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Impatto del Cross-Phase Modulation sui canali PSK coerenti e non coerenti in sistemi WDM ibridi

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Outline

- Motivation and Objectives
- XPM small-signal model revisited
- Blachman's BER model in optical QPSK
- Sensitivity Penalty: Theory vs Simulation
- Conclusions

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Motivation and Objectives

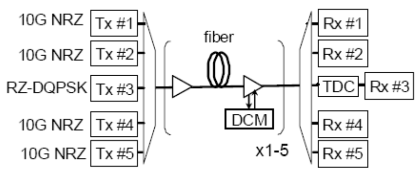
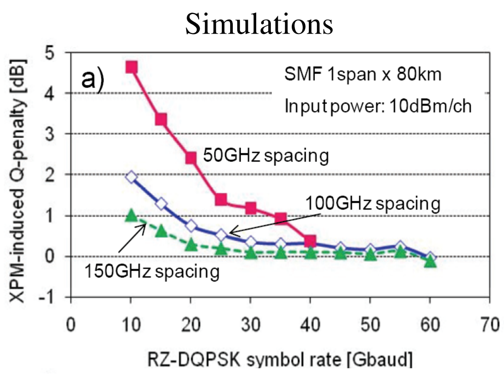


Figure 1: Simulation model



O. Vassilieva, T. Hoshida, J.C.Rasmussen, and T. Naito, “Symbol rate dependency of XPM-induced phase noise penalty on QPSK- based modulation formats,” in Proc. ECOC 2008, paper We.1.E.4

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The starting point of this work is an interesting observation reported by Vassilieva at al. at ECOC 2008, where it was shown by simulation that the penalty induced by the XPM induced by 10G OOK channels on a higher rate QPSK channel decreases as the QPSK baudrate increases.

The effect was seen to decrease with increasing channel spacing and intuitively attributed to the increased OOK channel walk-off seen by the shorter QPSK symbols.

Our objective is here to extend the resuts to a more realistic DM scenario and clearly understand the physical reasons of such a behavior.

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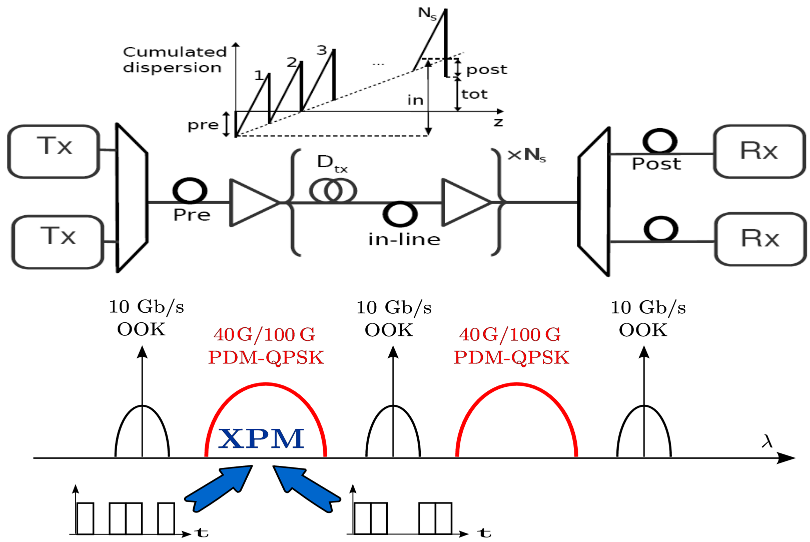
DM Hybrid WDM System



So, we considered a full-fledged DM link, with pre-compensation, in-line compensation over each span, and finally post-compensation, so as to reach a desired total cumulated dispersion, as pictorially shown by the cumulated dispersion map.

The transmitted WDM multiplex we are interested in is a hybrid mixture of legacy 10G OOK channels and higher-rate QPSK channels, usually multiplexed over two orthogonal polarizations on each laser carrier.

The dominant impairment for QPSK channels in such a hybrid WDM is in fact the XPM induced by the time-varying power of the OOK channels.

I will first describe the XPM mechanism in the DM line, and then move to describe the receiver and the performance evaluation.

