Transmission Limitations due to Fiber Nonlinearity

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Abstract: We review recent advances in understanding Kerr nonlinear limitations in high-capacity long-haul coherent systems, with emphasis on PDM-QPSK transmissions. Both homogeneous and hybrid dispersion-managed WDM systems are addressed, as well as homogeneous non-dispersion-managed systems.

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1. Introduction

Polarization division multiplexed (PDM) transmissions with multilevel modulation formats and digital signal processing (DSP) based coherent reception is emerging as the new paradigm for long-haul networks, because of the very efficient use of the optical spectrum and the field equalization capabilities of coherent receivers. Since coherent receivers are polarization sensitive, a new nonlinear impairment known as cross-polarization modulation (XPolM) is of concern in long-haul transmissions, and its role in comparison with other nonlinearities is the focus of much ongoing research [1-7]. This paper reviews recent progress in assessing the dominant nonlinear effects in PDM long-haul coherent transmissions. The interest is in both dispersion managed (DM) systems that support a hybrid mix of >40 Gb/s coherent channels and legacy 10 Gb/s on-off keying (OOK) channels, and new non-DM (NDM) format-homogeneous coherent systems. A clear picture of the role played by each relevant nonlinear effect as the baud-rate of the coherent channels is scaled helps the designer to select the most appropriate system countermeasures. Since a completely analytical approach able to capture the major impairments in coherent systems is still missing, brute-force simulation is today the only available approach to realistically predict performance. Meaningful system simulations must include many diverse effects, and are therefore necessarily slow. In the following section we will review and extend the results of the nonlinear threshold simulation approach developed in [8-11]. We will focus here on the quadrature phase-shift keying (PDM-QPSK) format.

2. Nonlinear Threshold vs. Symbol rate

Using the open-source software Optilux [12], we simulated a wavelength-division multiplexed (WDM) transmission with a central PDM-QPSK test channel on standard single mode fiber (SMF) along either an ultra-long-haul terrestrial 20x100 km link, or a transatlantic submarine 120x50 km link. The link was either DM or NDM. In the DM case, an optimal precompensation [9] and an in-line residual dispersion per span of 30 ps/nm were used, the total dispersion of the test channel being reduced to zero in a standard DSP coherent receiver [13]. In the NDM case, neither precompensation nor in-line compensation were used. In the DM case, the neighboring WDM channels were either all PDM-QPSK at the same symbol rate as the test channel (homogeneous WDM) or OOK 10 Gb/s (hybrid WDM). Pulse shaping was non return to zero (NRZ) for all formats. In the NDM case we only considered homogeneous PDM-QPSK transmission. The objective of the simulations was to estimate the nonlinear threshold (NLT) versus PDM-QPSK symbol rate B when nonlinearities (NL) are selectively activated: from NLT comparisons the dominant NL is established [11]. The simulations methodology is detailed in [9]. Here we recall the main assumptions. The NLT is defined here as the transmitted channel power yielding an optical signal to noise ratio (OSNR) penalty of 1 dB at a bit error rate (BER) of 10^{-3}. In homogeneous WDM, the channel spacing was scaled with baudrate as $\Delta f = 1.79 \cdot B$ (i.e., 50 GHz at $B = 28$ Gbaud, which required a supergaussian filter of order 2 at the transmitter with bandwidth $0.9B$ to reduce crosstalk, while in [9] we had a wider spacing $\Delta f = 2.5 \cdot B$ and no filtering) so as to keep a constant spectral efficiency. In hybrid WDM, the first OOK channels on the right/left of the filtered PDM-QPSK channel were spaced by $\Delta f = 1.79 \cdot B$, while the inter-OOK spacing was 50 GHz. OOK channels were unfiltered. The OOK to PDM-QPSK power ratio was fixed to the value that in back-back yields BER=10^{-3} for both formats. The number of WDM channels was also scaled inversely with B [9]. In simulating the coherent receiver we assumed polarization recovery through a least-mean-square algorithm, and neglected frequency offset and linewidth of the local oscillator. The Viterbi and Viterbi (V&V) PDM-QPSK phase estimation was performed with $2K + 1$ taps, with $K = 13$. Propagation was performed by a vectorial split-step Fourier method (SSFM), by solving the Manakov equation in the nonlinear step [5, 11]. PMD in the line and nonlinearity in the compensating fibers were neglected. WDM input states of polarization were random. We also used random symbols on all WDM channels, an approach shown to be preferable over the use of pseudo-random sequences at a large BER=10^{-3}, especially at large dispersion [14]. Monte Carlo (MC) simulations were run to count on average 100 errors on the test channel. Amplified spontaneous noise (ASE) was either loaded at the receiver, thus ignoring nonlinear signal noise interactions (NSNI) but allowing for faster simulations, or generated in a distributed way at every amplifier, thus correctly reproducing NSNI at the cost of a much longer run time.

