Polarization-Dependent Loss Induced Penalties in PDM-QPSK Coherent Optical Communication Systems

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Abstract: We evaluate PDL-induced penalties in PDM-QPSK coherent systems with both lumped model and distributed model. We find the lumped model significantly over-estimates PDL penalties and PDM coherent systems can tolerate more PDL than single-polarization systems.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications; (260.5430) Polarization

1. Introduction

Polarization-division-multiplexed (PDM) optical coherent systems with digital signal processing (DSP) is considered a promising technique for next generation optical networks [1][2]. With the full optical field information accessible after coherent detection, optical coherent systems have the potential to significantly increase the spectral efficiency and the ability to perform transmission impairment compensation in the electrical domain by high-speed DSP. PDM quadrature-phase-shift-keying (PDM-QPSK) coherent optical communication systems are a good candidate to upgrade existing 10-Gb/s dense wavelength-division-multiplexed networks with 50-GHz channel spacing to 40-Gb/s or 100-Gb/s.

Although chromatic dispersion and polarization-mode dispersion can be easily compensated in a coherent receiver by powerful DSP, polarization-dependent loss remains a problem and its effects cannot be well compensated in a coherent receiver. PDL causes signal power and optical signal-to-noise-ratio (OSNR) fluctuation and depolarizes amplified spontaneous emission (ASE) noise. In addition, PDL induces non-orthogonality between two originally orthogonal polarizations for a PDM signal. For system designers, it is important to understand PDL impairments and allocate appropriate margin to PDL for a system to operate properly.

PDL effects on direct detection optical communication systems have been well studied and understood [3]-[7], but there are few studies on PDL impairments in coherent systems [1][8][9]. In [1] and [8], PDL penalties in a coherent system were measured with a lumped PDL model, and in [9], theoretical analysis on PDL impairments in a PDM coherent system was presented. In this paper, we evaluate PDL induced penalties in a PDM-QPSK system with both lumped model and distributed model from both average penalty and outage probability aspects. In addition, the PDL impairments in PDM-QPSK and single polarization (SP) QPSK coherent systems are compared.

2. PDL Models

In the study of PDL effects on optical communication systems, two PDL models have been used. One is a lumped model and the other is a distributed model, as shown in Fig. 1.

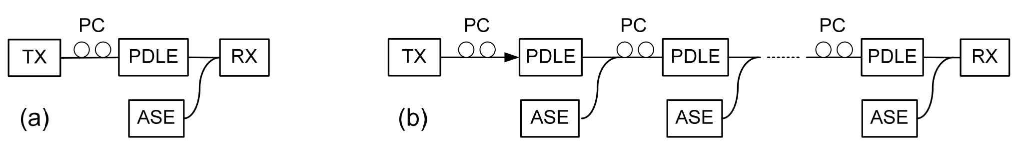

Fig. 1. PDL models. (a) lumped model, (b) distributed model.

In the lumped model, there is one PDL emulator (PDLE) and amplified spontaneous emission (ASE) noise is loaded at the receiver, and in the distributed model, many PDLEs and ASE noise are distributed along a link, with random polarization rotations between PDLEs. The lumped model is simple. It is helpful to understand some PDL effects and usually used in lab tests. But it does not include all the PDL effects such as depolarization of ASE noise. Typically a polarization controller (PC) or polarization scrambler (PS) is inserted before the PDLE to get the PDL penalty at a particular input state of polarization (SOP) or average PDL penalty. The distributed model is similar to a real system and automatically takes into account all the PDL effects. But the distributed model is challenging to deal with and has to be analyzed statistically.

3. PDL Induced Penalties in 112-Gb/s PDM-QPSK Coherent Systems

Simulations were performed to investigate PDL penalties in PDM-QPSK coherent systems. In the simulations, 112-

Gb/s non-return-to-zero (NRZ) PDM-QPSK was used, which was generated by two nested Mach-Zehnder QPSK modulators driven with 2^{10} De Bruijn bit sequence at 56-Gb/s. The QPSK signal is differentially encoded. In the receiver, the constant modulus algorithm (CMA) was employed for polarization demultiplexing [10] and phase noise of both the transmitter and the local oscillator was neglected. 200 different ASE noise realizations were used to calculate bit error ratio (BER) for each PDL realization, and the BER was the average BER over both polarizations.

a) Lumped model

With a lumped model, PDL penalties are specified at a certain input SOP. The average penalty and outage probabilities can also be obtained if the statistics of input SOP and PDL are given. For a PDM signal, the worst and best performance degradation occur when a PDM signal is 0^o and 45^o aligned to the axes of a PDL element, respectively. In the worst case, the performance of one polarization tributary is degraded while that of the other tributary is improved, therefore the overall performance degradation induced by PDL in the worst case for a PDM signal is smaller than that for a SP signal. In the best case, PDL induces the largest non-orthogonality between the two polarization tributaries and the two tributaries have the same PDL penalty [7].