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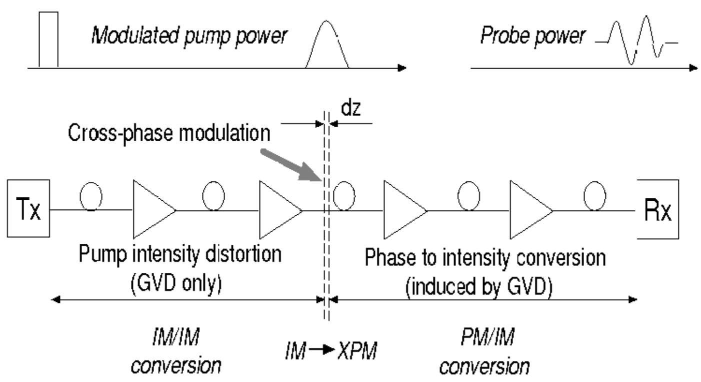
XPM Small-signal Model



Assumptions:

1. CW probe
2. Co-polarized pump-probe
3. neglect SPM

G. Bellotti, M. Varani, C. Francia, and A. Bononi, “Intensity distortion induced by cross-phase modulation and chromatic dispersion in optical fiber transmissions with dispersion compensation,” PTL, pp. 1745–1747, Dec. 1998.

In this study we resorted to a well known small-signal model for XPM which our group and at the same time two more groups around the world developed about 10 years ago for OOK modulation. In the model one OOK modulated pump channel propagates along with an initially CW probe channel CO-POLARIZED with it, and SPM on both pump and probe is neglected.

The infinitesimal phase perturbation generated at z by the pump IM is then converted to probe IM through the GVD induced PM-IM conversion and the overall effect is the integral of all infinitesimal perturbations.

For our purpose, it is enough to substitute to the PM-IM GVD conversion the PM-PM GVD conversion to obtain the output PM on the CW induced by the OOK pump IM.

In this study therefore we will only analyze the co-polarized WDM case, and will not tackle the PDM case.

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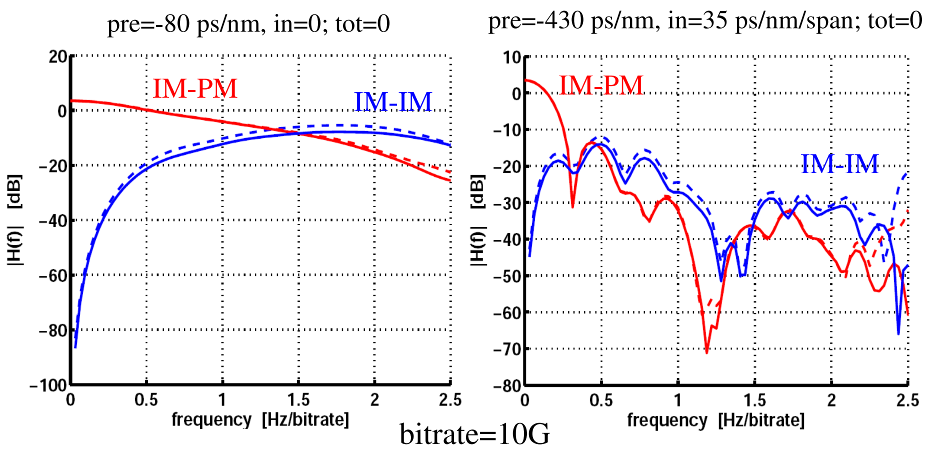
XPM Small-signal Model

LEAF D_{TX}=4 ps/nm/km; Δf=50 GHz; 20 span. Solid: theory; Dashed: simulation.



This slide shows the amplitude of both the well-known IM-IM "classical" high-pass filters (IM of pump to IM of probe), along with the novel IM-PM low-pass filter for 2 different 20-span dispersion mapped systems, one (on the left) with full in-line compensation (in=0), optimized pre-compensation and zero total dispersion (a best case for QPSK channels), and (on the RIGHT) with a non-zero in-line per span. Solid lines give theory, while dashed lines simulations. The TX fiber was LEAF, dispersion 4 ps/nm/km, and the two channels' spacing was 50 GHz. The average nonlinear phase here was 0.3pi for both channels. Frequency is normalized to 10 GHz.

we note:

1) the accuracy of the IM-PM filter is always better than that of the classical IM-IM

2) in-line dispersion shrinks the"bandwidth" of the lowpass IM-PM filter, i.e. reduces XPM on the probe channel.