Results In Fig. 1 we show the NLT versus symbol rate B for: 1) single-channel transmission (label "SPM"); 2) WDM transmission with solution of individual propagation equations for all channels, when only XPM or XPolM are active (labels "XPM" and "XPolM"); 3) WDM comb propagated as a single channel, hence with all nonlinearities ON (label "WDM"). In all three cases, we provide both the NLT obtained by noiseless signal SSFM propagation and receiver noise loading (solid lines, no NSNI case), and by noisy signal propagation with distributed ASE generation at each amplifier (dashed lines, case including NSNI). The left column refers to the 20x100km link, the right column to the 120x50km case. The top row refers to the hybrid PDM-QPSK/OOK DM case, the central row to the homogeneous PDM-QPSK DM case, and the bottom row to the homogeneous PDM-QPSK NDM case. Please note that a high NLT means a weak nonlinearity.

Discussion Let's begin with the 2000km link. In the DM case, in single channel the NSNI (here showing up as nonlinear phase noise) is the dominant NL up to roughly 60 Gbaud, followed by noiseless SPM. In DM hybrid (left-top plot), when all NL are "on" ("WDM", squares, lowest NLT curves) there is no substantial dependence on NSNI. The reason is found by looking at the XPM-only and XPolM-only NLTs: here XPM is by far the dominant NL up to 40 Gbaud, while above that noiseless SPM dominates. The dominant XPM originates from the large data-driven intensity fluctuations of the OOK channels, while the extra noise-induced fluctuations are a second-order effect: hence we have negligible impact of NSNI. If we move to the DM WDM homogeneous PDM-QPSK case (left-central plot), we note a reversal of the dominance. This time XPolM dominates over XPM. The XPM NLT In the noise loading case (diamonds solid) is the largest since the differential phase reception in the V&V almost completely cancels XPM. With distributed ASE the intensity becomes aperiodic and XPM cannot be completely canceled, and a lower NLT results (diamonds dashed). XPolM does not show any dependence on NSNI since it is mostly due to the stochastic motion of the *pivot*, i.e., the vector sum of the WDM Stokes vectors [5], and such a motion is due to the data-driven random jumps of the Stokes vectors. Hence ASE-induced intensity fluctuations are a second-order cause of pivot fluctuations, justifying the negligible NSNI impact. Finally, in homogeneous PDM-QPSK NDM systems (bottom-left plot) we note that XPM and XPolM NLTs are comparable at lower baudrates, with XPM being slightly dominant at higher B. This is attributed to the fact that the PDM-QPSK intensity becomes wildly varying in NDM links, thus increasing the importance of XPM over XPolM, although both cross-channel effects are highly suppressed by the large walkoff of the line. Note also that in NDM the NSNI has been pushed to much lower baudrates, outside the shown range [11].

Let's now look at what changes in a longer 6000km line (plots on right column). Although the relative strength of XPM with respect to XPolM remains qualitatively unchanged, we note that passing from 2000 to 6000 km the SPM NLT sinks more than cross-channel NLTs, which means that single-channel effects accumulate faster with distance with respect to cross-channel effects, thus extending the range of dominance of single-channel effects with baudrate. For instance, in NDM links at 6000 km only single channel effects matter. In this case it would be very useful to compensate the dominant SPM distortions. Unfortunately, techniques such as back-propagation become prohibitively time/hardware-consuming for increasing accumulated dispersion.

