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Polarization Effects in ULH Agile Photonic Networks

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Abstract: Error-free transmission under all polarization conditions in ≥10 Gbit/s UHL agile optical networks is achieved through dynamic control and through margining for low-probability events. Simulation and experimental results are presented that help to derive bounds on speed and magnitude of polarization-induced impairments.

1. Introduction

A new generation of physical transmission infrastructure enables agile all optical networking [1], where optically transparent wavelength paths are established on demand across the network without OEO regeneration at intermediate nodes. As a consequence of enhanced transparent reach and flexibility, polarization effects such as polarization-mode dispersion (PMD) and polarization-dependent loss (PDL) pose a significant challenge. Dynamic control, comprehensive modeling and in-service self-diagnostic capabilities of the system are promising approaches to limit the margin requirements for polarization effects. In particular, the PDL impact is expected to be larger for agile networks with high flexibility density than for point-to-point (P-P) transmission, whereas PMD accumulation is still dominated by the transmission fiber. This paper describes estimated bounds on speed and magnitude of PDL effects, and presents insights into the impact of control loops.

2. Transmission design for agile optical networking

An arbitrary optical path traversing the agile optical network is shown in Fig.1 where channel λ_{ref} shares fiber link cross-sections with other channels which go on and off the physical optical train arbitrarily at optically transparent nodes such as OADM and wavelength cross-connect (WXC). The path traffic patterns are dynamic, with new connectivities established and old ones taken off on customer demand. Traditional P-P DWDM transmission based demarcation sections between MUX/DEMUX and regen's/terminals are smeared out and replaced by time varying arbitrary paths.

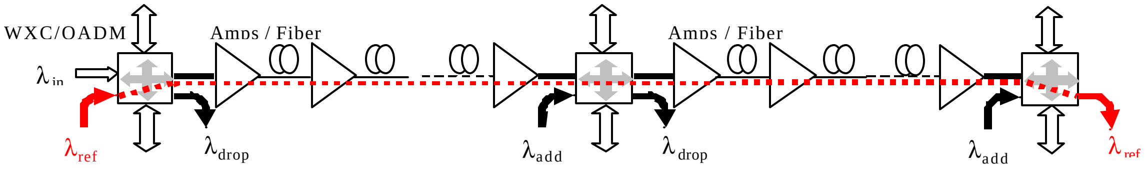

Figure 1. Agile network arbitrary optical path

In an agile DWDM network, an optical path may extend over several thousand kilometers and pass through 100 to 1000 nonzero PMD and PDL elements, in addition to the PMD of the transmission fiber. Main polarization-induced optical impairments include OSNR fluctuations, distortions due to PMD and PDL, and time-varying cross-talk due to nonlinear optical fiber propagation as well as interaction between channels through amplifier gain dynamics and broadband compensators. Potential remedies include fast, single-channel dynamic control in the photonic and electronic layer, novel modulation formats, forward error correction (FEC), optical regeneration as well as the selection of fiber plant and components that exhibit low polarization sensitivity. Scaling rules for low-probability statistical transmission impairments are derived from numerical and analytical models.

3. Margin estimates for agile optical networking

We examine the OSNR fluctuations that originate from state-of-polarization (SOP) and path-accumulated PDL variations. A straightforward simulation approach is to setup a concatenation of PDL elements with random SOP scattering between elements, and spontaneous emission noise added periodically at amplifier sites. As a result of a large number of realizations of such a path, we obtain statistical distributions for the accumulated PDL [2], for the received signal and noise power and for the polarization properties of the optical noise field. The $OSNR$(dB) = S(dB)-N(dB), where S and N are the signal and the noise power, will fluctuate with a variance of $\sigma^2_{OSNR} = \sigma^2_S + \sigma^2_N \approx \sigma^2_S$ (Fig. 2a). The noise power is hardly affected by PDL and the variance σ^2_N ($<< \sigma^2_S$) can be neglected. For calculating signal-spontaneous beat noise, however, the noise power N_p that is polarized

