Impact of Nonlinear Fibre Impairments in 112 Gb/s PM-QPSK Transmission with 43 Gb/s and 10.7 Gb/s Neighbours

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ABSTRACT

We numerically investigate the nonlinear tolerance of 112 Gb/s polarization multiplexed quadrature phase-shift keying co-propagating with 43 Gb/s differential quadrature phase shifted keying and 10.7 Gb/s amplitude modulated phased shifted keying and non-return-to-zero on-off keying neighbours under various dispersion maps. The results indicate that with phase-modulated neighbours, considerable tolerance to nonlinear effects is observed both with and without inline optical compensation whilst inline dispersion compensation greatly increases the influence of fibre nonlinearity arising from intensity-modulated low bit-rate neighbouring channels. No significant nonlinear cross polarization effects are observed with either single polarization or polarization multiplexed neighbouring channels due to the dominance of cross phase modulation.

Keywords: Kerr fibre nonlinearity, wavelength division multiplexing, polarization multiplexing

1. INTRODUCTION

In the view of increasing requirements for information capacity, the need to upgrade the existing wavelength division multiplexing (WDM) infrastructure primarily based on 10.7 Gb/s intensity modulated channels is essential. During a managed changeover process a combination of existing channels and a number of high bit-rate channels employing advanced modulation formats is a cost effective solution. Such systems are typically referred to as hybrid systems. Polarization multiplexed quadrature phase-shift keying (PM-QPSK) has emerged as the leading solution for data rates in the region of 100 Gb/s offering increased spectral efficiency with the minimum increase in the required optical signal-to-noise-ratio (OSNR) [1-2]. However, the robustness of PM-QPSK against nonlinear impairments arising from co-propagating intensity modulated signals is still a serious concern, since fibre nonlinearity largely degrades the system performance and cannot be mitigated using conventional (linear) equalization structure. One of the major nonlinearities is cross phase modulation (XPM) induced phase/polarization modulation which can lead to significant penalties in hybrid systems under specific network scenarios which have been studied to date [3-4].

In this paper we numerically investigate the effects of fibre nonlinearity for 112 Gb/s PM-QPSK signals, followed by a study of the impact of numerous combinations of hybrid channels. Specifically, 10.7 Gb/s on-off keying (OOK), 10.7 Gb/s amplitude modulated phased shifted keying (AM-PSK) – also known as duo-binary-, and 43 Gb/s differential quadrature phase-shift keying (DQPSK) neighbours are considered, co-propagating with a central 112 Gb/s PM-QPSK signal. The dependence of inter-channel cross-talk on the relative polarization alignment between the central channel and its neighbours is also studied.

2. NUMERICAL SIMULATION SETUP

All the numerical simulations were carried out using VPItransmissionMaker®, and digital post-processing is performed in Matlab®. Fig. 1 depicts the PM-QPSK transmitter setup at 112 Gb/s, the transmission link, and the coherent receiver structure. The transmission system comprised up to three WDM channels, where the central channel was always 112 Gb/s PM-QPSK, and each neighbour employed either 112 Gb/s PM-QPSK, 10.7 Gb/s OOK, 10.7 Gb/s AM-PSK neighbours, or 43 Gb/s DQPSK modulation. The channel spacing was set to 50GHz. As shown in Fig. 1b, the transmitter was operated at 1550nm (negligible line-width for simplicity), where two bit sequences of length 2^n were used to modulate the in phase and quadrature components using a conventional nested Mach-Zehnder Modulator (n-MZM) structure. For each polarization component, the bit sequences driving the n-MZM were properly pre-coded such that the resulting QPSK optical signal was phase-modulated by a De Bruijn sequence B(4,n) of order n. Different sequence order (n=13, and n=12 respectively) and n-MZMs were used for each polarization state, and the two polarization states were combined using an ideal polarization beam combiner. A total of 65,536 bits were simulated at 16 samples per symbol. All the channels had the same average power level and were combined using a multiplexer with a 30 GHz 3rd order Gaussian pass band. The transmission link had ten spans (Fig. 1a) each of which comprised an erbium doped fibre amplifier (EDFA) followed by 60km of standard single mode fibre (SSMF). Dispersion maps with and without inline dispersion compensation were considered. For the dispersion managed link, the SSMF was followed by a second EDFA and a dispersion compensating fibre (DCF). The input power to the DCF was kept 5dB lower than the input power to the SSMF (see Table I for fibre parameters). The optical amplifiers were modelled as ideal noise-free
EDFA and white Gaussian noise was added at the receiver in order to calculate the required OSNR. Cross-polarization non-linear effects were included according to the Manakov model [5] and PMD was neglected.