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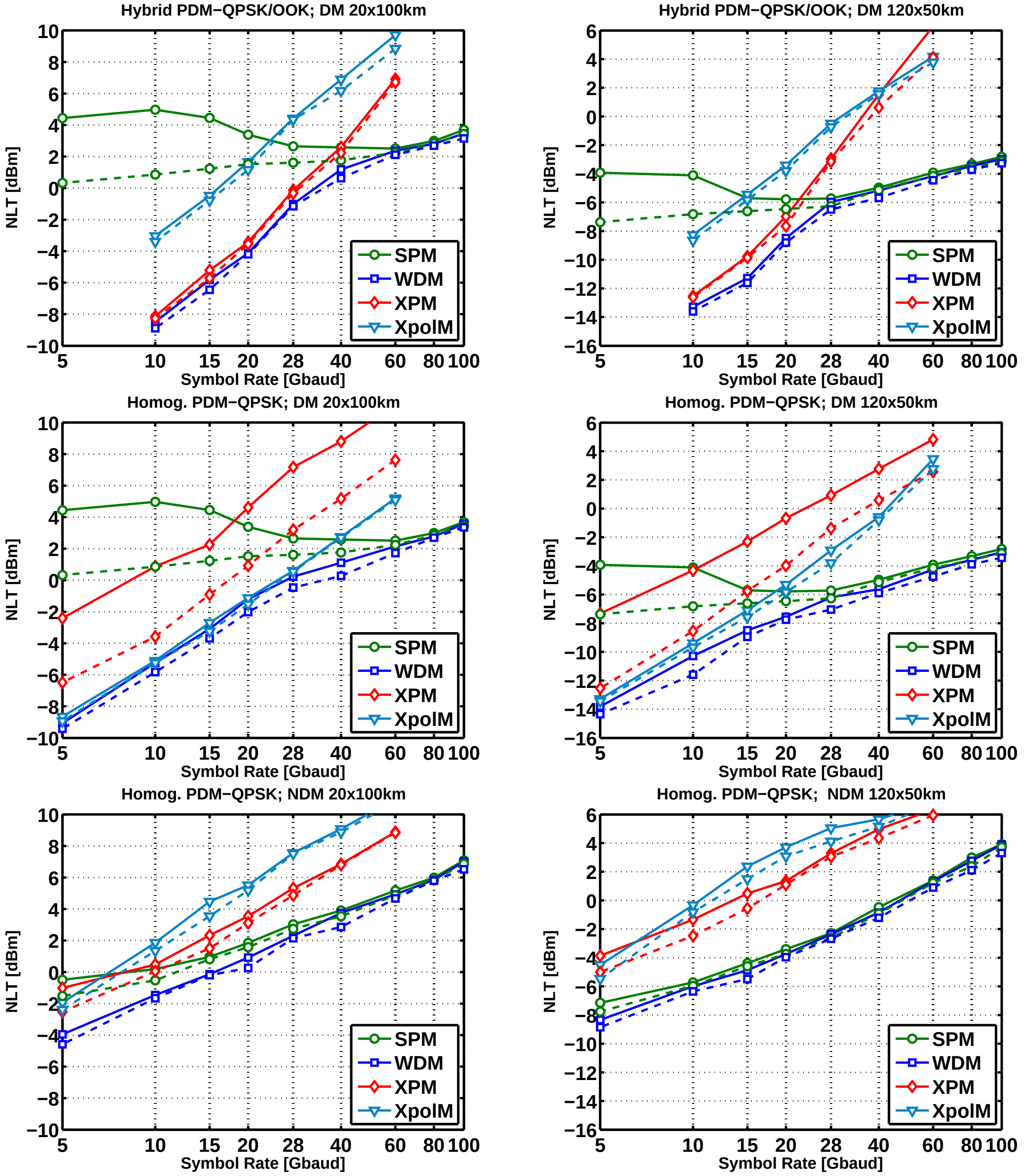

Figure 1. Nonlinear threshold (NLT) vs PDM-QPSK symbol rate B on SMF links. Distance: **(left colum)** 20x100 km; **(right column)** 120x50km. WDM Formats/Links: **(top row)** DM (optimized pre-comp., RDPS=30 ps/nm) and hybrid WDM (central PDM-QPSK+ lateral blocks of 10G OOK. Blocks spaced $\Delta f = 1.79B$ from PDM-QPSK, while OOK spacing within blocks is 50 GHz); **(center row)** same DM as top row and homogeneous WDM PDM-QPSK; **(bottom row)** NDM and homogeneous WDM PDM-QPSK. Channel spacing is $\Delta f = 1.79B$ for all homogeneous WDM. **Legend** for all plots: Solid=noise loading; Dashed: distributed ASE. Nonlinear effects: “SPM”=single-channel, self-phase modulation only; “XPM”=scalar cross-phase modulation only; “XPolM”=vector cross polarization modulation only; “WDM”=all Kerr nonlinearities ON.