Experimental Probing and Modeling of the PDL Impact on the Optical Signal-to-Noise Ratio

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Abstract: The PDL impact upon the OSNR is systematically probed in an experimental setup using coherent optical technology for the first time. Extending the observation through a Monte Carlo analysis, the PDL-induced OSNR penalty is modeled. © 2023 The Author(s)

1. Introduction

Deployment of coherent optical technologies is rapidly expanding from core to metro network segments to support IP traffic growth in metropolitan areas [1]. Moreover, starting from metro scenarios, white-box based solutions are being considered, in order to enable cross-vendor interoperability [2]. From this perspective, the adoption of a vendor-neutral QoT estimator (QoT-E) is suitable to enable light-path computation and ensure the reliability of transceiver (TRX) settings, maximizing deployable capacity [3]. Metro networks are typically characterized by topologies including several optical switches that are based on wavelength selective switches (WSS). Each crossed WSS inserts a non-negligible polarization-dependent loss (PDL) on the switched lightpaths, summing randomly due to random polarization rotations induced by the fiber spans. Such rotations vary over time due to temperature cycles and mechanical stresses, meaning that the PDL affecting the two orthogonal polarization states used for modulation is a time-varying random process. The performance impact of PDL on coherent optical technologies is consequently the optical signal-to-noise ratio (OSNR) penalty, depending also upon where the amplified spontaneous emission (ASE) noise is introduced with respect to the PDL sources [4]. Thus, an accurate model is needed to describe the PDL penalty induced by the crossed WSSs for a reliable lightpath QoT-E, specifically for metro network segments. As an example, for a given optical line system (OLS), the worst case performance impact due to the WSS PDL can be evaluated by considering a system total PDL, Σ_{PDL}, which is the sum of all PDL contributions (in logarithmic units) introduced by each WSS, and the ASE noise generated entirely at the OLS termination. This results in a significant penalty, equal to $\Sigma_{\mathrm{PDL}}/2$, nevertheless, this worst case is extremely conservative with respect to the reality as the ASE noise generation is, in general, distributed along the OLS, and the extreme Σ_{PDL} realization is very improbable, as it requires a specific combination of polarization rotations. Therefore, to properly estimate the OSNR penalty and to avoid PDL-induced out-of-service (OOS), as typically applied to the polarization mode dispersion (PMD) impairment, an adequate investigation is required in order to characterize the complex interplay between the PDL and ASE noise distributions.

The PDL impact has been extensively analyzed for propagation of polarized intensity-modulated channels [5], while the impact on dual-polarization coherent technologies has not yet been entirely clarified in order to be used within physical layer models of optical networks [3]. As a matter of fact, even if PDL-induced polarization power variations throughout the transmission have been statistically quantified for an arbitrary number of PDL-introducing components [6, 7], the impact of the PDL on transmission performance has been reduced to a generic GSNR penalty that must be included as a margin [8]. The OSNR is affected by the interplay of the PDL and transmission impairments, and this complexity may vary significantly depending on the optical system under consideration [9, 10]. Recently, the effect of PDL on the OSNR has been investigated on a sub-sea scenario using a numerical approach [11]. In this work, the effect of the accumulated PDL as an OSNR penalty is experimentally observed on a 100 G DP-QPSK commercial TRX crossing 4 WSSs, exploring a large number of polarization rotation realizations by means of 3 polarization scramblers (PSs) and different noise injection configurations: the

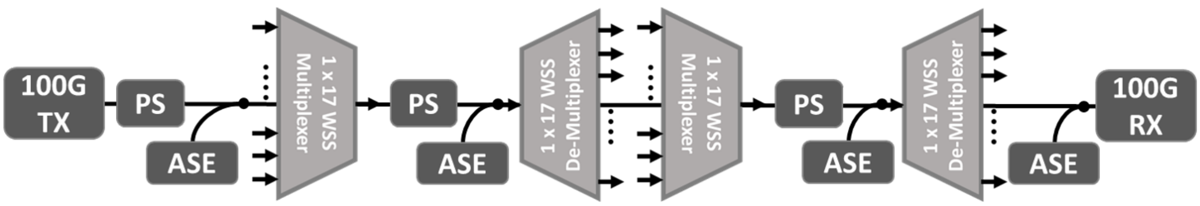


Fig. 1: Sketch of the experimental setup.

