XPM reduction in hybrid 10G/40G transmission using 10-Gb/s narrow-filtered DPSK modulation

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Abstract: We propose a possible improvement for optical hybrid transmission systems, based on 40G differential quadrature shift Keying (DQPSK) and 10G differential phase shift keying (DPSK) received by means of a Gaussian narrow filter. We report a reduced cross phase modulation (XPM), at the cost of a slightly more complex setup. This technique is especially effective for systems with low inline dispersion and offers similar performances on different types of fiber.

OCIS codes: (060.2330 Fiber optics communications); (060.5060 Phase modulation); (190.3270 Kerr effect);

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1. Introduction

The increase in the capacity demand requires an upgrade of existing 10 Gb/s on-off keying (OOK) wavelength division multiplexing (WDM) systems. To make this improvement cost effective, one should be able to increase the bitrate of some selected channels to 40 Gb/s or more, according to the traffic requirements. A possible solution for the upgrade is to resort to advanced modulation formats [1]. Systems characterized by two or more different modulation formats and possibly data rates are often called *hybrid*.

Differential quadrature phase shift keying (DQPSK) is considered one of the most suitable modulation formats for high-bitrate channels in hybrid systems, because of its reduced spectral width and higher polarization mode dispersion tolerance w.r.t. binary formats at the same bitrate [1]. However many studies, both simulative [2] and experimental [3], proved that DQPSK performance is strongly limited by the cross phase modulation (XPM) of neighboring OOK channels. A proposed solution is to turn off OOK channels next to DQPSK ones [3]. This is suboptimal, since it i) reduces the maximum capacity, ii) requires an accurate channel planning and iii) limits the degree of freedom in channel allocation.

In this paper we propose to change the modulation format of the 10 Gb/s OOK channels located next to 40 Gb/s channels to differential phase shift keying (DPSK), and to receive them using a narrow optical filter (narrow filter DPSK, NF-DPSK) [4–6]. The rationale is that DPSK is an almost constant amplitude format and thus the XPM generated on the DQPSK channels should be reduced. On the other hand one may fear that inter-channel nonlinear phase noise [7] (NLPN), i.e. the XPM generated by the amplitude noise of DPSK channels on the 40G channels, could be the dominant impairment. Numerical Monte Carlo (MC) simulations accounting for NLPN are carried out to support our proposal. This work extends and complements the results presented in [8].

2. Setup and simulation parameters

Before focusing on the parameters used in the simulations, we will describe the necessary modifications in the transmitter and receiver to upgrade OOK channels to NF-DPSK. At the transmitter, a DPSK electronic precoder must be added and the bias of the Mach-Zehnder modulator must be set to the null point: the drive voltage can be doubled or left unaltered (V_π, instead of $2 \times V_\pi$), since it gives only a small penalty on performance [9] which is easily compensated by the improved sensitivity of NF-DPSK. This gain is due to the narrow optical filter employed at the receiving side which is very effective in rejecting the amplified spontaneous emission noise [5]. The best filter is Gaussian shaped with bandwidth $\simeq 0.65\times$baudrate [6]. The filter is very narrow, thus wavelength tracking must be put in place to cope with the drift of the laser over the whole lifespan. The proposed solution requires to replace 10G linecards; this is an additional cost, but the components are very similar to those used in OOK linecards and thus the upgrade cost should be limited. Moreover, if upgraded 40G channels are packed together, only the two OOK linecards next to the 40G channels block should be replaced by NF-DPSK linecards.

We now discuss the numerical setup of the hybrid system, whose scheme is depicted in Fig. 1. All the simulations were performed using an internally developed Matlab™ toolbox. The system under test was composed of 5 channels, with 50 GHz spacing, launched over a link comprising a pre-compensating fiber, a variable number of identical spans and a post-compensating fiber before the receiver. Each span was the concatenation of a transmission fiber (either Leaf™ or Teralight™), a compensating fiber and an amplifier. The odd channels were always DQPSK modulated at 40 Gb/s (20 Gbaud) with full drive voltage ($2 \times V_\pi$) using a pseudo random quadrature sequence of length 4^5, while the even ones were in turn OOK or NF-DPSK modulated using a pseudo random binary sequence of length 2^9. All the results refer