To get the average PDL penalty and outage probabilities, without loss of generality, we assume that the PDL axes are aligned with x and y axes, and the SOP of a signal is expressed as $\vec{E} = \left(\cos(\theta/2),\ \ \sin(\theta/2)e^{i\phi}\right)^T$ in the Jones space, where the superscript T means the transpose of the vector. For a uniform distribution of SOP on the Poincaré sphere, the probability density function of θ and ϕ are

$$f(\theta) = \sin\theta/2\,,\ \ 0 < \theta \le \pi\,, \qquad f(\phi) = 1/2\pi,\ \ 0 < \phi \le 2\pi \tag{1}$$

The PDL penalty is independent of ϕ. With a PS in front of the PDLE, the average BER can be calculated as

$$BER_{ave} = \int_0^{\pi}\int_0^{2\pi} BER(\theta,\ \phi)\, f(\theta)\, f(\phi)\, d\phi d\theta = \int_0^{\pi} BER(\theta)\, f(\theta)\, d\theta \tag{2}$$

The outage probability can be obtained

$$OP = \int_0^{\infty}\int_0^{\pi} I(PDL,\theta)\cdot f(PDL)\cdot f(\theta)\cdot d\theta\cdot dPDL\ ,\ \ I(PDL,\ \theta) = \begin{cases} 1, & BER(PDL,\ \theta) > BER_0 \\ 0, & \text{else} \end{cases} \tag{4}$$

where BER_0 is the threshold BER and an outage is defined as $BER > BER_0$.

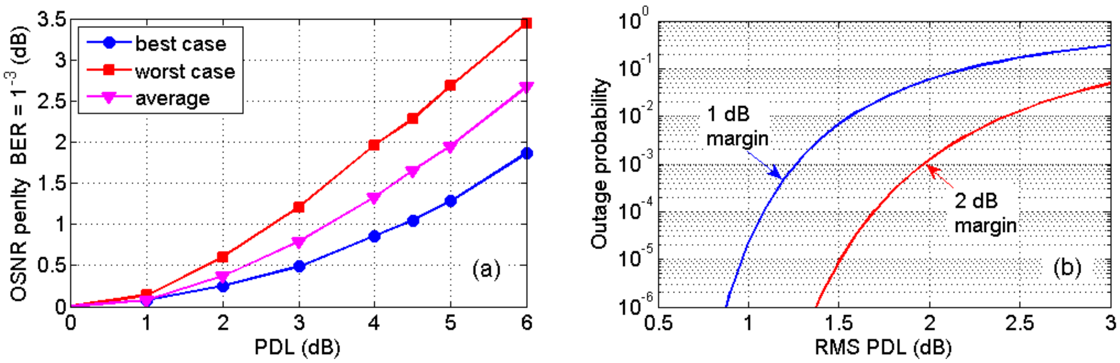

Fig. 2. (a) PDL induced OSNR penalty versus instant PDL value at BER = 10^{-3} in different cases using the lumped model, (b) outage probabilities at BER = 10^{-3} versus root mean square (RMS) PDL value using the lumped model.

Fig. 2 (a) gives PDL induced average OSNR penalty (assuming the PS generates a uniform SOP distribution on the Poincaré sphere) at BER = 10^{-3} and the penalty in the worst and best cases. There is a large difference of the penalties among different cases. With 4-dB PDL value, the OSNR penalty is about 0.8 dB and 2 dB in the best and worst case, respectively, while the average penalty is about 1.3 dB. The outage probabilities versus root mean square (RMS) PDL value at 1-dB and 2-dB margins calculated with the lumped model are illustrated in Fig. 2 (b), where PDL value in dB is assumed to be Maxwellian distributed [11]. It shows that at outage probability of 10^{-5}, the tolerable RMS PDL is about 1.0 and 1.5 dB with 1- and 2-dB margins, respectively.

b). Distributed model

In the lumped model, the ASE noise power is fixed at the receiver, while in a real system, ASE noise is generated along the link and when PDL attenuates the signal, it attenuates the noise as well. Therefore, the lumped model over-estimates OSNR variations and thus PDL penalties. This is confirmed in Fig. 3, which depicts the probability distribution of OSNR variations in one polarization calculated with the lumped model and distributed model at 3-dB RMS PDL value. For the distributed model, 20 PDL elements are used and PDL and ASE noise are equally distributed along the link. These results show that the lumped model generates much larger OSNR variations than the distributed model.