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<th>Table 1. Fibre Parameters</th>
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<td><strong>SSMF</strong></td>
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<td>Length/Span (km)</td>
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<td>Loss (dB/km)</td>
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<td>Dispersion (ps/nm/km)</td>
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<td>Nonlinearity (1/W/km)</td>
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The test channel (PM-QPSK) was demultiplexed from the received signal using a 30 GHz bandwidth 3rd order Gaussian optical band-pass filter. The test channel was then coherently detected using an ideal homodyne receiver, low pass filtered and sampled at 2 samples/symbol (see Fig. 1c). The digital field was reconstructed using the inphase/quadrature components of each polarization and the signal was digitally processed. The transmission impairments were compensated using finite impulse response (FIR) filters (fractionally-spaced taps) which were adapted using normalized least mean square (NLMS) algorithm. The equalization was performed in two stages: a) Dispersion compensation (DC): single stage equalization with one FIR filter for each polarization, b) Polarization de-multiplexing and residual effects compensation (PD): double stage equalization, where a modified butterfly structure [6] of FIR filters is used (5 taps/double filter). Inputs from the two polarizations were interleaved and a bank of two double filters rather than equivalent 4 filter butterfly structure was deployed. Finally the symbol decisions were made and errors were counted.

![Figure 1. Simulation Setup](https://example.com/f1.png)

3. RESULTS AND DISCUSSIONS

We first consider a WDM link with three channels, where all the channels are 112 Gb/s PM-QPSK and their states of polarizations are aligned with the central test channel. The results are plotted in terms of required OSNR penalty (OSNR$_{\text{req}}$), which is defined as the difference between the back-to-back OSNR$_{\text{req}}$ at a bit error rate of $10^{-3}$ and the OSNR$_{\text{req}}$ at $10^{-3}$ following transmission. As can be seen in Fig. 2, for the two dispersion maps considered, at low power levels the OSNR$_{\text{req}}$ shows negligible penalty. The single channel performance is similar with and without optical dispersion compensation, with a 1dB OSNR$_{\text{req}}$ penalty at around 3dBm. For the three channel WDM system, the 1dB penalty in OSNR$_{\text{req}}$ occurs at around 1dBm with full inline compensation, and 3dBm with no inline compensation. Note that in case of no inline dispersion compensation (see Fig. 2b), the DCF is removed and the accumulated dispersion is compensated using the DC stage described in the setup, followed by PD stage (5 taps/double filter), while in case of full inline dispersion compensation DC stage is bypassed. The improvement in tolerance to non-linear effects without inline dispersion compensation can be attributed to the reduced phase matching conditions due to increased walk-off for links having high residual dispersion per span (RDPS). Also, as we can see that the single channel performance for both the maps is better than the WDM case, which signifies the importance of inter-channel nonlinear effects for WDM transmissions. However, as reasoned above, with increased RDPS the inter-channel nonlinearity is considerably minimized.