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XPM Small-signal Model

Can prove that:

$$H_{\text{IM-PM},p}(\omega) = -\frac{\Phi_{\text{NL}}}{2}\left[\mathrm{e}^{j\frac{\xi_{\text{tot}}\omega^2}{2}} H_p(\omega) + \mathrm{e}^{-j\frac{\xi_{\text{tot}}\omega^2}{2}} H_p^*(-\omega)\right]$$

$$H_{\text{IM-IM},p}(\omega) = -j\Phi_{\text{NL}}\left[\mathrm{e}^{j\frac{\xi_{\text{tot}}\omega^2}{2}} H_p(\omega) - \mathrm{e}^{-j\frac{\xi_{\text{tot}}\omega^2}{2}} H_p^*(-\omega)\right]$$

where

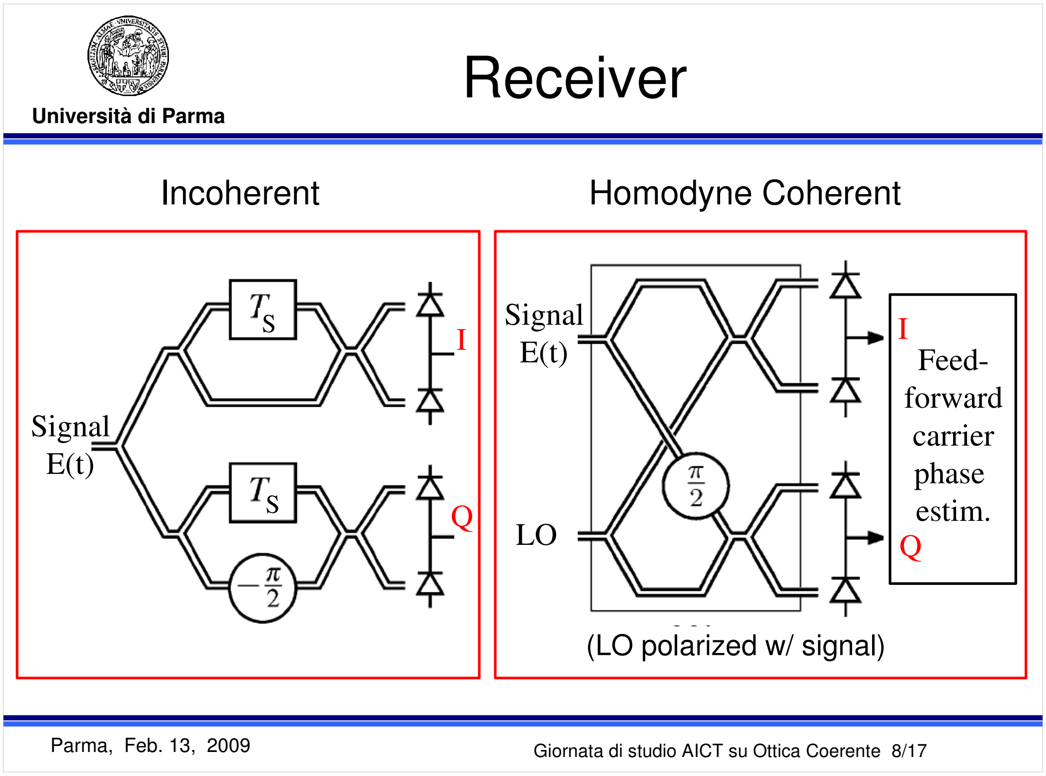
$$H_p(\omega_m) \triangleq \left[\eta\left[\omega_m\left(\omega_m + p\frac{2\pi}{\eta s d}\right)\right] + \eta\left[\omega_m p\frac{2\pi}{\eta s d}\right]\right]$$

$$\eta(w) \triangleq \frac{\int_0^L \gamma(s)G(s)\mathrm{e}^{-jC(s)w}\mathrm{d}s}{\int_0^L \gamma(s)G(s)\mathrm{d}s}$$

DM kernel

A. Bononi, P. Serena and M. Bertolini, "Unified Analysis of Weakly-Nonlinear Dispersion-Managed Optical Transmission Systems from Perturbative Approach," Comptes Rendus - Physique., invited paper, vol. 9, 2008, pp. 947-962.

