NONLINEAR POLARIZATION EFFECTS IN A HYBRID 100Gb/s PDM-QPSK — 10Gb/s OOK SYSTEM

D. Sperti, P. Serena, A. Vannucci, A. Bononi
Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Parma
v.le G.P.Usberti 181/A, 43124 Parma, Italy. Email: donato.sperti@nemo.unipr.it

In a network upgrade scenario, we numerically investigate cross-channel polarization-sensitive nonlinear effects induced by "legacy" OOK channels on an "upgraded" RZ-PDM-QPSK channel. The impact of WDM channel spacing and state-of-polarization on the cross effects is investigated.

1. Introduction

The increasing demand for capacity requires upgrading the current 10Gb/s Wavelength Division Multiplexed (WDM) networks to 100Gb/s. The coherent Polarization-Division-Multiplexed Quadrature Phase Shift Keying (PDM-QPSK) solution is a promising candidate to this aim. Thanks to a high spectral efficiency and a remarkable resilience against Polarization Mode Dispersion (PMD) and Group Velocity Dispersion (GVD), it offers the advantage of increasing the total system capacity without incurring performance degradation due to a wider spectrum. However, optical cross-channel nonlinear effects can strongly impair PDM-QPSK channels [1].

One possible upgrading scenario can be the progressive insertion of several 100Gb/s PDM-QPSK "upgraded" channels into an infrastructures originally designed for "legacy" non-return-to-zero (NRZ) OOK channels at 10Gb/s, with a dense channel spacing (50 GHz), relying on dispersion management. In such a *hybrid system*, the performance of the upgraded channel is degraded by the penalties induced by legacy channels through cross-channel nonlinear effects. These penalties are both of scalar and vectorial nature: namely, Cross-Phase Modulation (XPM) and Cross-Polarization Modulation (XPolM). In the last few years, several works have appeared in the literature [2,3], demonstrating how cross-channel effects are enhanced on such hybrid systems.

We wish to investigate, by numerical simulation, the dependence of XPM and XPolM on the WDM bandwidth spacing and on the State Of Polarization (SOP) of OOK interfering channels. In particular, we want to find the best and worst SOPs, i.e., those for which the dependence of performance on channel spacing, as pointed out in [3], is minimized.

2. Cross-Channel Polarization-Sensitive Nonlinear Effects

The propagation of an optical field $\vec{A}(z,\tau)$ (in its time-reference τ) inside a randomly birefringent optical fiber with Kerr nonlinearity and negligible PMD, is usually dealt with the simplified Manakov-PMD equation

$$\frac{\partial \vec{A}}{\partial z} + \frac{\alpha}{2}\vec{A} - \frac{i}{2}\beta_2 \frac{\partial^2 \vec{A}}{\partial \tau^2} + i\frac{\Delta\beta_0(z)}{2}\left(\vec{l}(z)\cdot\vec{\sigma}\right)\vec{A} = -i\gamma\frac{8}{9}\left|\vec{A}\right|^2\vec{A} \tag{1}$$

where (besides the usual symbols for scattering loss, chromatic dispersion and nonlinear coefficient) $\Delta\beta_0(z)$ and $\vec{l}(z)$ are the birefringence strength and orientation in Stokes space (we use lower-case letters for Stokes vectors and capital letters for Jones vectors), both varying along the fiber, while $\vec{\sigma}$ is the *spin-vector*.

In a DWM transmission, $\vec{A}(z,\tau) = \sum_k \vec{A}_k(z,\tau_k)\exp^{i\Delta\omega_k\tau}$ is a sum of fields with frequency offsets $\Delta\omega_k$ and variable delays, included in τ_k, induced by channel walk-off due to GVD. The propagation equation for each n-th channel, in its time reference, has the same linear terms (left hand side) as (1), while the nonlinear term (right hand side of

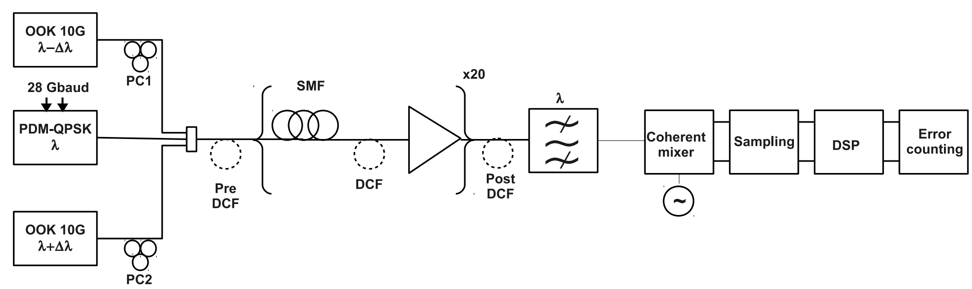

Fig. 1: System Setup of the hybrid PDM-QPSK — OOK transmission.