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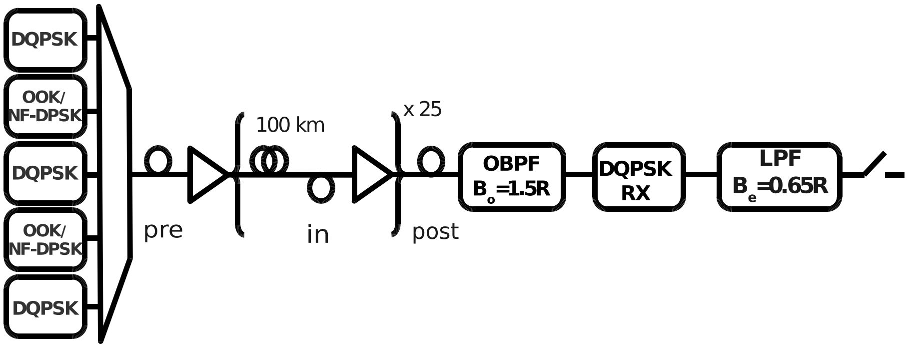

Fig. 1. Schematic of the simulated system.

to the central (DQPSK) channel. We separately verified that increasing number of channels does not significantly impact the performance. The propagation was modeled using a variable step-size split step Fourier method, accounting for all linear and non linear impairments but polarization mode dispersion. The maximum nonlinear phase rotation per step was 3×10^{-3} rad. The amplifiers along the line had flat gain and a noise figure of 6 dB.

3. White noise analysis

Initially we tested both hybrid configurations by simulating transmission over 25×100 km spans of Leaf™ fiber (loss $\alpha = 0.2$ dB/km, dispersion $D = 4$ ps/nm/km @ 1550 nm, slope $S = 0.085$ ps/nm^2 /km, effective area $A_{\text{eff}} = 72\ \mu\text{m}^2$, nonlinear coefficient $n_2 = 2.7 \times 10^{-20}$ m^2 /W) or Teralight™ fiber ($\alpha = 0.2$ dB/km, $D = 8$ ps/nm/km @ 1550 nm, $S = 0.058$ ps/nm^2 /km, $A_{\text{eff}} = 65\ \mu\text{m}^2$, $n_2 = 2.7 \times 10^{-20}$ m^2 /W) and measuring the sensitivity penalty (SP) vs. back to back at bit error rate (BER) 10^{-5} as a function of both the average launched power per channel P_{in} and the in-line residual dispersion per span, D_{in} . The dispersion of the pre-compensating fiber was chosen using the rule in [10], while the overall cumulated dispersion was optimized in the range [-600;600] ps/nm, by acting on the post-compensating fiber.

The BER of the central DQPSK channel 3 was computed using Karhunen-Loéve (KL) method [11], thus assuming noiseless transmission and a noisy amplifier before the receiver, yielding the same amount of noise as 25 amplifiers. These semi-analytical simulations were very fast, enabling the exploration of a wide parameters range, but assumed that the noise at the receiver is white, i.e. the effect of NLPN was not taken into account.

Figure 2 depicts the contour plots of SP vs. P_{in} and D_{in}. When the even channels are OOK modulated (top), for values of $|D_{\text{in}}|$ up to $\simeq 50$ ps/nm the performance is heavily degraded. When we use NF-DPSK (bottom), this range is strongly reduced. For the Leaf™ case (bottom left), there is a negligible penalty for $P_{\text{in}} \leq -3$ dBm, while for higher values of P_{in} the penalty diverges only when $|D_{\text{in}}| \leq 20$ ps/nm. Moreover, even for higher values of D_{in}, NF-DPSK still shows a gain of $\simeq$1 dB in SP. The results obtained for the Teralight™ case (bottom right) are very similar to the Leaf™ case, except for a larger penalty around $D_{\text{in}} \simeq 0$ ps/nm, even at low values of P_{in}. This behavior clearly shows that the main nonlinear impairment is XPM. What happens is that the power variations of OOK channels induce phase shifts on the DQPSK channel through XPM, thus distorting the DQPSK phase, i.e. the carried information. On the other hand, NF-DPSK features a more constant amplitude in comparison to OOK, so that the XPM induced phase rotation is almost constant and can be in part canceled by the differential decoding.

We also repeated these simulations using either 10G OOK or NF-DPSK on odd channels and