Incidentally, I would like to mention that we recently proved that both the classical and the novel IM-PM filters can be expressed as simple functions of the so-called DM kernel, a frequency-domain quantity whose inverse Fourier transform is the so-called Power Weighted Dispersion Distribution: both such quantities are key design tools for DM systems, as they uniquely determine all nonlinear properties of a given dispersion map.



Let's now move to describe the receivers for the QPSK channels.

The incoherent DQPSK receiver (LEFT) is the classical one based on delay interferometers, which recovers the inphase I and quadrature Q components of the field.

The coherent receiver (RIGHT) is homodyne (LO frequency matching the signal frequency), with a 90 degrees hybrid and balanced photodetection to recover the field I and Q components, and with subsequent feedforward carrier phase estimation.

In both RX an optical filter extracts the desired signal from the WDM comb.

Consistently with the co-polarized WDM assumption in the line propagation, we suppose the LO polarization tracks the incoming signal polarization. In actual coherent receivers a polarization diversity configuration is commonly used instead.

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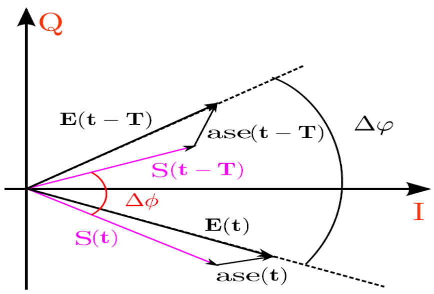
BER model: Incoherent RX



Assumptions:

1. RX optical filter (bandw. B_o))limits ase, does not distort signal.

2. Gaussian ASE and phase offset Δϕ

$$\mathrm{BER} = \frac{3}{8} - \frac{\rho}{4} e^{-\rho} \sum_{n=1}^{\infty} \left[I_{\frac{n-1}{2}}\left(\frac{\rho}{2}\right) + I_{\frac{n+1}{2}}\left(\frac{\rho}{2}\right) \right]^2 \frac{\sin(n\frac{\pi}{4})}{n} e^{-\frac{\mathrm{Var}[\Delta\phi]}{2} n^2}$$

ρ = optical signal-to-ase power ratio

N. Blachman, “The effect of phase error on DPSK error probability,” Trans. Commun., pp. 364–365, Mar. 1981.

K. P. Ho, “The effect of interferometer phase error...,” Photon. Technol. Lett.., pp. 308–310, Jan. 2004.

For performance evaluation in the Incoherent RX case, we adopt a simple model due to Blachman, where the input fields received a times t and t minus one symbol time are observed on the complex I-Q plane when the same 0 phase information symbol is transmitted. The RX field is the sum of signal S and ASE noise. Assuming that the RX optical filter does not distort the signal and band-limits the ASE, and assuming Gaussian ASE and Gaussian phase offset between signal vectors, using Blachman's method one gets a closed form of the BER, which only depends on the optical SNR rho, and on the variance of the Gaussian phase offset.

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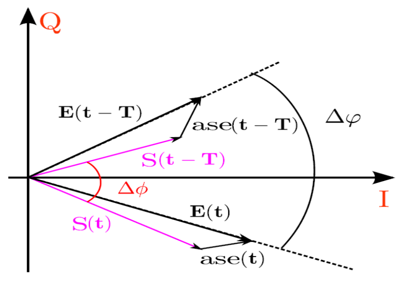
BER model: Incoherent RX



Assumptions:
Dominant XPM: neglect laser phase noise & nonlinear phase noise:

$$\Delta\phi = \phi_{XPM}(t) - \phi_{XPM}(t-T)$$

$$\Downarrow$$

$$\Delta\Phi(\omega) = \Theta_{XPM}(\omega) H_D(\omega)$$

Differential filter $H_D(\omega) = 1 - e^{-j\omega T}$

When QPSK channel has M OOK left channels + M OOK right channels:

$$\mathrm{Var}[\Delta\phi] = 2\sum_{p=1}^{M} 2\int_0^{B_o} C_{OOK}(f)\,|H_{XPM,p}(f)|^2\,|H_D(f)|^2 \mathrm{d}f$$

$$\Uparrow$$

IM-PM

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We assume here that the dominant phase noise is XPM, i.e. we neglect laser phase noise and QPSK self-induced nonlinear phase noise (this last noise becomes more important at higher baudrates). Hence the phase offset is seen to be the difference of two XPM samples, i.e. a "differential" filtering of the XPM process with frequency response H_D.