(1)), neglecting Four Wave Mixing (FWM), is

$$-i\gamma\frac{8}{9}\left[\left|\vec{A}_n\right|^2+\sum_{k\neq n}\left|\vec{A}_k\right|^2+\sum_{k\neq n}\vec{A}_k\vec{A}_k^\dagger\right]\vec{A}_n=-i\gamma\frac{8}{9}\left[\left(A_n^2+\frac{3}{2}\sum_{k\neq n}A_k^2\right)\sigma_0+\frac{1}{2}\sum_{k\neq n}\left(\vec{a}_k\cdot\vec{\sigma}\right)\right]\vec{A}_n \tag{2}$$

where σ_0 is the identity matrix, $\vec{a}_k$ the Stokes vector associated with $\vec{A}_k$ and A_k^2 its intensity. From (2), Kerr effect has an impact both on the phase of $\vec{A}_n$, since the terms associated with σ_0 produce SPM and XPM, and on its polarization, since the term associated with $\vec{\sigma}$ produces XPolM. When all signals $\vec{A}_k$ have the same polarization as $\vec{A}_n$, XPolM is absorbed by the XPM term, yielding the usual factor 2 that characterizes scalar propagation.

All WDM signals $\vec{A}_k$ obey a similar equation, whose nonlinear term is as in (2), and, at the same time, they *walk-off* each other due to GVD. In the absence of walk-off, a *pivot* vector $\sum_k \vec{a}_k$ exists, which is constant along the fiber, and the SOP of each channel rotates around it in Stokes space [6]. Walk-off breaks this picture. As is known [4], walk-off reduces the impact of XPM, so that it is possible to define a *walk-off window* $\Delta\omega_{wo}$, which plays the role of *effective WDM interfering bandwidth*, as seen by the channel under consideration: channels with frequency spacing $\Delta\omega_k > \Delta\omega_{wo}$ produce negligible degradation on $\vec{A}_n(z,\tau)$. A similar effect is expected for XPolM, but with a larger window [3], although it is not well understood, in the literature, how large this bandwidth is, nor how it depends on the lauched signal SOPs. We want to investigate this issue in the hybrid PDM-QPSK — OOK system described hereafter.

3. System Setup

In the system setup in Fig. 1, we transmit a reference 112Gb/s (100Gb/s plus FEC overhead) RZ-PDM-QPSK channel, with 50% duty cycle and mean power -1 dBm, surrounded by two 10Gb/s NRZ-OOK channels, with mean power 4 dBm and whose equal spacing $\Delta\lambda$ is varied from 0.4 nm to 25 nm. In fact, for fixed channel spacing, the number of channels required to estimate the performance depends on the walk-off window [3]. Instead, we use here only two OOK channels with variable spacing, in order to estimate $\Delta\omega_{wo}$ with faster simulations. The optical link is made by 20 spans of 100km Single Mode Fiber, with dispersion management including pre- and post-compensation fibers, with zero total dispersion. Fiber birefringence is modelled by 50 discrete random waveplates per span, with zero PMD. The propagation, through the coupled nonlinear Schroedinger equation, is solved with the Split Step Fourier Method, neglecting FWM. The PDM-QPSK signal is detected by means of a coherent receiver, with a noise-figure of 20 dB, and performance is estimated in terms of the Q-factor. Each simulation is repeated 25 times, in order to correctly sample the variability due to random symbol pattern, fiber birefringence, and launched signals SOPs. All simulations were performed with the open source software Optilux, develped by our research