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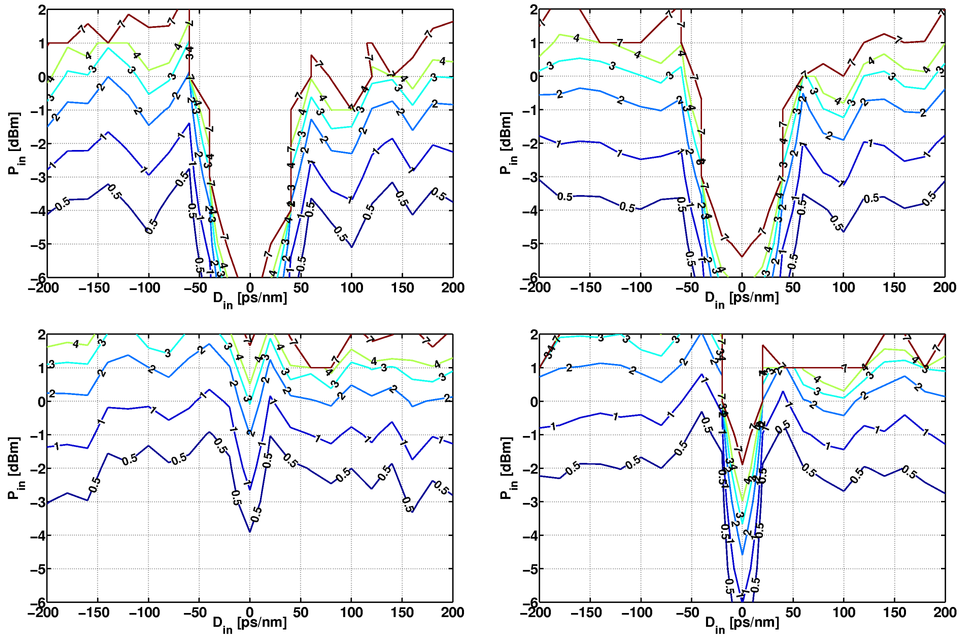

Fig. 2. Sensitivity penalty [dB] vs. P_{in} and D_{in} for the central (3rd, DQPSK) channel over a Leaf (left) or a Teralight (right) fiber. Channels 1, 3, 5 are DQPSK. Channels 2, 4 are OOK (top) or NF-DPSK (bottom).

40G DQPSK on the even ones and measured the performance of the central channel 3. Both configurations yield similar BER and negligible penalties, thus we can conclude that the system reach is limited only by 40G DQPSK channels, while 10G channels pose no design issues.

4. Nonlinear phase noise impact

To account exactly for NLPN, we next simulated a 25 × 100 km system in both OOK and NF-DPSK configurations, using noisy amplifiers along the line. We measured the Q-factor of the central DQPSK channel vs. P_{in}, for four different values of D_{in} (12.5, 25, 50, 100 ps/nm) and for two different types of transmission fiber, (Leaf™ and Teralight™). Again, the dispersion of the pre-compensating fiber was chosen using the rule in [10], while the post-compensating fiber was such that the total cumulated dispersion was 0. The Q-factor was derived from the BER computed using the standard MC algorithm. The simulations ended when the relative error on the estimated BER reached 20% with a Gaussian confidence of 95%. At least 100 errors were counted for every estimated BER value.

Figure 3 shows the Q-factor as a function of P_{in} for the four different values of D_{in} on both fibers. When comparing curves at the same D_{in}, the performance of the reference signal of the hybrid DQPSK/NF-DPSK system is better by at least $\simeq$2 dB than the DQPSK/OOK one, for values of in-line dispersion up to 50 ps/nm. For higher values, neighboring NF-DPSK and OOK channels give similar impairments. Also note that the dependence of the performance on the value of D_{in} is clearly stronger in the OOK case.

Focusing on the case of Leaf fiber (top), we can say that, provided that the value of D_{in} is larger than 25 ps/nm, the system with NF-DPSK channels works close to its optimum. This constraint is further relaxed employing fibers with higher D, like Teralight™ (bottom). When

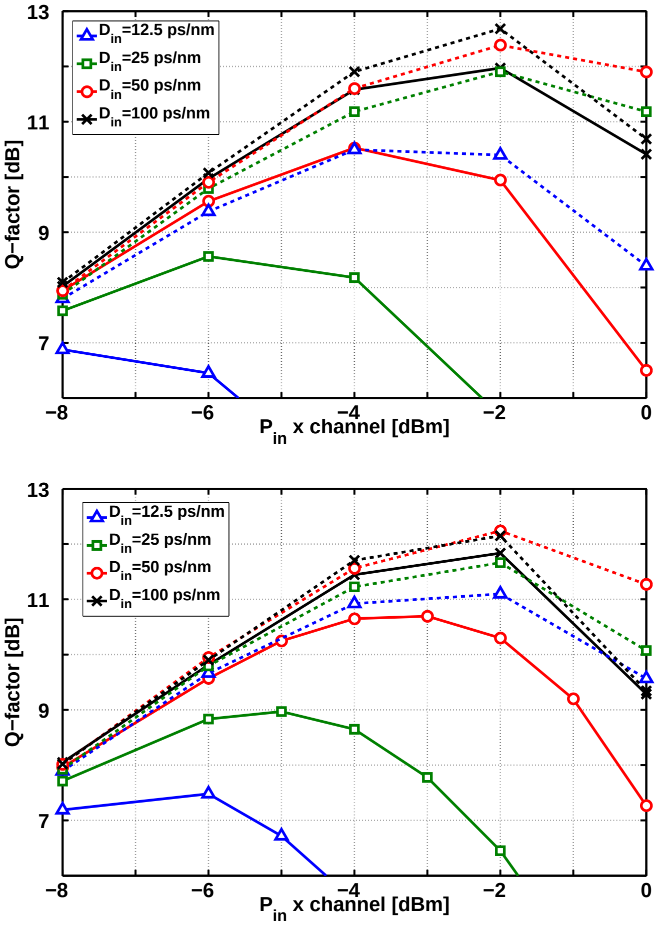

Fig. 3. DQPSK Q-factor vs. P_{in} for four values of D_{in} on Leaf™ (top) or Teralight™ (bottom) fiber. Even channels OOK (solid lines) or NF-DPSK (dashed lines).

