

Monte Carlo Estimation of PDM-QPSK/OOK and DQPSK/OOK Hybrid Systems Tolerance against Nonlinear Effects

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Abstract—We compare through Monte Carlo simulations the performance of polarization-division multiplexed (PDM) quadrature phase shift keying (QPSK) and differential QPSK (DQPSK) copropagating with on-off keying (OOK) channels, taking into account nonlinear phase noise. DQPSK turns out to be better with optimal dispersion-management, while PDM-QPSK proves to be a good candidate for bitrates higher than 40 Gb/s.

Index Terms—phase shift keying, optical transmission, coherent detection, cross phase modulation

I. INTRODUCTION

THE Internet traffic growth calls for an increased capacity of dense wavelength division multiplexing (DWDM) optical transmission systems. Advanced modulation formats [1] allow to design optical systems with bitrate per channel of 40 Gb/s or higher and good tolerance against linear and nonlinear impairments. The complete substitution of deployed non-return to zero on-off keying (NRZ-OOK) systems is a very expensive option, thus a cost effective solution is to upgrade one or more selected channels, following the market demand. Systems that employ two or more modulation formats and possibly different data rates are commonly referred to as “hybrid”.

Many different formats have been proposed as candidates for the channel upgrade. Phase Shaped Binary Transmission (PSBT) and differential quadrature phase shift keying (DQPSK) have been studied both numerically [2] and experimentally [3], [4] in hybrid systems. To the authors knowledge, polarization-division multiplexing coherent QPSK (PDM-QPSK) has been only once studied experimentally in a hybrid environment [5]. PSBT and DQPSK require a simpler incoherent receiver, but allow for a maximum bitrate of 40 Gbit/s in a DWDM system (channel spacing 50 GHz). On the other hand, PDM-QPSK needs a quite complex coherent receiver and a post-reception digital signal processing (DSP) unit, but allows for very high bitrates (80 Gb/s or 100Gb/s) on the same grid.

The purpose of this work is to compare numerically by means of Monte Carlo simulations the performance of PDM-QPSK and DQPSK in a hybrid scenario and try to determine which one is the most suitable for a system upgrade. We will account

for linear and nonlinear system impairments and will highlight pros and cons of the proposed solutions.

II. SIMULATION SETUP

All the simulations were performed using an internally developed optical transmission simulator. We tested a 5-channel system on a 50 GHz grid that propagates along a dispersion managed (DM) system composed of 20x100 km spans of Teralight™ fiber ($D=8$ ps/nm/km, $\alpha=0.2$ dB/km, $\gamma=1.7$ $\frac{1}{\text{W}\cdot\text{km}}$ @1550 nm) and single mode fiber (SMF, $D=16$ ps/nm/km, $\alpha=0.2$ dB/km, $\gamma=1.3$ $\frac{1}{\text{W}\cdot\text{km}}$ @1550 nm). All the results refer to the central channel. We separately verified that increasing the number of channels does not cause significant variations of performance [3]. The line was composed of 20 identical spans, each comprising transmission and linear compensating fibers, followed by an amplifier with flat gain and a noise figure of 6 dB. Purely linear pre-/post-compensating fibers were inserted before/after the transmission link.

The even channels were always NRZ-OOK modulated at a bitrate of 10 Gb/s (10 Gbaud). The odd channels were in turn 40 Gb/s DQPSK (20 Gbaud), 40 Gb/s PDM-QPSK (10 Gbaud) or 80 Gb/s PDM-QPSK (20 Gbaud). The OOK channels were modulated using pseudo-random binary sequences (PRBS) with different seeds and length 2^9 , while the DQPSK and PDM-QPSK were modulated using a pseudo-random quaternary sequence (PRQS) of length 4^5 . All channels had the same average power and were synchronous at the input of the pre- fiber. We verified that inserting random delays among channels shows very limited impact thanks to the decorrelation induced by pre-compensating and inline fibers. OOK channels were copolarized with one polarization of coherent channels in PDM-QPSK configuration.

The propagation of signal and amplified spontaneous emission (ASE) noise along the fibers was modeled using a variable step-size split step Fourier method (SSFM), that takes into account all linear and non-linear effects, except polarization mode dispersion (PMD). The maximum nonlinear phase rotation per step was $3 \cdot 10^{-3}$ rad which we verified to be small enough for the considered system.