Thus the phase offset variance is obtained as usual as the integral of the covariance function of the filtered XPM, which is additive in case of 2M OOK interferers.

In the variance formula, C_ook is the OOK spectrum, and we can clearly spot out both the IM-PM line filter and the Differential filter.

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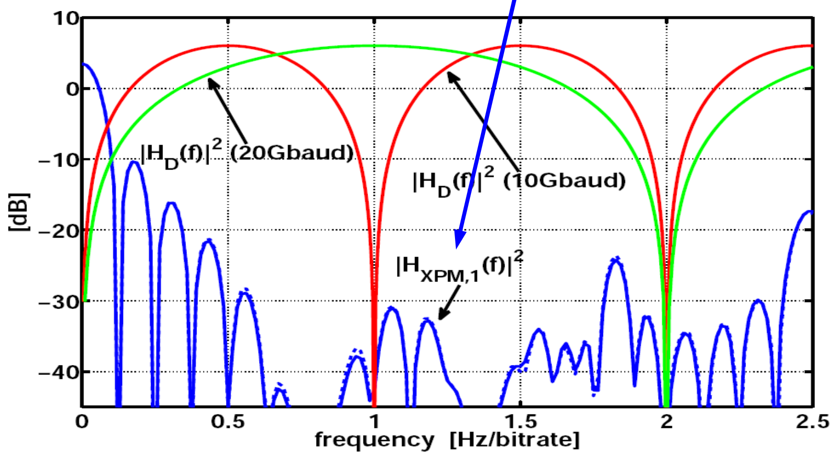
BER model: Incoherent RX

$$\mathrm{Var}[\Delta\phi] = 2\sum_{p=1}^{M} 2\int_0^{B_o} C_{OOK}(f)\,|H_{XPM,p}(f)|^2\,|H_D(f)|^2 \mathrm{d}f$$



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This slide superposes the magnitude of the line IM-PM filter (BLUE) with that of the differential filter (in RED for a baudrate of 10 Gbaud, and in GREEN for a baudrate of 20 Gbaud). The product of the blue and red (or green) filters gives the overall filtering that multiplies the OOK spectrum.

Hence it is seen that the most significant OOK low-frequency spectral components get more suppressed at HIGHER baudrates because of the action of the differential filter.

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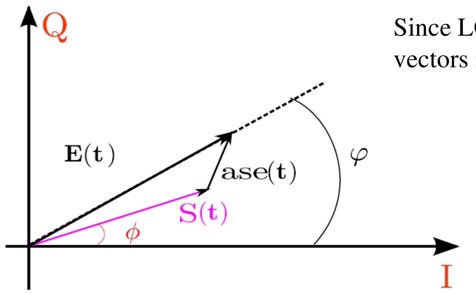
BER model: Coherent RX



Since LO is noiseless, the phase of 1 of the two vectors in the incoherent scheme is ideally recovered.

If ϕ is Gaussian,

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

For performance evaluation in the Coherent RX case, we adopt the same Blachman model, where now one of the two fields is the LO which is noiseless and whose phase is known. Thus the picture is the one depicted in the figure, and Blachman's method leads also to a simple BER formula based on the same ingredients as before.

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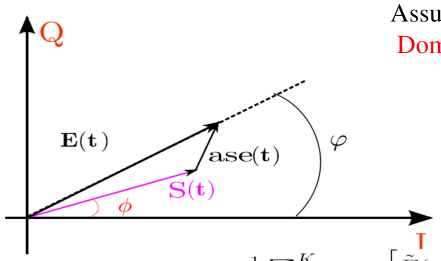
BER model: Coherent RX



Assumptions:

Dominant XPM: in phase recovery neglect laser phase noise & nonlinear phase noise & ase:

$$\phi(t) = \phi_{XPM}(t) - \hat{\theta}(t)$$

Viterbi&Viterbi phase estimator:

$$\hat{\theta} = \frac{1}{4}\arg\left[\frac{1}{K}\sum_{k=1}^{K}\tilde{E}(t-kT_s)^4\right]$$