using OOK, instead, the value of D_{in} must be at least 100 ps/nm to provide the same results, no matter the type of fiber used. It is worth to notice that at D_{in} =100 ps/nm, NF-DPSK and OOK provide very similar performance over almost the whole considered range of powers. This evidence suggests that when using this dispersion management, the inter-channel effects are well suppressed.

Finally, we want to clarify the role of NLPN and how its effect compares with that of XPM. We thus repeated the simulations of Fig. 3, by fixing the average input power P_{in} to -2 dBm and extending the study to the following values of D_{in}: -100, -50, -25, -12.5, 0, 12.5, 25, 50, and 100 ps/nm. We isolated the impact of NLPN by computing the BER with MC (NLPN “on”) and KL (NLPN “off”) methods. Fig. 4 shows the DQPSK central channel Q-factor vs. D_{in} for DQPSK/NF-DPSK (circles) and DQPSK/OOK (squares) both computed using MC (solid) and KL (dashed) algorithms. The difference between the MC and KL curves is the NLPN penalty. This penalty is stronger for positive values of D_{in} . When neighboring channels are OOK, the penalty is almost negligible since the effect of XPM is largely dominant; when using NF-DPSK channels, the NLPN causes a slightly larger penalty and it can become the dominant impairment

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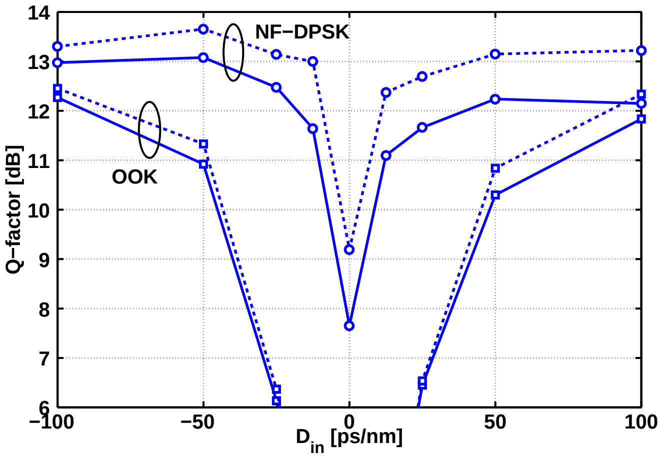

Fig. 4. DQPSK Q-factor vs. D_{in} @ P_{in}=-2 dBm on a Teralight™ fiber. Even channels OOK (squares) or NF-DPSK (circles). Solid lines with NLPN, dashed lines with white noise.

since the effect of XPM is strongly reduced.

Summarizing, the amplitude of NF-DPSK is more constant than the amplitude of OOK and produces a more constant XPM phase shift on the DQPSK signal, which the differential receiver can partially cancel. At the same time NLPN cannot be removed at the receiver because it generates almost independent phase shifts on neighboring bits. Moreover NLPN acts on every bit because the power of the NF-DPSK signals is never null. However the overall balance is in favor of NF-DPSK, since the XPM penalty is higher than the NLPN penalty.

5. Conclusion

Upgrading 10 Gb/s OOK channels to NF-DPSK requires to replace some 10G linecards, but proves to be a viable alternative for the upgrade of deployed WDM systems. For the implementation of the proposed scheme, a narrow optical filter with a 3-dB bandwidth of about 6.5 GHz is needed at the receiver and the laser frequency drift needs to be limited (e.g., to within $\sim$2 GHz), thus requiring wavelength tracking. The slightly more complex setup is compensated for by a largely reduced XPM, which is the main impairment in such hybrid systems for D_{in} as high as 100 ps/nm. NF-DPSK is thus a good option for deployed system with low D_{in}, where the influence of XPM increases dramatically.

For higher values of this key parameter (D_{in}) OOK gives acceptable performance, making the upgrade unattractive. However, for a wide range of D_{in} (e.g., $|D_{\text{in}}| < 100$ ps/nm), even with the consideration of the inter-channel NLPN induced on DQPSK channels, the DQPSK performance improves when the 10G OOK channels are converted to NF-DPSK.

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