The DQPSK channel was received using a second order supergaussian optical filter with 3-dB bandwidth $2 \times$ baudrate (20 or 40 GHz), followed by a standard receiver and a 5th order Bessel filter with 3-dB bandwidth $0.65 \times$ baudrate (6.5 or 13 GHz) [6]. The PDM-QPSK receiver used the same filters, and was composed of two coherent mixers (one for each polarization), used to combine the signal with the local oscillator,

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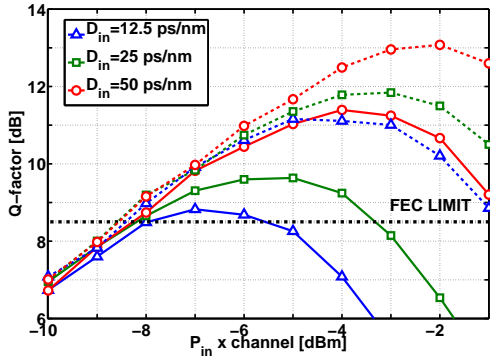


Figure 1. Q-factor vs. P_{in} for DQPSK @ 40 Gb/s with 10G OOK neighboring channels. Dashed lines with SMF fiber, solid lines with Teralight

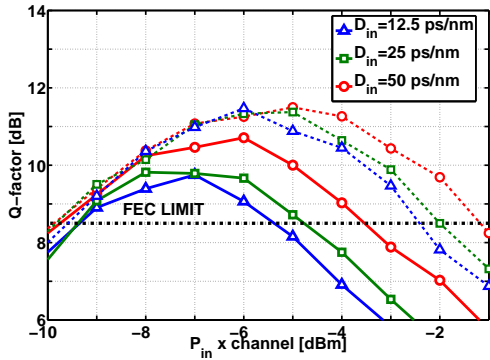


Figure 2. Q-factor vs. P_{in} for PDM-QPSK @ 40 Gb/s with 10G OOK neighboring channels. Dashed lines with SMF fiber, solid lines with Teralight

followed by four balanced photodetectors and the DSP unit. The incoming signal is sampled at twice the symbol-rate and no quantization is performed. The receiver is the same as described in [7], with no digital dispersion compensation.

III. RESULTS AND DISCUSSION

For each configuration, we measured the Q-factor as a function of the average launched power P_{in} , for three different values of residual dispersion per span, $D_{in} = 12.5, 25, 50$ ps/nm and using Teralight [8] and SMF. The Q-factor was computed from Monte Carlo simulations of the bit error rate (BER) in order to account for nonlinear phase noise, which is often neglected [2]. The simulations were stopped when the relative estimation error on BER reached 20% with a Gaussian confidence of 95%, providing in each case at least 100 error counts. The pre-compensating fiber cumulated dispersion was -292, -411 and -649 ps/nm for the three tested D_{in} respectively when using Teralight fiber, and -488, -607 and -844 ps/nm when using SMF. These values were chosen using the “straight line rule” [9]. The dispersion of the post-compensating fiber was optimized for a QPSK transmission using Karhunen-Loève method [6], assuming white noise. Typically the residual total dispersion was close to 0 and in every tested case it was within the range [-40;40] ps/nm.

In such systems, the main nonlinear impairment was found to be the cross phase modulation (XPM) due to 10G OOK

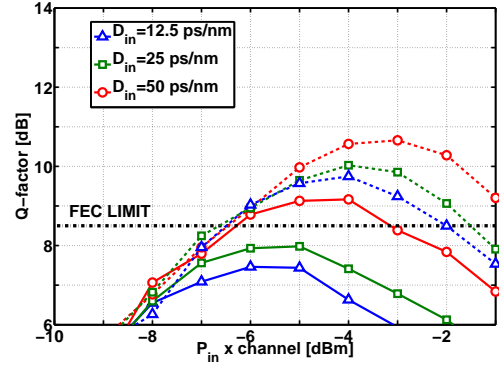


Figure 3. Q-factor vs. P_{in} for PDM-QPSK @ 80 Gb/s with 10G OOK neighboring channels. Dashed lines with SMF fiber, solid lines with Teralight

Table I
IMPROVEMENT OF THE BEST Q-FACTOR [dB] WHEN USING 100 GHz SPACING ON TERALIGHT FIBER

	DQPSK 40G	PDM-QPSK 40G	PDM-QPSK 80G
$D_{in} = 12.5$ ps/nm	1.96	0.78	0.33
$D_{in} = 25$ ps/nm	2.24	1.17	0.24
$D_{in} = 50$ ps/nm	2.12	0.83	0.24

channels on 40G/80G channels [3]. Though not reported here, we ran single channel simulations for DQPSK and 80G PDM-QPSK configurations with Teralight fiber. We verified that cross-channel effects are dominant. Among these, four-wave mixing is negligible because of the sizable in-line dispersion, while switching cross-polarization effects in simulation of PDM-QPSK systems did improve the Q-factor by no more than 0.7 dB over the shown input power range. Hence we conclude that XPM is by far the dominant non-linear effect.

