On the XPM-induced distortion in DQPSK-OOK and Coherent QPSK-OOK Hybrid Systems

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Abstract: We prove that the phase estimation process makes coherent QPSK more vulnerable than DQPSK to the XPM induced by 10G-OOK channels. A novel sensitivity penalty formula is presented and verified against simulations.

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1. Introduction

Spectrally efficient modulation formats are a promising solution for upgrading optical systems towards large capacity links. Among them, special attention has been devoted to quadrature phase shift keying (QPSK)-based formats, like non-coherent differential-QPSK (DQPSK) and coherent QPSK. To make the upgrade cost-effective, only a few channels of the wavelength division multiplexing (WDM) grid may be upgraded, depending on capacity demand. The market demand for hybrid configurations based on QPSK signals and standard 10 Gbit/s on-off keying (OOK) is expected to grow in the next years. Such a hybrid configuration has been studied both experimentally [1], and numerically [2, 3], showing that cross-phase modulation (XPM) is the limiting impairment on the phase modulated signals in the nonlinear regime. However, little theoretical insight about XPM distortions is available.

In this work we fill the gap by explaining and demonstrating analytically why the impact of XPM on QPSK signals decreases when their baudrate increases, being largest at 10 Gbaud. The reason is traced back to the differential phase estimation, and not to the walk-off [3]. In the analysis we extend a well-known small signal model for predicting the XPM variance [4] and provide novel sensitivity penalty expressions for both DQPSK and coherent QPSK.

2. Theory

Following the work in [5, 6], the bit-error rate (BER) of a DQPSK/QPSK system can be evaluated as:

$$\mathrm{BER} = \frac{3}{8} - C\rho^{k/2}e^{-\frac{k\rho}{2}}\sum_{m=1}^{\infty}\left[I_{\frac{m-1}{2}}\left(\frac{\rho}{2}\right) + I_{\frac{m+1}{2}}\left(\frac{\rho}{2}\right)\right]^k \frac{\sin\left(m\frac{\pi}{4}\right)}{m} e^{-\left(\frac{m^2}{2}\mathrm{Var}[\Delta\Phi]\right)} \tag{1}$$

where: ρ is the signal-to-noise ratio; I_m is the modified Bessel function of order m; Var $[\Delta\Phi]$ is the variance of the Gaussian nonlinear phase distortion induced by XPM; $k = 1$ and $C = \frac{1}{2\sqrt{\pi}}$ for QPSK, while $k = 2$ and $C = 1/4$ for DQPSK. From (1) we find that an excellent fit of the sensitivity penalty w.r.t. back-to-back at BER=$10^{-3} \div 10^{-9}$ is:

$$\mathrm{SP}\ [\mathrm{dB}] \cong -N_1 \log_{10}\left(1 - \rho_{b2b} N_2 \mathrm{Var}\left[\Delta\Phi\right]\right) \tag{2}$$

where ρ_{b2b} is the signal to noise ratio in back-to-back, $N_1 = 8.5$ and $N_2 = 1$ for DQPSK, while $N_1 = 7.3$ and $N_2 = 1.75$ for QPSK. From (2), the sensitivity penalty can be evaluated once the variance of the phase is known. A fast and accurate approach to estimate the XPM-induced phase variance can be based on the small-signal approach taken in [4] for estimating the XPM-intensity distortion, that here we adapt to phase-distortion. Such a model gives the following XPM variance for a QPSK-based channel surrounded by OOK channels:

$$\mathrm{var}\left[\Delta\Phi\right] = \sum_{p=1}^{M}\int_{-\infty}^{\infty} S_p(f)\left|H_{IM-PM,p}(f)\right|^2\left|H_D(f)\right|^2\left|H_E(f)\right|^2 df \tag{3}$$

where M is the number of neighboring channels, $S_p(f)$ is the power spectral density of the p-th OOK interfering channel, $H_E(f)$ is the transfer function of the electrical lowpass filter, $H_D(f)$ is the transfer function of the phase

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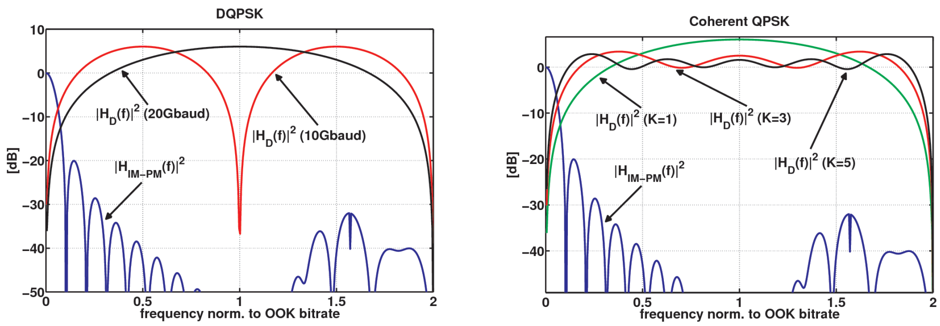