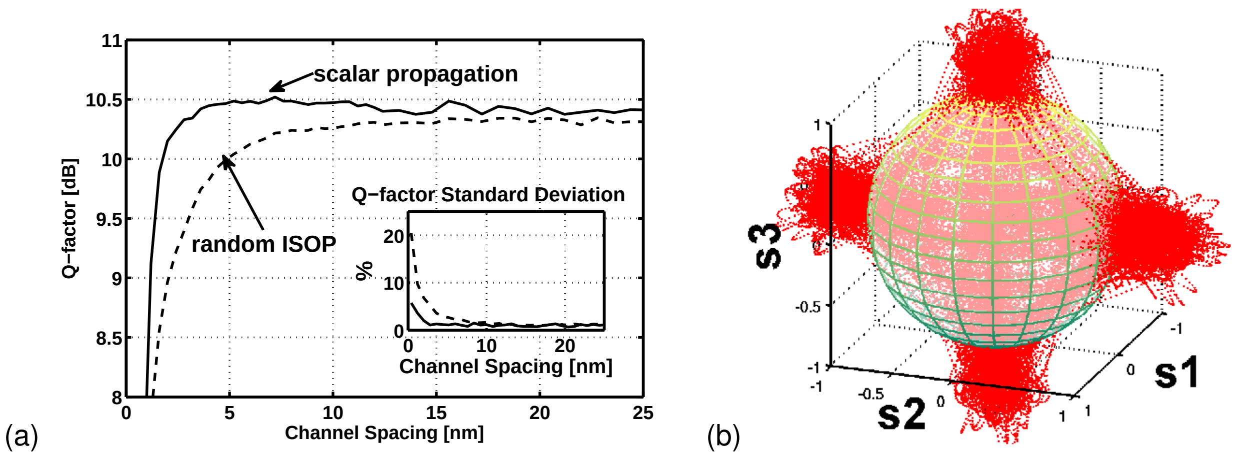

Fig. 2: (a) Average Q-factor vs channel spacing: scalar propagation and vectorial propagation with random OOK ISOPs; (b) PDM-QPSK: SOP trace of time samples.

group [5].

4. Simulation Results

To clarify the reasons behind the assertions of [3], we first compare the performance of single polarization QPSK and PDM-QPSK. In the first case, we align the polarizations of QPSK and OOK channels: hence, XPM is the same as in scalar propagation, while XPolM is nullified. For the PDM scenario, instead, XPolM is always present. We set the SOP of each OOK channel randomly, which corresponds to a system without polarization control at the transmitter. Fig. 2(a) depicts the average Q-factor vs. channel spacing, for both single polarization QPSK (labelled "scalar propagation") and PDM-QPSK ("random ISOP"). Results confirm that, as stated in Sec. 2, the case including XPolM (PDM-QPSK) experiences a larger $\Delta\omega_{wo}$, since the curve saturates after the QPSK case (XPM only). In the inset, we also note a larger statistical fluctuation, because of the dependence of XPolM on the SOPs orientation.

In order to better understand the impact of OOK polarization on XPolM, we now control their SOP with three different configurations: i) all SOPs are linear horizontal ($\hat{s}_1$, in Stokes space); ii) all SOPs are linear $45°$ ($\hat{s}_2$); iii) all SOPs are right-circular ($\hat{s}_3$). Choosing a common SOP for all OOK channels represents a worst case for XPolM. In all cases, the transmitted PDM-QPSK signal employs subcarriers with linear horizontal and vertical polarizations ($\pm\hat{s}_1$), so that the SOPs of its time samples are those shown on the Poincarè sphere in Fig. 2(b). For each of the three configurations above, the average Q-factor vs. channel spacing is shown in Fig. 3(a), where the scalar case is reported from Fig. 2(a) for comparison. When the OOK polarization is oriented along $\hat{s}_2$ or $\hat{s}_3$, performance experiences the largest dependence on channel spacing, and the curve saturates approximately after 15 nm ($\Delta\omega_{wo}$). Note that these two cases yield a similar Q-factor, which is in turn very similar to the random SOP case reported in Fig. 2(a). On the contrary, when the OOK signals are aligned with $\hat{s}_1$, the Q-factor takes its best value, which is in turn very close to the case of scalar propagation.

Given the dependence of performance on OOK channels polarization, we now test all possible SOP orientations, at a fixed $\Delta\lambda = 1.2$ nm. Fig. 3(b) reports the measured Q-factor, on the Poincaré sphere, as a function of the common OOK SOP. Most of the sphere shows a Q-factor similar to the worst case, in agreement with the fact that the average Q-factor shown in Fig. 2(a) (random case) is very close to the worst cases in Fig. 3(a) (SOPs $\hat{s}_2$,$\hat{s}_3$). In addition, results confirm that aligning the OOKs along $\hat{s}_1$ is the best choice. The impact of XPolM is thus minimized when the interfering OOK channels have the same polarization as one of the two PDM subchannels ($\hat{s}_1$). This