Figs. 1,2,3 sketch the measured Q-factor vs. launched power for the configurations under investigation. The best performance is always obtained with SMF fiber which is not surprising since increasing the dispersion is known to reduce XPM. Also the use of SMF reduces the impact of D_{in} (the Q-factor curves for SMF are closer than for Teralight), thus relaxing the dispersion mapping constraints. From a comparison of Fig. 1 and Fig. 2, we note that the best Q-factor is better for the DQPSK case (~ 0.8 dB with Teralight and ~ 1.5 dB with SMF). 40G PDM-QPSK shows an enhanced optical signal-to-noise ratio (OSNR) sensitivity in the linear region on the left of the maximum Q-factor. On the other hand DQPSK shows a superior nonlinear threshold (NLT, defined as P_{in} per channel @ best Q-factor). Fig. 3 shows that 80G PDM-QPSK suffers from a reduced OSNR sensitivity due to its higher bitrate (~ 3 dB in Q-factor @ $P_{in} = -8$ dBm) and for low values of D_{in} the nonlinear penalties are enhanced, compared to 40G PDM-QPSK. However the NLT is better than 40G PDM-QPSK (~ 2 dB with both fibers). Over such a long distance this configuration cannot offer adequate performance. However with a careful DM (higher values of D_{in}) and on shorter links (1000÷1500 km), PDM-QPSK could be a good candidate for 80G or even 100G channel upgrades.

We also investigated the effect of increasing the channel spacing from 50 to 100 GHz on a Teralight fiber. Table I

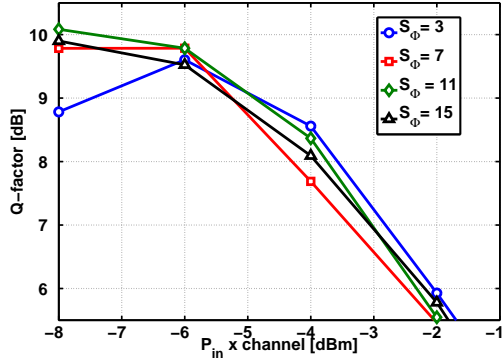


Figure 4. Q-factor vs. P_{in} of PDM-QPSK @ 40 GB/s + OOK, $D_{in} = 25$ ps/nm on Teralight fiber for four different values of S_{Φ}

reports the improvement of the best Q-factor for the considered configurations. As expected the Q-factor is always better at 100 GHz, but this effect is more evident for DQPSK (~ 2 dB) than for 40/80G PDM-QPSK (~ 1 and ~ 0.3 dB, respectively). This is probably due to the fact that increasing the channel spacing doesn't reduce nonlinear depolarization [10].

A possible solution to improve PDM-QPSK robustness against SPM and XPM is to improve the phase estimation algorithm. In our simulations, we used a Viterbi&Viterbi [7]. The number of samples used to average the phase (S_{Φ}) was 7. It is a well-known fact that the value of S_{Φ} has an influence on the quality of the estimation process; high values of S_{Φ} are better in ASE-limited systems, while smaller values are better when non-linear effects arise. Fig. 4 shows the performance of the 40G PDM-QPSK+OOK system, using $D_{in} = 25$ ps/nm and Teralight fiber, for different values of S_{Φ} . $S_{\Phi} = 7$ is near the optimum for low values of P_{in} , but gives a penalty of almost 1 dB for $P_{in} = -4$ dBm. Using smaller values of S_{Φ} (es. 3) could thus reduce the impact of XPM, but could be insufficient to provide a decisive improvement. On the other hand, the DSP unit allows for a suboptimal DM design. Comparing Figs. 1 and 2 for $D_{in} = 12.5$ ps/nm with Teralight fiber, we see that the Q-factor of PDM-QPSK is decreased by 2 dB w.r.t. $D_{in} = 50$ ps/nm, while the Q-factor of DQPSK is 4.5 dB smaller. The enhanced tolerance of PDM-QPSK is due to the constant modulus algorithm (CMA) used at the receiver that acts as a generic adaptive equalizer, thus relaxing the impact of DM [7].

