Do’s and Don’ts for the Emulation of Four-Wave Mixing in 10Gb/s WDM Systems Based on Low-Dispersion Fibre

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Abstract: We numerically investigate simulation conditions to accurately emulate the impact of four-wave mixing in 10Gbit/s systems based on low-dispersion fibre, such as the statistical impact of phase/time shifts between channel or combs of channels.

Introduction

Four-Wave-Mixing (FWM) is one of the main sources of impairment for current DWDM Nx10Gb/s systems based on low dispersion fibres such as widespread LEAF^{TM} fibre (dispersion D<3ps/nm/km @1530nm). It is known that system performance depends on the interference conditions between channels, especially their relative frequencies, optical phases and time shifts, as illustrated in [1, 5], and numerous models have been developed accounting or not for such conditions [2, 5, 6]. Though, few papers focus on the actual performance of systems. [1] is one of them, it emphasizes the impact of time and phase shifts between channels, but for 40Gbit/s systems at a very high information spectral density (0.8bit/s/Hz) where the spectral overlap between channels is significant.

The present paper focuses on the conditions for accurate emulation of 10Gbit/s NRZ systems with 50GHz channel spacing based on LEAF fibre, following three axes: the impact of dispersion slope mismatch between line fibre and DCF, too often overlooked in the literature in numerical studies; the statistics of system performance depending on channel to channel phase and time shifts; and the relevance of a widely-used experimental trick consisting in interleaving two 100GHz-spaced channel combs, with all channels of a comb modulated by the same pattern generator thus time-synchronized, as compared to the more realistic approach where all channels are randomly time-shifted with respect to each other.

System set-up

The system under investigation is a typical WDM 10Gb/s NRZ system, with 15 channels separated by 50GHz, for wavelengths ranging within [1529.2nm; 1534.8nm]. The link consists of twelve or twenty-five 100km-long spans of LEAF fibre. A double-period dispersion map has been assumed, similar to that described in [3]. The Residual Dispersion Per 5-span Subdivision (RDPSub) is set to 0 at 1550nm (corresponding for instance to a typical section between two adjacent nodes, in an optical network). The residual dispersion per span and the pre-compensation are respectively set to 100ps/nm and –320ps/nm @1550nm. Simulations have been performed around 1530nm in order to focus on the most penalized channels (D≈2.5ps/nm), accounting for the realistic dispersion values of LEAF and dispersion compensating (DCF) fibres. The uncertainty on all dispersive elements of the link has been considered and has been simulated by setting a residual dispersion per subdivision of -300 ps/nm. At receiver, a post-compensation DCF was optimized on a per channel basis, to minimize the Bit-Error Rate, computed using Karhunen-Loewe method [4].

Impact of dispersion slope

Quite often, in numerical simulations, the impact of dispersion slope is overlooked for the emulated multiplex, leading to resonant effects such as observed in [2], when varying the dispersion map. Indeed, if we consider one particular channel, it appears quite natural to observe a quasi-periodic behaviour [2] when varying residual dispersion per span or per subdivision, due to the changes in phase matching conditions of the FWM process from one span/subdivision to another. Nonetheless, dispersion slope causes dispersion and dispersion maps to actually differ from one channel to another, sufficiently with respect to FWM, as illustrated by **Figure 1**.

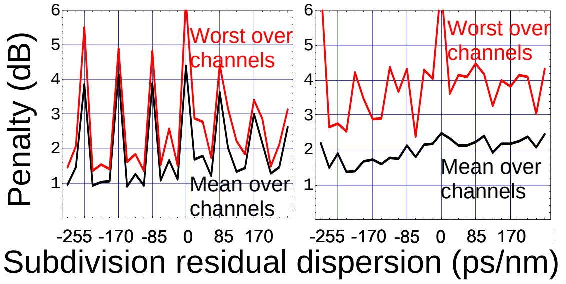

Figure 1: Transmission penalties versus residual dispersion per subdivision (@1550nm) without (left) and with (right) dispersion slope, for worst / mean values over the 10 central channels out of 15.

This figure shows the transmission penalty after 3x500km with 3dBm channel input power versus RDPSub with zero (left) or actual (right) dispersion slope. With zero dispersion slope, all penalty peaks have been found to fall on top of each other whatever the channel number, as illustrated by the superposition of peaks for worst and mean values of penalty over the multiplex (left). In contrast, with the actual dispersion slope, the penalty averaged over all channels does not show any more peak versus RDPSub. This suggests that the RDPSub yielding the best performance at one wavelength can actually be a worst case for another wavelength of the multiplex. This outlines the necessity to properly account for dispersion slope and to measure several channels for true system assessment.