ASE noise has been loaded either purely at the transmitter side (**Scenario TX**), at the receiver side (**Scenario RX**), or in a uniformly distributed manner by using all the 4 ASE noise sources (**Scenario DIST**). The experimental results clearly show the complex interplay of the PDL and noise source distribution. Following this, a numerical Monte Carlo PDL/OSNR simulator is verified over the experimental results and extended to OLSs with uniform PDL and ASE distributions, in order to provide a quantitative OSNR penalty analysis in reference use cases.

2. Experimental Setup

The experimental setup used for the direct observation of the PDL-induced OSNR degradation is schematized in Fig. 1. An optical source consisting of a commercial card generates a 100 GBd, DP-QPSK channel with 25% roll-off at 194.3 THz. The signal is propagated through a cascade of 4 1x17 WSSs, replicating a characteristic optical line system (OLS) in a metro transmission scenario. Each port of the WSS is programmed by setting the filter bandwidth at 50 GHz, centred at the channel frequency without any extra attenuation; the latter condition assures fixed PDL values for each device maintained, for all the measurements. In particular, the first WSS is used as a multiplexer which introduces the channel in the OLS (*add* operation). Next, a de-multiplexer and a multiplexer are coupled, constituting the equivalent of a crossed reconfigurable optical add & drop multiplexer (ROADM), and lastly a de-multiplexer is used to filter out the channel (*drop* operation). Finally, 3 optical PSs are used in place of fiber connections between the OLS components mentioned above, each modifying the polarization state of the input signal, exploring the entire Poincaré sphere, and replicating in roughly 1 minute the long-time variations of the polarization rotation induced by the fiber spans in real systems. For the specific port and frequency, the PDL introduced by each component has been separately characterized before the setup installation along with the resulting PDL of the entire OLS. We obtain 0.2, 0.8 and 0.4 dB for the first multiplexer WSS, the ROADM equivalent coupled WSSs and the last de-multiplexer WSS, respectively; as the PS rotates the propagated signal along the entire Poincaré sphere, the measured total PDL roughly equals the PDL sum of the three components at 1.4 dB. Four distinct ASE noise sources are distributed along the OLS enabling a tunable distributed noise loading. For all three investigated scenarios, the amount of ASE noise injected has been precisely calibrated in order to provide a fixed overall OSNR value of 7.4 dB. After the propagation, the signal has been received and the OSNRs relative to the two distinct polarization directions have been separately obtained by converting the $\mathrm{BER_X}$ and $\mathrm{BER_Y}$, respectively, evaluated by the commercial card. As the OSNR measurements on the two polarization directions provide equivalent results, in the following only one of the two metrics is considered and addressed simply as OSNR.

3. Results

The measured distributions of the PDL-induced OSNR variations, ΔOSNR, with respect to the reference 7.4 dB value are shown in Fig. 2 for the three different scenarios. As quantitative metrics characterizing ΔOSNR are reported in Tab. 1, showing; the difference between the maximum and minimum measured ΔOSNR in dB, χ^m_{OSNR}, and the standard deviation of the OSNR variations, σ^m_{OSNR}, expressed in dB as $\sigma^m_{\mathrm{OSNR,dB}} = 10\log_{10}(1+\sigma^m_{\mathrm{OSNR,lin}})$. As expected, ΔOSNR is strictly correlated to the noise distribution along the OLS. In particular, in **Scenario RX**, the PDL effect has the largest contribution and the ΔOSNR distribution coincides with the signal variation distribution, as the ASE noise introduced at the end terminal is constant. Moving the amount of added ASE noise towards the transmitter side, the ΔOSNR distribution shrinks reaching the minimum variation for **Scenario TX**. In this case, both the signal and the ASE noise undergo the same amount of PDL, therefore, the OSNR is conserved along the entire OLS; in principle, the observed ΔOSNR should be equal to zero in this case. The residual PDL effect observed in **Scenario TX** can be attributed to the PDL experienced by the loaded ASE noise, which is filtered over the channel bandwidth using a separate WSS before being injected in the OLS.