Figure 1. Frequency response of the main building blocks $\left|H_{IM-PM,1}(f)\right|^2$ and $|H_D(f)|^2$of XPM variance (3). Left: $H_D(f)$ for DQPSK at 10 and 20 Gbaud; Right: $H_D(f)$ for coherent QPSK at 20 Gbaud by varying the number of phase estimation samples K. SMF fiber, 50 GHz spacing (more DM parameters in text).

detector (see next), $H_{IM-PM,p}(f)$ is the small-signal filter describing the intensity to phase conversion of XPM due to channel p. Such a filter can be inferred following the same steps of [4] but applied to the phase distortion instead of the intensity distortion. For a dispersion-managed (DM) terrestrial link with end-span linear compensation we obtain:

$$H_{IM-PM,p}(\omega) = -\frac{1}{2}\sum_{k=1}^{N}\gamma_k e^{j\omega d_a(k)}\left\{\frac{e^{j(\beta_r - 2\beta_a(k))\frac{\omega^2}{2}}}{\alpha_k + j\left(\omega^2\beta_{2,k} - \omega d_{sp,k}\right)} + \frac{e^{-j(\beta_r - 2\beta_a(k))\frac{\omega^2}{2}}}{\alpha_k - j\left(\omega^2\beta_{2,k} + \omega d_{sp,k}\right)} + 2\frac{\cos\left(\beta_r\frac{\omega^2}{2}\right)}{\alpha_k - j\omega d_{sp,k}}\right\} \tag{4}$$

where: N is the number of spans; γ_k and α_k are the nonlinear coefficient and linear attenuation of fiber k, respectively; $\beta_a(k)$ and $d_a(k)$ are the cumulated dispersion/walk-off from system input to k-th span input, respectively; $\beta_{2,k}$ and $d_{sp,k}$ are the chromatic dispersion coefficient/walk-off between signal and channel p into transmission fiber k, respectively; β_r is the total cumulated dispersion along the entire link (including possible pre- and post-compensating fibers before/after transmission).

The impact of the link parameters on XPM depends on the filter frequency response in (4). However, the XPM variance in (3) also depends on the differential phase filter $H_D(f)$, which can partially counteract the effect of $H_{IM-PM,p}(f)$. For DQPSK, the received phase is $\Delta\Phi(t) = \Phi(t) - \Phi(t - T_s)$, being T_s the symbol time, so that $H_D(f)$ is simply $H_D(f) = 1 - e^{-j\omega T_s}$. For coherent QPSK with feed-forward Viterbi&Viterbi phase estimation [2], the received phase is $\Delta\Phi(t) = \Phi(t) - \widehat{\Phi}$, being $\Phi(t)$ the symbol phase and $\widehat{\Phi}$ the estimated phase of the average signal on K previous symbol times. By approximating the phase of the average with the average of the phases, $\Delta\Phi(t)$ can be related to $\Phi(t)$ by a linear filtering, whose frequency response is $H_D(f) = 1 - \frac{1}{K}\sum_{n=1}^{K} e^{-j\omega n T_s}$. Note that $K = 1$ yields the same $H_D(f)$ as DQPSK.

To sketch the idea, in Fig. 1 (left) we report an example of $|H_{IM-PM,1}(f)|^2$ and $|H_D(f)|^2$. The system under analysis is the same as detailed in the next Section, with 10Gbaud DQPSK channel, and SMF fiber. From the figure we observe that $H_{IM-PM,1}$ has a typical lowpass behavior, showing that XPM affects more the small frequencies. On the other hand, H_D can be viewed as a high-pass filter over the signal bandwidth. In the figure we show H_D for 10Gbaud and 20Gbaud, showing that an increase in baudrate better suppresses the XPM low frequency components. This conclusion can be supported also by reasoning in the time domain: a DQPSK signal working at 10 Gbaud has the same symbol time of the OOK, thus XPM terms from adjacent symbols are almost independent and the differential detection cannot help. On the contrary, a 20Gbaud DQPSK has two times a smaller symbol time than the OOK channel, thus the XPM terms on DQPSK are expected to be correlated between neighboring symbols, and hence partially removed by the differential phase detection. Fig. 1(right) shows instead $|H_D(f)|^2$ for coherent QPSK at a baudrate of 20 Gbaud, for phase estimated over K=1, 3 and 5 bits. It is seen that increasing K (which is usually done to suppress ASE) has the effect of increasing the XPM variance with respect to the DQPSK case ($K = 1$).

