Numerical Monte Carlo Comparison between Coherent PDM-QPSK/OOK and Incoherent DQPSK/OOK Hybrid Systems

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

Abstract *We asses through Monte Carlo simulations PDM-QPSK/OOK and DQPSK/OOK Hybrid systems performance. DQPSK works better with optimal dispersion-management. PDM-QPSK is more robust to system impairments.*

Introduction

The recent progress in the field of advanced modulation formats allows the design of dense wavelength division multiplexing (DWDM) commercial systems at bitrates of 40Gb/s and higher. A cost effective solution for the deployment of such systems is to selectively upgrade some non-return to zero on-off keying (NRZ-OOK) channels, following the growth of the capacity demand. This scenario is commonly referred to as Hybrid system.

Different formats have been proposed as a candidate for the channel upgrade. Among the others, differential quadrature phase shift keying (DQPSK) and polarization-division multiplexing coherent QPSK (PDM-QPSK) have been studied experimentally [1, 2]. DQPSK is a cheaper solution but allows for a maximum bitrate of 40 Gb/s in a DWDM system with channel spacing of 50 GHz; on the other hand PDM-QPSK is more expensive but allows for much higher bitrates (80 Gb/s or 100Gb/s) on the same DWDM grid.

The purpose of this paper is to compare numerically the performance of PDM-QPSK and DQPSK in a Hybrid scenario and determine which one is the most suitable for a system upgrade. We will focus on linear and non-linear impairments and we will highlight pros and cons of the two solutions.

Simulations

The simulations were performed using an internally developed Matlab$^{\text{TM}}$ toolbox. We tested a 5 channels DWDM comb with 50 GHz spacing that propagates along a dispersion managed (DM) system composed of 20x100 km spans of Teralight$^{\text{TM}}$ fiber (8 ps/nm/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 the performance.

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 were synchronous; OOK channels were copolarized with the X polarization of coherent channels.

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 nonlinear effects, but polarization mode dispersion (PMD). The maximum nonlinear phase per step was $3 \cdot 10^{-3}$ rad. Before/after transmission a pre/post compensating fiber was inserted. The amplifiers along the line were modeled as erbium doped fiber amplifiers (EDFA) with flat gain and a noise figure of 6 dB. The DQPSK channel was received using a second order supergaussian optical filter with bandwidth 2× baudrate, followed by a standard receiver and a 5th order Bessel filter with bandwidth 0.65 × baudrate [3]. The PDM-QPSK receiver used the same filters, and its structure is described in [4].

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. The Q-factor was computed from Monte Carlo simulations of bit error rate (BER) in order to account exactly for nonlinear phase noise, which is often neglected [5]. The simulations were stopped when the relative estimation error on BER reached 20% with a Gaussian confidence of 95%. In each case we counted at least 100 errors. The precompensating fiber cumulated dispersion was -292, -411 and -649 ps/nm for the three tested D_{in}, respectively. The dispersion of the post-compensating fiber (D_p) was optimized for a QPSK transmission using Karhunen-Loève method [3], assuming white noise.

Finally we assed the tolerance of the two different formats to total residual dispersion D_{tot}.