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parallel to the signal is required. Simulations show that this variance $s^2_{Np} \approx 0.3 s^2_S$ cannot be neglected. Therefore, when polarized noise and signal fluctuations are combined in a polarized-OSNR estimate (Fig. 2b), we might conclude that $\tilde{s}^2_{\mathrm{OSNRp}} = s^2_S + s^2_{Np} \approx 1.3\, s^2_S$ is larger than the depolarized OSNR calculated above. In contrast, the correct simulation shows a much compressed rather than broadened probability distribution for the parallel-polarized OSNR (Fig. 2c). It is important to realize that fluctuations of noise and signal power are actually highly correlated. In fact, the linear correlation coefficient is as high as $r = 0.84$. Therefore, the variance of the parallel-polarized OSNR is reduced to $s^2_{\mathrm{OSNRp}} = s^2_S + s^2_{Np} - 2 s_S s_{Np} r_{SNp} \approx 0.4\, s^2_S$. The PDL penalty is less severe than a simpler model might suggest. Adequate modeling of these correlations yields a 30-% reduced standard deviation for OSNR. These and other correlations between physical transmission parameters are significant for accurate margin estimates.

Further significant reduction of PDL-induced power fluctuations is expected through dynamic per-channel power control throughout the network. Here, the speed rather than the magnitude of PDL events poses a challenge. Experimental and numerical results for various scenarios of mechanical perturbation of pieces of fiber show that a significant part of power transients are faster than 100 ms. A 3-dB reduction of the largest power fluctuation amplitudes that occur with 1% probability require control loops with a response faster than 10 Hz.

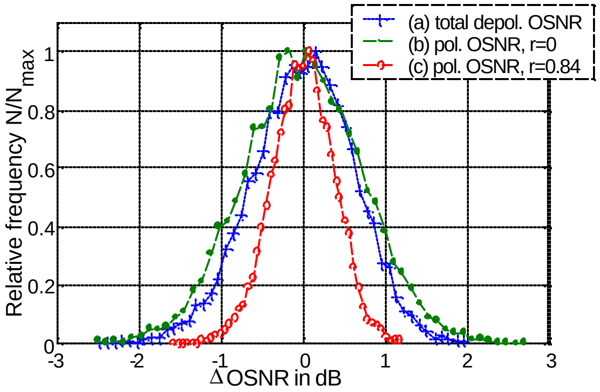

Figure 2. Magnitude of OSNR fluctuations for (a) total received noise power, (b) noise power parallel polarized to the signal (c) parallel-polarized noise power from correlated data sets which originate from identical random realization of the link. The standard deviations are (a) 0.62 dB, (b) 0.72 dB, and (c) 0.38 dB.

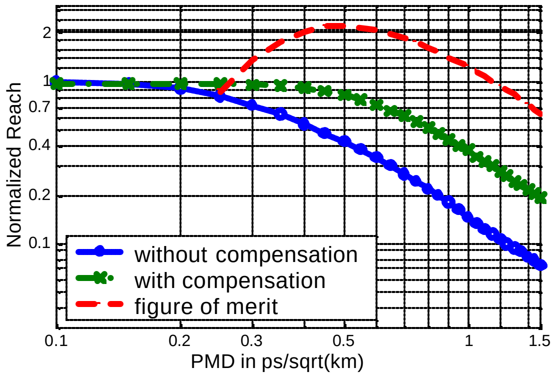

Figure 3. Simulation of normalized reach with and without dynamic PMD compensation. A figure of merit is defined as $F = DL/L_{\mathrm{Reg}}$, where DL is the absolute gain in reach and L_{Reg} is the distance between regeneration sites.

4. Dynamic compensation of PMD in agile networks

A typical PMD-induced reach degradation for a 10 Gbit/s NRZ system is shown in Fig. 3. A PMD compensator with an attractive reduction of DGD-induced penalty, even extending beyond one bit period, is applied to the accumulated effect of PMD. The reach is calculated from the available margins. As shown in Fig. 3, the reach is extended only up to a “ceiling” where non-PMD impairments terminate the path. A 2 to 3-fold increase in reach is observed in the high-PMD limit. On an absolute scale, the reach enhancement in low- and high-PMD situations is incremental. A figure of merit is the “reach enhancement in (integer) units of regeneration distances”, i.e. $F = DL/L_{\mathrm{Reg}}$, which shows the best compensation benefit for 0.4 to 0.6 ps/km$^{1/2}$ PMD. Yet, the physical limitations of various compensation schemes have to be explored including higher-order PMD, bounds on speed, and PDL.

5. Summary

Bounds on the polarization tolerance of ULH agile photonic networks are redefined when physical correlation mechanisms, such as PDL-induced signal and noise fluctuations, are taken into account. Furthermore, through experiment and simulation we have identified speed requirements and compensation benefits for dynamic control in next-generation communication systems.

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