Statistical impact of phase and time shifts

Firstly, let us consider the particular case where all the channels carry the same information (64 bits De Bruijn sequence). Three sets of 500 simulations have then been realized for different types of decorrelation between channels: one set with random phase shifts only, one with random time shifts only, and the last one with a combination of random phases and time shifts (from left to right in Figure 2). The transmission link is composed of 5 subdivisions, i.e. 2500 km. BER histograms representing the resulting probability density function (pdf) of the BER are displayed in Figure 2 for channels 7 and 10 (λ=1531.6 and 1532.8nm). We can see that the BER variations due to the random phases only (2 decades) is much less important than the variation due to the random time shifts (4 decades). We have also drawn two lines for each histogram: the solid and the dashed lines respectively correspond to the mean BER over all 500 realizations and the BER obtained when all channels are synchronised in phase and in time. A system where all channels are completely synchronised has not necessarily the worst performance but is not representative.

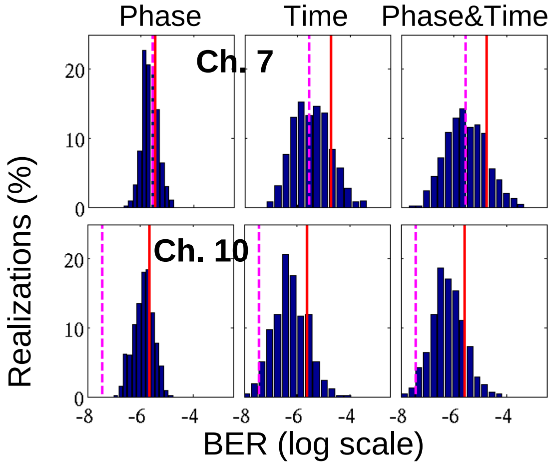

Figure 2 BER histograms for two different channels (up, and down) with random phase shifts only, random time shifts only, and with a combination of random phase and time shifts (from left to right).

Relevance of using interleaved channel combs

In Figure 3, we have represented the probability density function of the nonlinear threshold (NLT) for a 2.5 dB transmission penalty out of sets of 500 simulations, for three types of channel-to-channel decorrelation, as mentioned in the introduction, and for channel 6 (λ=1531.2nm). The reference curve (Line with triangles) is the previously studied case, corresponding to time and phase random shifts for each channel, using the same pattern generator (64 bits De Bruijn sequence). This reference can be compared with the “experimental-like” cases consisting of two interleaved channel combs for odd and even channels respectively, and only one pattern generator for the channels of each comb. In doing so, time shifts occur only from one comb to the other, whereas phase shifts are still randomly generated for each channel. Two strategies are then considered, using complementary binary data from one comb to another (line with squares) such as in most WDM experiments, or using different pattern lengths for each comb (here 64 and 128bits).

The NLT pdfs for these three strategies yield quite different mean values 14.4dBm (reference), 12.5dBm (complementary data) and 13dBm (different pattern lengths), as well as significantly different worst values. The same trends are observed for all the channels of the simulated multiplex. For the dispersion map considered here, the NLT evaluated from an experiment using two combs with complementary data could be underestimated by 2dB, with respect to a more realistic case of full channel decorrelation.

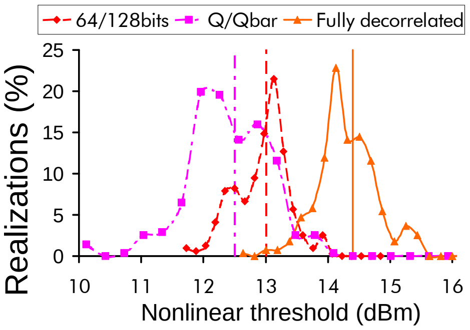

Figure 3 NLT probability density function (channel 6) for three combinations of bit pattern between adjacent channels: all channels fully decorrelated in time and phase (triangle), and odd/even channels with complementary information (Q/Qbar, squares) or with different sequence lengths (diamonds).

Conclusions

We have shown in this article that the system performance strongly depends on the interference conditions between channels even low spectral density systems. We have also particularly outlined that experiments done with odd/even channels coded with complementary informations can lead also to a wrong estimation of the performance compared to the real case where all channels are independently uncorrelated in time and phase. This work is supported by French Pole de Compétitivité System@TIC and project CARRIOCAS.

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