due to NPN is rather small because the linear phase noise and intra-channel effects dominate over NPN.

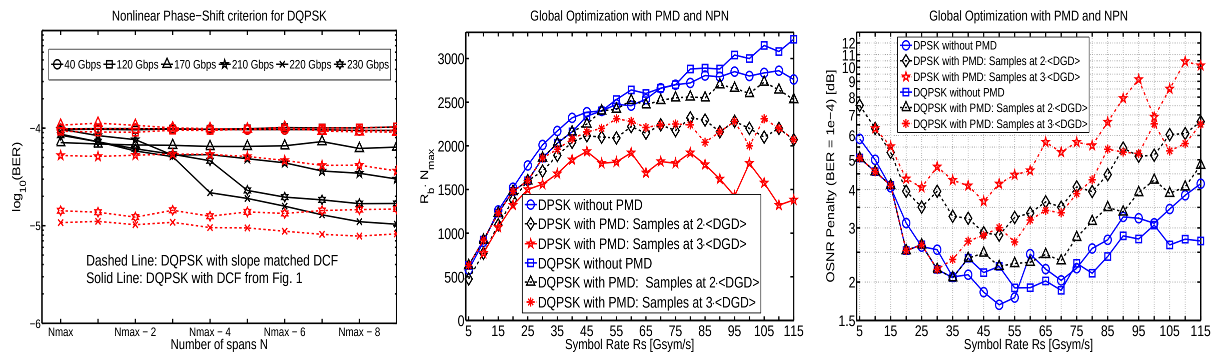
In Fig. 2(b), the global optimization algorithm was applied to a system with NPN, but without PMD. The results show that NPN limits the reach for symbol rates smaller than $40\,\mathrm{Gsym/s}$. Fig. 2(c) shows the performance in terms of the bandwidth-distance product. In the presence of NPN, both modulation schemes have the same performance, while the performance can be quite different if NPN is neglected. Moreover, Fig. 2(c) shows that a quadratic fitting of $R_b \cdot N_\mathrm{max}$ can be used to predict the system reach with high accuracy.



(a) (b) (c)

Fig. 2. Impact of NPN on the BER (a), maximum reach (b) and bandwidth-distance product (c) for DPSK and DQPSK

At each iteration of the global optimization algorithm, the evaluation of the system reach in the presence of PMD is a very time-consuming task, because the PSPs [9] have to be calculated for different number of spans N until the maximum reach is found. However, if we consider the effect of PMD as a small perturbation on the optimum set of parameters $\mathcal{S}_{\mathrm{opt}}^{\mathrm{NPN}}$, then the nonlinear phase-shift criterion [4] can be used to determine the impact of PMD on $N_{\max}^{\mathrm{NPN}}$. The nonlinear phase-shift is defined as $\phi_{\mathrm{NL}} = N \cdot P_{\mathrm{SMF}} \cdot (\gamma_{\mathrm{SMF}} \cdot L_{\mathrm{eff}}^{\mathrm{SMF}} + \eta \cdot \gamma_{\mathrm{DCF}} \cdot L_{\mathrm{eff}}^{\mathrm{DCF}})$, where $\eta = P_{\mathrm{DCF}}/P_{\mathrm{SMF}}$, $L_{\mathrm{eff}}^{\mathrm{SMF}}$ and $L_{\mathrm{eff}}^{\mathrm{DCF}}$ are the effective lengths of the respective fibers. Our simulations confirmed that the BER remains constant, if $\phi_{\mathrm{NL}}^{\mathrm{opt}}$, η^{opt}, $D_{\mathrm{pre}}^{\mathrm{opt}}$ and $D_{\mathrm{acc}}^{\mathrm{opt}}$ are constant and N and D_{res} are varied according to the straight-line rule [5,6], as shown in Fig. 3(a). For high data rates, dispersion slope accumulation induces a small penalty, which does not interact with PMD. Therefore, the maximum reach in the presence of PMD and NPN was determined for each data rate by reducing the number of spans N from $N_{\max}^{\mathrm{NPN}}$ until the BER was equal to or lower than 10^{-4}. In Fig. 3(b), we observed that for symbol rates lower than $40\,\mathrm{Gsym/s}$, PMD has a small impact on the maximum reach $N_{\max}$, while for symbol rates above $40\,\mathrm{Gsym/s}$, PMD limits the system performance. In Fig. 3(c), the OSNR penalty is defined as the difference between the accumulated OSNR after $N_{\max}$ spans ($\mathrm{BER} \leq 10^{-4}$) and the required back-to-back OSNR ($\mathrm{BER} \leq 10^{-4}$). Small penalties were found between 30 and $50\,\mathrm{Gsym/s}$, which indicates an optimum range of symbol rates. Figs. 3(b) and 3(c) reveal that DQPSK is more tolerant to PMD. In fact, this occurs because the maximum reach of DQPSK is approximately two times lower than that of DPSK, which implies a smaller <DGD>.