Approximate as: $$\hat{\theta} = \frac{\frac{1}{4}\sum_{k=1}^{K}\arg\left[\tilde{E}(t-kT_s)^4\right]}{K} = \frac{\sum_{k=1}^{K}\theta_{XPM}(t-kT_s)}{K}$$

Hence $$\phi(t) = \theta_{XPM}(t) \otimes h_D(t)$$

with $$h_D(t) = \delta(t) - \frac{1}{K}\sum_{k=1}^{K}\delta(t-kT_s)$$

$$H_D(\omega) = 1 - \frac{1}{K}\sum_{k=1}^{K} e^{-j\omega kT_s}$$

"Differential filter"

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to simplify analysis, we now assume that in the phase recovery process the dominant noise source is again XPM, so that the phase offset is the XPM of the incoming field minus the estimated phase, which -- using the V&V algorithm, would be as shown here....

but sliding the ARG function inside the summation (which is a good approximation at large OSNR) the V&V estimated phase is seen to be a linear combination of XPM samples at previous symbols.

Hence the offset is again a linear filtering of the XPM process, with the shown "generalized differential filter" frequency response.

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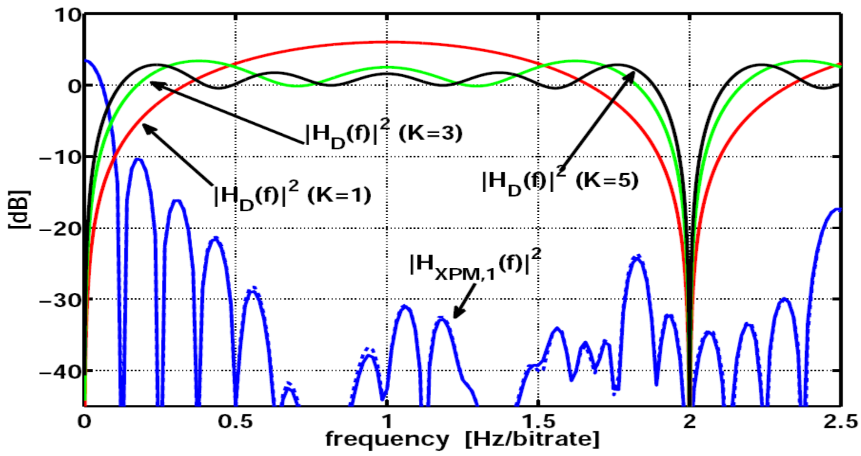
BER model: Coherent RX

$$\mathrm{Var}[\Delta\phi] = 2\sum_{p=1}^{M} 2\int_0^{B_o} C_{OOK}(f)\,|H_{XPM,p}(f)|^2\,|H_D(f)|^2 \mathrm{d}f$$



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Again we superpose here on the same graph the magnitude of the line IM-PM filter (BLUE) and the “differential filter” at a QPSK baudrate of 20 Gbaud and for various values of the number of previous symbols K on which we smooth the estimated phase.

We see that increasing K has the effect of increasing the portion of low-frequency OOK spectrum, and hence increasing the offset variance.

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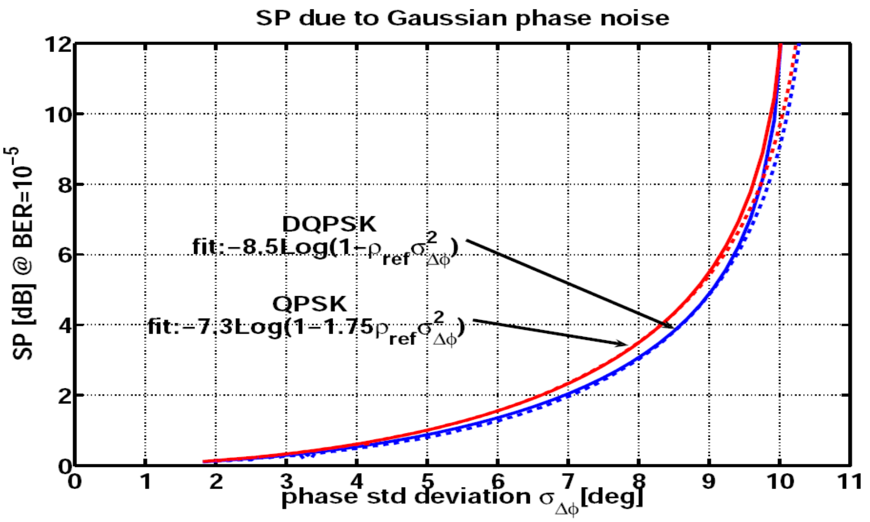
Sensitivity Penalty