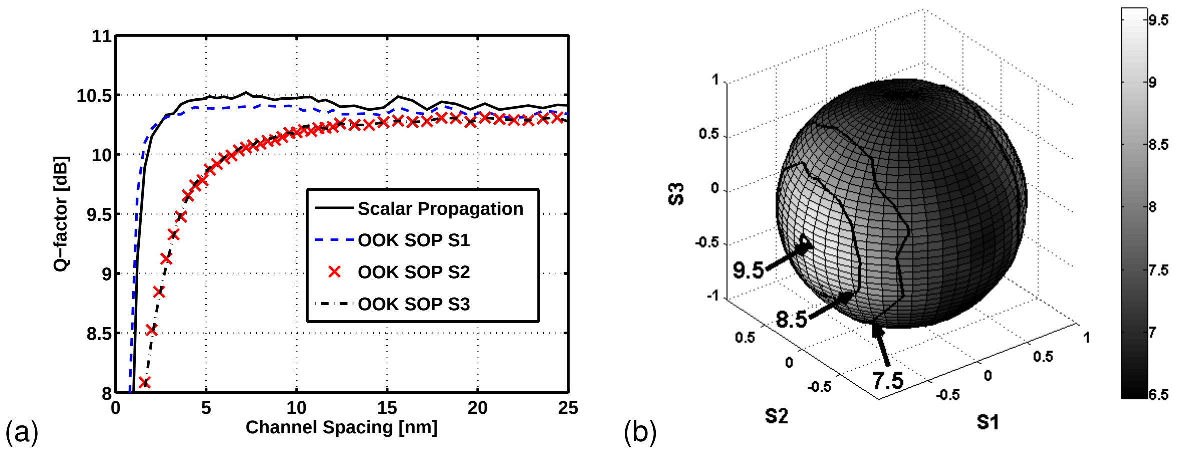

Fig. 3: Average Q-factor vs channel spacing in Scalar and Vectorial Propagation (OOK SOPs: $\hat{s}_1, \hat{s}_2, \hat{s}_3$) (a), Q-factor vs variable OOK SOP orientation (b).

result is noteworthy, since it is known that in an homogeneous OOK WDM system, channels should have alternate-orthogonal polarizations, to minimize XPM [6]. Recalling that the PDM-QPSK channel has the SOP reported in Fig. 2(b), an explanation of this result is that $\hat{s}_1$ is orthogonal (in Stokes) to the SOP of any time sample of the PDM-QPSK signal, thus inducing, through XPolM, a similar average rotation on all symbols. The worst case is when the polarization of OOK lies on the ($\hat{s}_2$,$\hat{s}_3$) plane, where the angle between the OOK SOP and the SOPs of the PDM-QPSK strongly differs from sample to sample, a situation where XPolM is maximum.

5. Conclusions

In a hybrid PDM-QPSK — OOK system, the performance of the *upgraded* PDM channel is often set by cross-channel polarization-sensitive nonlinear impairments induced by *legacy* OOK channels. We numerically investigated the dependence of such impairments on the polarization of legacy channels, showing that the *effective WDM interfering bandwidth* (*walk-off window*) strongly varies with their SOP, since XPolM enhances the impact of “far” channels. In the worst case of co-polarized interferers, we analized all SOP configurations, and found the polarizations that minimize the effect of cross-channel nonlinearities.

Bibliography

[1] G. Charlet, “Coherent detection associated with digital signal processing for fiber optics communication ”, C. R. Physique 9 (2008), Dec. 2008, pp 1012-1030.
[2] O. Bertran-Pardo et al. “Nonlinearity Limitations When Mixing 40-Gb/s Coherent PDM-QPSK Channels With Preexisting 10-Gb/s NRZ Channels”, IEEE Photon. Technol. Lett., Vol. 20, N. 15, Aug. 2008, pp. 1314-1316.
[3] J. Renaudier et al., “On the Required Number of WDM Channels When Assessing Performance of 100Gb/s Coherent PDM-QPSK Overlaying Legacy Systems”, ECOC 2009, Wien (Austria), Sep. 2009.
[4] A. Bononi et al., ”Cross-Phase Modulation Induced by OOK Channels on Higher-Rate DQPSK and Coherent QPSK Channels”, J. Lightw. Technol., Vol. 27, N. 18, Sep. 2009, pp. 3974-3983
[5] P. Serena et al., *Optilux - an open source of light*, http://optilux.sourceforge.net/
[6] A. Bononi et al., ”Degree of Polarization Degradation Due to Cross-Phase Modulation and Its Impact on Polarization-Mode Dispersion Compensators”, J. Lightw. Technol., Vol. 21, N. 9, Sep. 2003, pp. 1903-1913.