Finally, Fig. 5 shows the NLT as a function of D_{in} using Teralight fiber. These curves are obtained by interpolating the available values of Q-factor vs P_{in} . The NLT always grows for increasing values of $|D_{in}|$, because residual in-line dispersion reduces the dominant XPM impairment. The NLT of 40G PDM-QPSK is the lowest but its value is little dependent on D_{in} (1 dB). On the other hand, the NLT for 40G DQPSK and 80G PDM-QPSK is higher, but it decreases by more than 3 and 2.5 dBm, respectively, at $D_{in} = 0$.

IV. CONCLUSIONS

We provided a numerical Monte Carlo comparison between 40G DQPSK, 40G PDM-QPSK, and 80G PDM-QPSK, three of the best candidates for the deployment of hybrid systems,

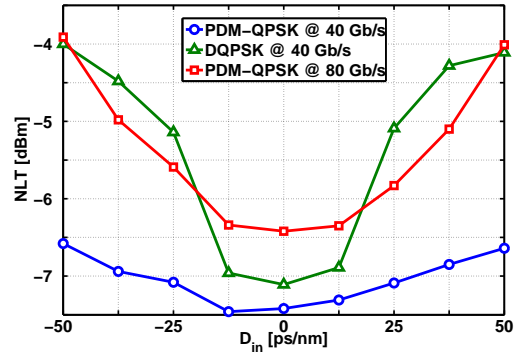


Figure 5. NLT vs. D_{in} of the 3 examined configurations on Teralight fiber

assessing their tolerances against non-linear effects.

PDM-QPSK is a very promising format that will enable to deliver bitrates up to 100 Gb/s per channel. However in order to ensure enhanced tolerance against cross channel non-linear impairments and thus extend the reach, the phase should be carefully estimated. At 40 Gb/s, PDM-QPSK is strongly affected by XPM while, with proper DM design, DQPSK has proven to be the best choice among the considered formats for this bitrate in ultra long haul systems.

V. ACKNOWLEDGMENTS

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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] M. Lefrancois, F. Houndonougbo, T. Fauconnier, G. Charlet, and S. Bigo, "Cross comparison of the nonlinear impairments caused by 10Gbit/s neighboring channels on a 40Gbit/s channel modulated with various formats, and over various fiber types," in *Proc. OFC 2007*, Paper JThA44, 2007.
- [3] S. Chandrasekhar and X. Liu, "Impact of channel plan and dispersion map on hybrid DWDM transmission of 42.7-Gb/s DQPSK and 10.7-Gb/s OOK on 50-GHz grid," *IEEE Photon. Technol. Lett.*, vol. 19, no. 22, pp. 1801–1803, Nov. 2007.
- [4] M. Birk, C. Skolnick, B. Curto, R. Marlieb, T. Schmidt, and R. Saunders, "Field trial of a 40 Gbit/s PSBT channel upgrade to an installed 1700 km 10 Gbit/s system," in *Proc. OFC 2005*, Paper OTuH3, 2005.
- [5] O. Bertran Pardo, J. Renaudier, H. Mardoyan, P. Tran, G. Charlet, and S. Bigo, "Investigation of design options for overlaying 40Gb/s coherent PDM-QPSK channels over a 10Gb/s system infrastructure," in *Proc. OFC 2008*, Paper OTuM5, 2008.
- [6] P. Serena, A. Orlandini, and A. Bononi, "Parametric-gain approach to the analysis of single-channel DPSK/DQPSK systems with nonlinear phase noise," *J. Lightw. Technol.*, vol. 24, no. 5, pp. 2026–2037, May 2006.
- [7] J. Renaudier, G. Charlet, M. Salsi, O. Bertrand Pardo, H. Mardoyan, P. Tran, and S. Bigo, "Linear fiber impairments mitigation of 40-Gbit/s polarization-multiplexed QPSK by digital processing in a coherent receiver," *J. Lightw. Technol.*, vol. 26, no. 1, pp. 36–42, Jan. 2008.
- [8] M. Bertolini, P. Serena, N. Rossi, and A. Bononi, "Numerical Monte Carlo comparison between coherent PDM-QPSK/OOK and incoherent DQPSK/OOK hybrid systems," in *Proc. ECOC2008*, paper P.4.15, 2008.
- [9] Y. Frignac, J.-C. Antona, and S. Bigo, "Enhanced analytical engineering rule for fast optimization dispersion maps in 40 Gbit/s-based transmission," in *Proc. OFC 2004*, Paper OTuN3, 2008.
- [10] S. Bigo, G. Charlet, O. Bertrand Pardo, and J. Renaudier, "Characterization of the impact of non-linear effects in coherent transmission experiments," in *Digest of the IEEE/LEOS Summer Topical Meetings 2008*, July 2008, pp. 125–126.