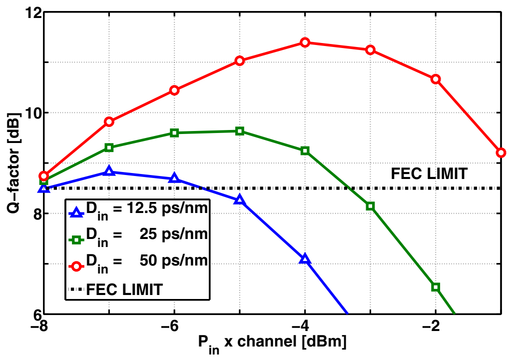

Fig. 1: Q-factor vs. P_{in} for DQPSK @ 40 GB/s + OOK

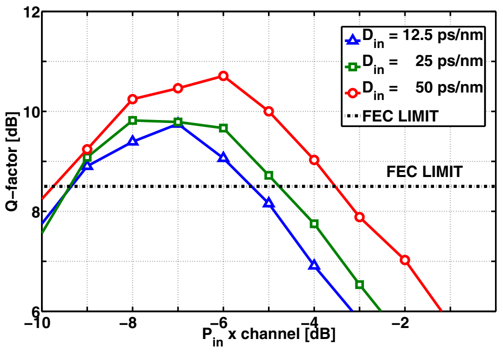

Fig. 2: Q-factor vs. P_{in} for PDM-QPSK @ 40 GB/s + OOK

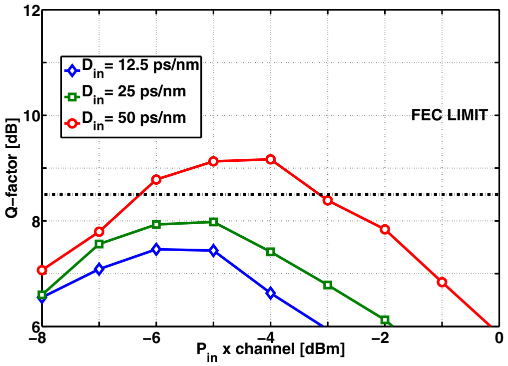

Fig. 3: Q-factor vs. P_{in} for PDM-QPSK @ 80 GB/s + OOK

Results and Discussions

Figs. 1,2,3 sketch the measured Q-factor (Q) vs. launched power for the three different configurations under investigation.

From a comparison of Fig. 1 and Fig. 2, we note that the best Q for the two systems is similar (~ 0.8 dB better for DQPSK). PDM-QPSK shows an enhanced optical signal-to-noise ratio (OSNR) sensitivity in the linear region (Q$=$ 10 vs Q$=$ 8 dB for DQPSK when $P_{in} =$-8 dBm, $D_{in} =$50 ps/nm). On the other hand DQPSK shows a superior nonlinear threshold (P_{in} @ 1 dB of penalty on Q) which is around $P_{in} =$-2 dBm, while for PDM-QPSK is near $P_{in} =$-4.5 dBm. The main nonlinear impairment is known to be cross phase modulation (XPM) due to OOK channels [1, 2].

A possible solution to improve PDM-QPSK robustness against XPM is to use a more effective phase estimation algorithm than the Viterbi&Viterbi averaged on 7 samples we used in this work. However this would have an impact on the load of Digital Signal Processing (DSP) unit at the receiver.

Note that even if DQPSK overcomes PDM-QPSK when $D_{in} = 50$ ps/nm, the opposite occurs when $D_{in} = 12.5$ ps/nm, showing that PDM-QPSK offers good performance also far from optimal DM.

Fig. 3 shows that 80G PDM-QPSK suffers from the reduced OSNR sensitivity due to its higher bitrate (3 dB in Q @ $P_{in} =$-8 dBm). Moreover it shows increased penalties for low values of D_{in}, compared to 40G PDM-QPSK. However with a careful DM and on shorter distances (1000-1500 km), this modulation format could be a very good candidate for 100G system upgrade.

Finally we measured the Q vs. total cumulated dispersion D_{tot}. We tested DQPSK with $P_{in} =$-3 dBm and 80G PDM-QPSK with $P_{in} =$-4 dBm, both with $D_{in} = 25$ ps/nm. Such a configuration leads to comparable nonlinear impairments in both cases. The results are depicted in Fig. 4. PDM-QPSK shows almost no penalties for D_{tot} as large as ± 300 ps/nm using a short FIR filter (16 taps). DQPSK range of tolerance is three times smaller. This suggests that even with limited DSP load, PDM-QPSK still provides a significant robustness to dispersion with respect to DQPSK.

Conclusions

We provided a numerical Monte Carlo comparison between three of the best candidates for the deployment of Hybrid systems, assessing their tolerances against both linear and 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 estimation should be improved.

With careful DM design DQPSK has proven to be a better choice for bitrates of 40 Gb/s, also for ultra long haul systems. However typical DM in OOK systems (relatively low D_{in}), causes severe penalties on DQPSK, while is more suitable for PDM-QPSK. This is mainly due to the equalizing properties of the DSP unit in the coherent receiver

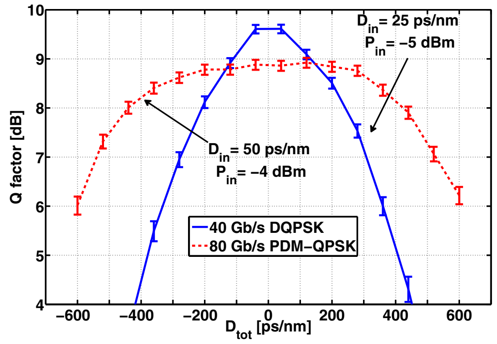

Fig. 4: Tolerance against total cumulated dispersion of coherent and noncoherent systems

Acknowledgments

This work was supported by Alcatel-Lucent Bell Labs. The authors would like to thank G. Charlet and M. Salsi for the fruitful discussions.

References

1. S. Chandrasekhar et al., PTL **19** (2007), p. 1801
2. O. Bertrand Pardo et al., OFC 2008, OTuM5
3. P. Serena et al., JLT **24** (2006), pp. 2026-2037
4. J. Renaudier et al., JLT **26** (2008), pp. 36-42
5. M. Lefrançois et al., OFC 2007, JThA44