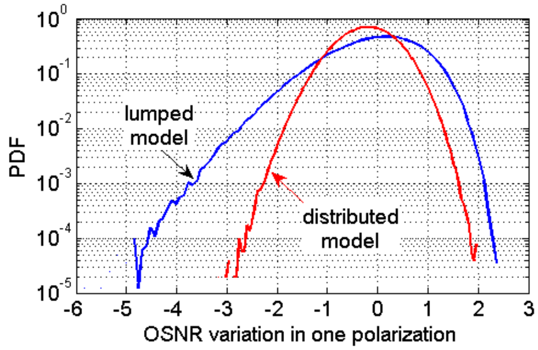

Fig. 3. Simulated probability density function (PDF) of PDL induced OSNR variations in one polarization using the lumped model and the distributed model at the RMS PDL value of 3 dB.

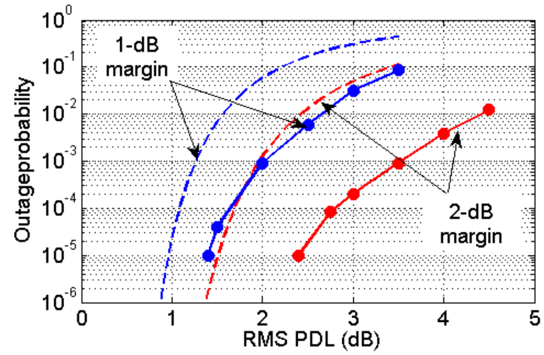

Fig. 4. PDL induced outage probabilities at BER = 10^{-3} versus RMS PDL value using the distributed model (symbol lines) and lumped model (dashed lines).

The outage probabilities at BER = 10^{-3} using the distributed model are given in Fig. 4, where 20 PDL elements and ASE noise are equally distributed along the link. Monte Carlo simulations were used and the lowest points in the two curves are the extrapolation result. For comparison, the results using the lumped model are also given. It clearly shows that the lumped model significantly over-estimates the PDL penalties. At outage probability of 10^{-5}, the tolerable RMS PDL value with 1- and 2-dB OSNR margin obtained using the distributed model is about 1.4 and 2.4 dB, respectively, while it is about 1.0 and 1.5 dB using the lumped model.

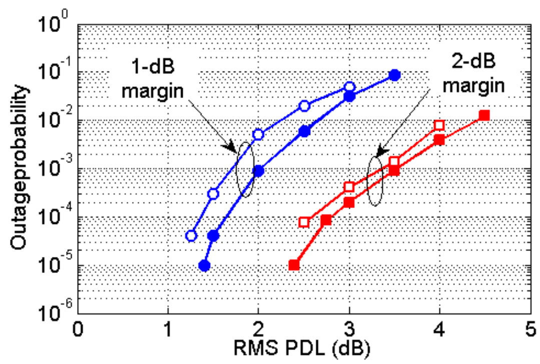

Fig. 5. PDL induced outage probabilities at BER = 10^{-3} versus RMS PDL value for 112-Gb/s PDM-QPSK (filled symbols) and 56-Gb/s SP-QPSK (open symbols). The distributed model is used.

Figure 5 compares the PDL tolerance between the SP-QPSK and PDM-QPSK coherent systems. It shows that the PDM system can tolerate about 10-20% more PDL than the SP system at low outage probabilities. This is because that the system outages mostly occur with the SOP in the worst case and the worst case degradations caused by PDL is smaller for a PDM system than for a SP system due to the average effect between the two polarization tributaries, as we discussed before. This effect is more pronounced at higher BER, so we expect that the difference between a PDM system and SP system becomes smaller if they operate at lower BER.

4. Conclusion

We have studied PDL penalties in 112-Gb/s PDM-QPSK coherent systems with both the lumped model and distributed model. We found that the lumped model significantly over-estimates the PDL penalties. We showed that at outage probability of 10^{-5} and BER of 10^{-3}, the PDM-QPSK system can tolerate about 1.4 and 2.4 dB RMS PDL with OSNR margin of 1 and 2 dB. We also found that a PDM coherent system can tolerate 10-20% more PDL than a SP coherent system.

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