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Let's now move to the last point of our outline: the evaluation of the sensitivity penalty. The figure shows the SP at BER 10^-5 versus std deviation of phase offset, both for incoherent RX (BLUE) and for coherent (RED). These curves have been obtained directly from “Blachman's” BERs. To speed up such computations, in the following we will use instead the two (NEW) analytical fits shown in dotted lines whose expressions are reported in the slide: they very simply depend on offset variance, and hold at reference BERs from 10^-3 to 10^-9

So using such fits, and calculating the XPM variance with the formulas given previously, we get......

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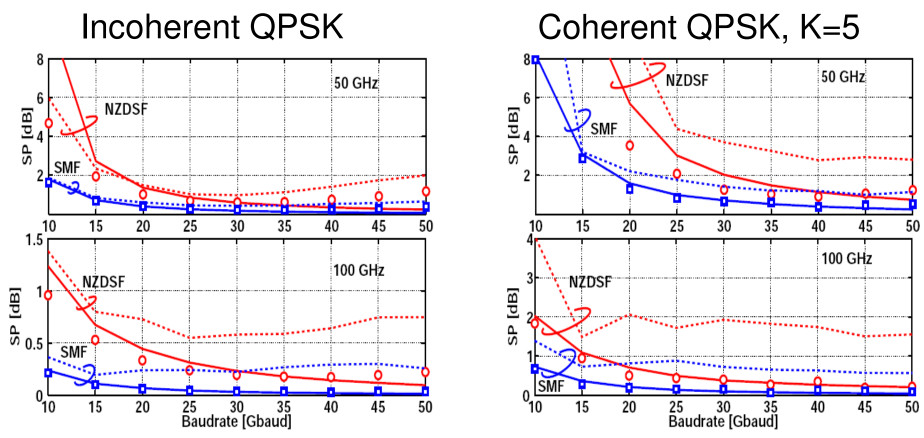
Sensitivity Penalty



XPM induced phase variance on DQPSK (left graphs) and coherent QPSK (K =5, right graphs) reference channel for a 5-channel 15-span hybrid DM system with $D_{\text{in}} = 100$ ps/nm, $D_{\text{pre}} = SLR$, $D_{\text{tot}} = 0$ and average input power P_{in} =2 dBm/ch. The channel spacing was 50 GHz (top) or 100 GHz (bottom), while the fiber is either NZDSF or SMF. Theoretical SP (2), (4) (solid); simulated SP without SPM (symbols); simulated SP with SPM (dashed).

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these SP curves versus QPSK baudrate, when the QPSK channel has 2 OOK to its left and 2 to its right., in a 15 span DM line.

On the left we have curves for DQPSK, on the right for Coherent QPSK.

In each case, we consider both 50 and 100 GHz channels spacing, and both SMF transmission fiber (17 picoseconds nanometer kilometer) and NZDSF (2 picoseconds).

Solid lines indicate theoretical SPs, open symbols simulations neglecting SPM, dotted lines are simulations including SPM.

We first see that if SPM is neglected, the small signal IM-PM model + Blachman's BER are sufficient to reproduce with satisfactory accuracy the SP in all cases, even though the Gaussian assumption for XPM is far from true with only 5 WDM channels.

Our theory thus confirms Vassilieva's observations, although when SPM is included a baudrate of minimum SP exists, and then at higher baudrates SPM dominates XPM.

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Conclusions

- Proved that “Differential filter” suppresses the low-frequency of XPM, more effectively when the baud-rate of QPSK channel is larger than that of 10G OOK
- Explained why increasing smoothing constant K in coherent feedforward phase estimation increases XPM impact.
- Analysis performed in a single-polarization setting. Still one can infer results on coherent PDM-QPSK by using the effective baud-rate. Predict that 40Gb/s PDM-QPSK (10 Gbaud) more impaired by 10G OOK channels than 100 Gb/s PDM-QPSK (25 Gbaud).
- A complete analysis including nonlinear polarization is required for PDM.