(a) (b) (c)

Fig. 3. BER with constant ϕ_{NL} (a), impact of PMD on the bandwidth-distance product (b) and OSNR penalty (c) for DPSK and DQPSK

4. Conclusions

Using a global optimization algorithm, the maximum reach of single-channel DPSK and DQPSK optical communication systems was determined in the presence of PMD and NPN. A detailed investigation into the impact of both effects was carried out and an optimum range of symbol rates around $40\,\mathrm{Gsym/s}$ was identified. In fact, the effect of NPN was dominant for symbol rates below $40\,\mathrm{Gsym/s}$, while PMD limits the system performance for symbol rates above $40\,\mathrm{Gsym/s}$. Moreover, in the absence of PMD we observed that DPSK and DQPSK have similar performance.

References

[1] P. J. Winzer and R. J. Essiambre, "Advanced Modulation Formats for High-Capacity Optical Transport Networks," *J. Lightw. Technol.*, vol. 24, no. 12, pp. 4711–4728, Dec. 2006.

[2] L. D. Coelho, L. Molle, D. Gross, N. Hanik, R. Freund, C. Caspar, E.-D. Schmidt, and B. Spinnler, "Modeling nonlinear phase noise in differentially phase-modulated opticalcommunication systems," *Opt. Express*, vol. 17, no. 5, pp. 3226–3241, 2009.

[3] J. P. Elbers, A. Farbert, C. Scheerer, C. Glingener, and G. Fischer, "Reduced model to describe SPM-limited fiber transmission in dispersion-managed lightwave systems," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 2, pp. 276–281, March–April 2000.

[4] J. C. Antona, S. Bigo, and J. P. Faure, "Nonlinear cumulated phase as a criterion to assess performance of terrestrial WDM systems," in *Proc. Optical Fiber Communication Conference and Exhibit OFC 2002*, 17–22 Mar 2002, pp. 365–367.

[5] R. I. Killey, H. J. Thiele, V. Mikhailov, and P. Bayvel, "Reduction of intrachannel nonlinear distortion in 40-Gb/s-based WDM transmission over standard fiber," *IEEE Photon. Technol. Lett.*, vol. 12, no. 12, pp. 1624–1626, Dec. 2000.

[6] A. Bononi, P. Serena, and A. Orlandini, "A unified design framework for single-channel dispersion-managed terrestrial systems," *J. Lightw. Technol.*, vol. 26, no. 22, pp. 3617–3631, Nov. 2008.

[7] L. D. Coelho, O. Gaete, and N. Hanik, "An algorithm for global optimization of optical communication systems," *AEU - International Journal of Electronics and Communications*, vol. 63, no. 7, pp. 541 – 550, 2009.

[8] G. P. Agrawal, *Nonlinear Fiber Optics*, 4th ed. San Diego, USA: Academic Press, 2006.

[9] C. D. Poole and R. E. Wagner, "Phenomenological approach to polarisation dispersion in long single-mode fibres," *Electronics Letters*, vol. 22, no. 19, pp. 1029–1030, Sep. 1986.