3. Results

We analyzed a 15×100 km system with either NZDSF ($D = 4$ ps/nm/km, $\gamma = 1.5$ 1/km/W) or SMF ($D = 16$ ps/nm/km, $\gamma = 1.4$ 1/km/W) fiber, with pre-compensation -613 or -352 ps/nm, respectively, and post-compensation yielding zero total cumulated dispersion. The WDM comb had 5 synchronous and co-polarized channels with either QPSK or DQPSK central channel, at variable baudrates, and all the others 10G OOK. The channel spacing was

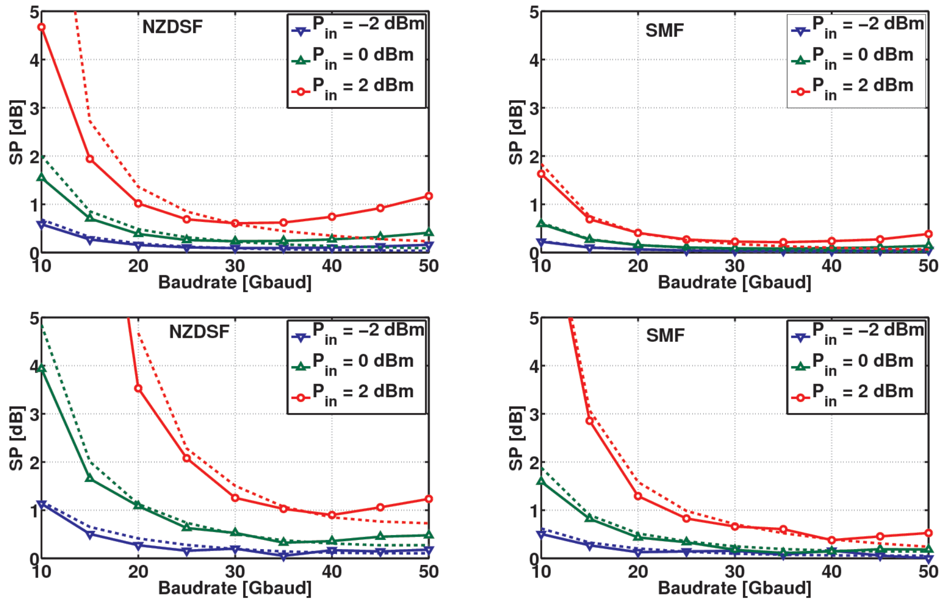

Figure 2. Sensitivity penalty SP@BER=10^{-5} vs. baudrate of the central DQPSK (top row) or QPSK (bottom row) channel with $K = 5$. Neighboring channels: 10G OOK. Solid lines: Monte Carlo results. Dashed lines: equation (2).

50GHz while the power per channel was -2, 0, 2 dBm. The link was simulated with the split-step Fourier algorithm and finally the SP measured with Monte Carlo simulations. Since we are focusing on XPM, we switched off any other nonlinear effect along the single-polarization fiber propagation. All numerical simulations were done using Optilux [7]. The non-coherent DQPSK receiver and the QPSK coherent receiver were implemented as in [2]. We set the in-line dispersion to 100 ps/nm/span for each configuration, thus fixing the XPM walk-off in (4). In Fig. 2 we show the measured SP for the considered systems, along with the analytical SP (2), which is seen provide a good fit and confirms that SP is indeed related to XPM variance. By comparing DQPSK and QPSK simulations, we observe a larger penalty in QPSK, especially at smaller baudrates, as understood in the previous Section. Moreover, the decreasing penalty (i.e. XPM variance) at higher baudrate supports our claim that such a decrease is due to the $H_D(f)$ filter, since in these simulations the walk-off was fixed. The SP discrepancy at large power and high baudrate between analysis and simulation is due to the failure of the linear model in (4).

4. Conclusions

We analyzed the impact of XPM in DQPSK-OOK and coherent QPSK-OOK hybrid systems, describing the origin of the induced sensitivity penalty. We showed using analytical arguments that coherent QPSK with phase estimation is more affected by 10 Gbit/s adjacent channels than DQPSK, and explained why the XPM penalty decreases for increasing QPSK baudrate. We also proposed a novel expression of the sensitivity penalty induced by XPM, and verified it against numerical simulations.

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