Coherent crosstalk in ultra-dense WDM systems

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Abstract *Coherent crosstalk between WDM channels at high spectral efficiencies can inflict large statistical penalty spreads and generate error bursts. We discuss OSNR penalty statistics and develop a technique to accurately predict coherent WDM cosstalk penalties.*

Introduction

Ultra-dense wavelength-division multiplexed (WDM) systems show noticeable overlap of adjacent WDM channels' optical spectra, leading to coherent WDM crosstalk, i.e. to beat frequencies of signal and WDM interferes falling within the receiver's electrical bandwidth. The resulting signal distortions are random, as adjacent WDM channels carry different, randomly aligned bit patterns, and as different channels are generated by mutually incoherent laser sources, implying randomly varying optical phase relationships among them. However, unlike amplified spontaneous emission (ASE) induced beat noise, whose correlation time is on the order of the bit duration, random variations of the WDM interferers occur on time scales *much larger* than the bit duration. Similar to other in-band crosstalk impaired systems[1-3], this can lead to *error bursts*, which may substantially degrade performance, even if forward error-correction (FEC) is used.

Here, we investigate penalty statistics of coherent WDM crosstalk, showing that *large statistical spreads* can prevent reliable predictions of ultra-dense WDM system performance[4-6]. We also introduce and assess a simulation technique to overcome these problems.

System model

As shown in Fig. 1, a WDM multiplexer combines the signals from three independent transmitters (TX). After the addition of ASE (in-line optical amplification), a demultiplexer separates the WDM channels and sends them to independent receivers (RX). We assumed carrier-suppressed return-to-zero (CSRZ) modulation (13-dB extinction) at a spectral efficiency of 0.8 bit/s/Hz (e.g., 50-GHz WDM channel spacing at a bit rate of R = 40 Gb/s, see Fig. 1). We compared the performance of the center channel (λ_2) in the presence of two co-polarized neighboring channels (λ_1, λ_3) with the case of no WDM interferers but the same mux and demux filters. Mux and demux were assumed 2nd-order Gaussian, with 3-dB bandwidths $B_{demux} = R$, and $B_{mux} = R$ or $B_{mux} = 1.3\,R$, respectively. These bandwidths are slightly smaller than the optimum values for an isolated channel. The RX has 5th-order Bessel electrical filter characteristics of bandwidth $B_e = 0.6\,R$. Beat-noise limited receiver performance was quantified by the optical signal-to-

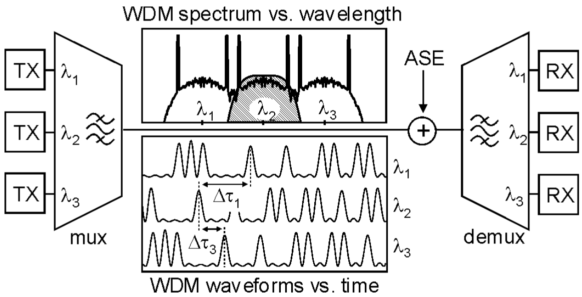

Fig. 1: Setup to predict WDM crosstalk penalty statistics.

noise ratio (OSNR) required to achieve a bit-error ratio of BER = 10^{-10} using *semi-analytic* simulations[7]: To account for inter-symbol interference (ISI), we used a De Brujin bit sequence, i.e. a pseudo-random bit sequence (PRBS) of length 2^L-1 with an additional zero added to the longest run of zeros. Closed-form expressions for the noise-free signal as well as for the time-varying ASE-induced beat noise variance at the decision gate were used to compute the BER by applying Gaussian detection statistics, while jointly optimising decision threshold and sampling instant.

Statistical OSNR penalty distributions

Figure 2 shows histograms of 10,000 statistically independent simulations of the required OSNR, referenced to the quantum limit[6]. For each realization we assigned to the two interfering WDM channels (λ_1, λ_3) a set $\{\Delta\tau_1, \Delta\tau_3\}$ of random, uncorrelated time shifts

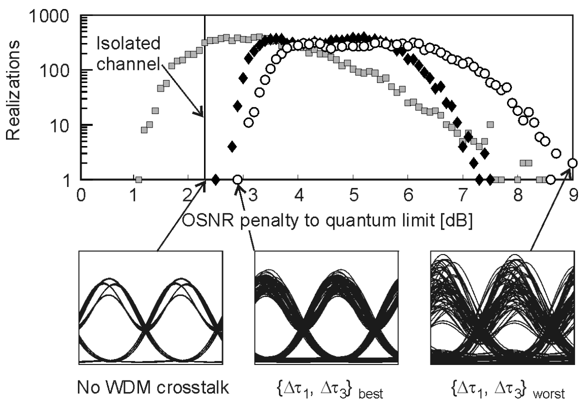

Fig. 2: Histograms of required OSNR caused by different relative WDM channel timings. (○ : 2^7-1 PRBS, $B_{mux} = 1.3\,R$; ◆ : 2^7-1 PRBS, $B_{mux} = R$; ■ : 2^3-1 PRBS, $B_{mux} = 1.3\,R$)