1 This was obtained by using the VectorPMD fiber model in VPItransmissionMaker® and by setting the birefringence step size to the fibre length and by using an identity matrix as the fibre rotation matrix.
We extend our investigation by studying the impact of fibre nonlinearities on PM-QPSK signal by comparing different hybrid scenarios as shown in Fig. 3 with and without optical dispersion compensation. We introduce neighbouring channels at two different bit rates and with typical modulation formats used at such bit rates, and study their effects on the test channel (PM-QPSK at 112 Gb/s). In all cases, the heterogeneous neighbours are single polarization and the centre channel is polarization multiplexed. The polarizations of the neighbouring channels are aligned to one of the polarization states of the test channel (PM-QPSK). As it can be seen in Fig. 3a, in the presence of phase modulated neighbours (either 112 Gb/s PM-QPSK or 43 Gb/s DQPSK), the test channel shows a similar tolerance to fibre nonlinearities since both the transmission schemes are transmitted with a constant intensity power profile. However, with single-polarization 43 Gb/s DQPSK neighbours, the test channel tolerance is slightly better than PM-QPSK (Fig. 2 curves included for comparison). As shown previously [7], such effect can be attributed to reduced baud-rate of 112 Gb/s PM-QPSK essentially increasing the phase matching.

Fig. 3 also shows that lower bit-rate intensity modulated neighbours induce considerably larger non-linear effects on the test channel and that OOK is slightly more detrimental than AM-PSK. Both formats present a considerably higher signal extinction ratio, especially for the first span, and so the pattern dependent phase shifts will be significantly higher. Where optical dispersion compensation is used, the extinction ratio is periodically restored, exacerbating this effect. For the AM-PSK it is the slightly lower extinction ratio and smoother intensity profile reduces this effect in comparison with an OOK formatted signal. Without inline optical dispersion compensation as shown in Fig 3b [8], the intensity modulated signals still have a strong impact in the first span, but as the signals disperse the peak to average power ratios of all formats begin to converge. The overall effect of this is to significantly reduce the detrimental impact of the intensity modulated signals, such that the 1dB OSNR\text{penalty} penalty occurs only 2 dB earlier than for constant intensity formats. Furthermore, the larger walk-off induced by the accumulated dispersion implies that the next XPM phase shift will be the averaging over a number of time slots, which will also reduce the impact of the fibre nonlinearity.

Recently, several studies have been carried out to characterize the effects of cross polarization induced penalties in a hybrid system including a polarization multiplexed channel [7, 9]. In order to quantify the impact of relative polarization alignment between channels we report the performance of the hybrid scenarios discussed before, but
with different polarization alignments in comparison to test channel. We selected the worst case, in-line optical dispersion compensation; and power levels corresponding to approximately 2dB total non-linear penalty. Fig. 4 shows the performance of test channel under different polarization alignment scenarios for each neighbor configuration. Whilst some variation is observed when the relative polarization is changed, the typical variation for single polarization neighbors is around 0.5dB (only ¼ of the total observed penalty) and is close to the uncertainty in the penalty due to the finite sample size. The penalty rises to around 1 dB (½ of the maximum penalty) for polarization multiplexed channels, which is still small compared to the overall penalty, which we attribute to direct phase modulation. However, further study in needed to come to a clear understanding of the complex nature of these non-linear interactions.

![Figure 4. Dependence of Nonlinear tolerance on relative polarization: Three WDM channels with full inline compensation: 50GHz spacing.](image)

4. CONCLUSIONS

We have numerically investigated the effects of XPM on 112 Gb/s PM QPSK transmission systems in several hybrid scenarios (10.7 Gb/s OOK and AM-PSK, 43 Gb/s DQPSK and 112 Gb/s PM-QPSK co-propagating channels). Both single polarization and polarization multiplexed phase modulated neighbours show high tolerance to fibre nonlinearity both with and without inline dispersion compensation. However, intensity modulated neighbours induce significant non-linear penalties, especially when optical dispersion compensation is employed. However, such penalties are significantly reduced if the inline optical dispersion compensation is replaced with electronic dispersion compensation. For the worst case scenarios, non-linear penalties are dominated by XPM induced phase modulation rather than XPM induced polarization modulation.

ACKNOWLEDGMENTS

The work described in this paper was carried out with the support of EUROFOS project, Network of Excellence funded by the European Commission through the 7th ICT-Framework Programme. The authors would like to thank Dr A.D. Ellis for useful discussions regarding this paper.

REFERENCES