with respect to the center channel (see Fig. 1). These time shifts (including both integer-bit *and* fractional-bit delays) were distributed uniformly over the length of one full bit sequence. The *open circles* in Fig. 2 refer to B_{mux} = 1.3 *R*. Note the *huge* (6-dB) spread between minimum (3 dB) and maximum (9 dB) OSNR penalty, which is *only* caused by different time shifts of the interfering WDM channels, and thus by different interference conditions (cf. electrical eye diagrams in Fig. 2, bottom). The *gray-squares* histogram uses a shorter (2^3-1) PRBS; this is the shortest sequence to fully capture ISI for the assumed filter constellation, and thus to still accurately predict single-channel performance. Note that in short-sequence simulations, WDM crosstalk can even lead to artificial performance *improvements* to values below the crosstalk-free case (Fig. 2, vertical line at 2.3 dB), since some of the interfering short bit patterns can actually open up the received eye. The *black-diamonds* histogram pertains to a 2^7-1 PRBS again, but with B_{mux} = *R*. Expectedly, the average OSNR penalty is lower for this decreased mux bandwidth, and so is the penalty spread.

Through further extensive simulations, we noticed that *(i)* depending on system parameters, *very different* sets of WDM channel time shifts can lead to maximum/minimum penalties, *(ii)* including sets $\{\Delta\varphi_1, \Delta\varphi_3\}$ of random, uncorrelated optical phase differences between the WDM channels does not change the statistics of the OSNR penalty, but affects the role of specific WDM time shifts, and *(iii)* keeping fixed the channel timings and varying *only* the WDM phase differences alters the penalty statistics noticeably.

Novel simulation technique for WDM crosstalk

Depending on the system under investigation, performance will either be characterized by the *full penalty statistics* (Fig. 2) or by the penalty corresponding to a *long-term averaged BER*, the latter being most easily accessible in laboratory experiments using standard BER test sets. We next discuss a simulation technique for the latter case. Within our simulation technique, we average the BER using the *same* sampling time and decision threshold not only for a single PRBS, but for *K* blocks of 2^L bits, where within each block we introduce randomly chosen sets of WDM time shifts and phase differences to arrive at the crosstalk-impaired signal field. The *K* blocks can be physically interpreted as short, temporally separated segments of a much longer bit sequence, over the course of which the WDM channels' optical phases or their relative timings have undergone random changes. By increasing the number of blocks, we become independent of the arbitrary choice of time shifts or phase differences between signal and interferers, which is responsible for the large spread in OSNR penalty seen in the histograms of Fig. 2.

The performance of our technique is assessed in Fig. 3, obtained by statistically evaluating 320 random

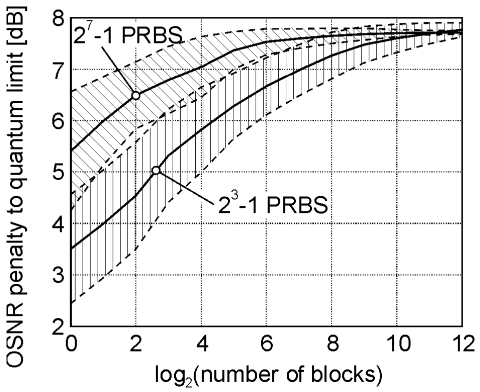

Fig. 3: Uncertainty regions of the OSNR penalty (hatched) for the proposed simulation technique. (To generate this graph, we simulated a total of 356 million bits.)

runs of our simulation model. The solid curves show average OSNR penalties (referenced to the quantum limit) as a function of the number of blocks, for PRBS lengths of 2^3-1 and 2^7-1, respectively. The hatched areas indicate the $\pm1\sigma$-regions of the simulated penalties, and thus specify the simulation accuracy. *Independent* of the PRBS length, the average OSNR converges to its "true" value for a sufficiently large number of blocks, and the statistical fluctuations become small. For a small number of blocks, longer bit sequences, *on average*, reproduce the correct penalties better than shorter bit sequences, but the statistical fluctuations are *not* reduced by just increasing the PRBS length. Even for PRBS lengths of 2^9-1 we did not observe a reduction in the statistical fluctuations at a low number of blocks.

An alternative simulation technique[4] suggests the use of a long PRBS (2^{12}-1) in combination with a ~ 4% bit rate difference between adjacent WDM channels to introduce a continuous walk-off between signal and interferers. However, such a change in bit rate always affects the interferers' spectra, and thus generates crosstalk conditions that may differ from physical reality. We also performed a statistical analysis based on this approach, but did not find the desired increase in simulation accuracy.

Conclusion

We discussed the statistics of coherent WDM crosstalk and its implications on system specification (occurrence of error bursts) and on simulative system design. We developed a technique to accurately predict OSNR penalties for long-term averaged BER.

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