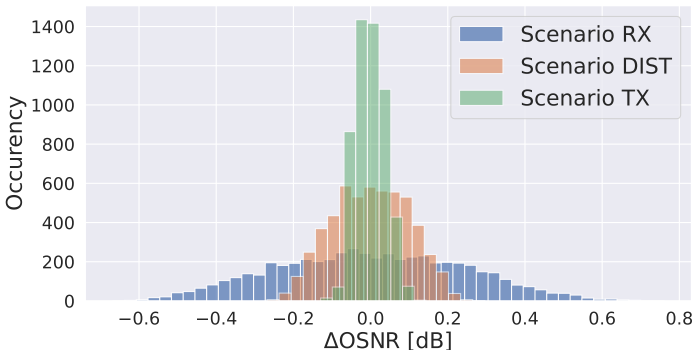
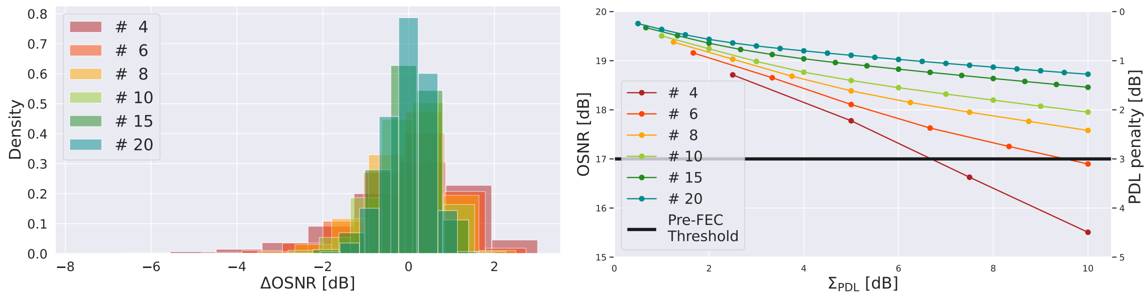


Fig. 2: Experimental distributions of the PDL-induced OSNR variation, ΔOSNR, for the three scenarios: RX, DIST and TX.

Scenario	TX	DIST	RX
σ^m_{OSNR} [dB]	0.0	0.1	0.2
χ^m_{OSNR} [dB]	0.3	0.6	1.4
σ^s_{OSNR} [dB]	0.0	0.2	0.3
χ^s_{OSNR} [dB]	0.0	0.7	1.4

Table 1: Summary of σ_{OSNR} and χ_{OSNR} obtained from the experiments, m, and the simulations, s, for each scenario.



(a) (b)

Fig. 3: (a) Simulated ΔOSNR distributions for a growing number of WSSs introducing a fixed total PDL, $\Sigma_{\mathrm{PDL}} = 10$ dB. (b) OSNR and PDL-induced penalty vs. Σ_{PDL} for a growing number of WSSs.

In order to extend the PDL-induced degradation of the final OSNR to various reference use cases, a Monte Carlo algorithm has been developed by replicating the propagation of the channel through the OLS, including the ASE noise injection, the local PDL effect, and the random polarization rotation of the channel induced by the fiber span. First, the measured ΔOSNR metrics with the simulated equivalents, χ^s_{OSNR} and σ^s_{OSNR}, are compared. In Tab. 1, it can be observed that the simulations provide compatible results in terms of the chosen metrics and, in particular, preserve the behaviours highlighted in the description of the measurements. In addition, the Monte Carlo analysis has been extended to different reference use cases characterized by a uniform distribution of both PDL, summing up to a fixed value of 10 dB, and ASE noise generation, giving a final OSNR of 20 dB, which is 3 dB above the reference pre-forward-error-correction (Pre-FEC) threshold for the 400 G transmission standard. In this work, the OSNR is expressed by considering the entire channel symbol rate as the noise bandwidth. The simulation is iterated by propagating the channel through different OLSs, including, in turn, an incremental number of WSSs and ASE noise sources while maintaining the same amount of final total PDL, Σ_{PDL}, and OSNR. In Fig. 3(a), the distributions of the simulated scenarios show that increasing the number of WSSs reduces the OSNR variation for a given fixed total Σ_{PDL} value, suggesting that the realization probabilities of the worst case scenarios decrease sharply as the number of WSSs introducing the same total amount of PDL increases. Finally, the PDL-induced OSNR penalty is quantified by fixing an arbitrary OOS probability of 0.1 %. By approximating the simulated OSNR distributions expressed in linear units with the equivalent truncated Gaussian distributions, it is possible to evaluate the minimum OSNR margin that guaranties the fixed OOS probability, defined as PDL-induced OSNR penalty. In Fig. 3(b), the evaluated OSNR and PDL-induced penalties are shown for all simulated scenarios, along with the reference Pre-FEC threshold given by the 400 G transmission standard. It can be observed that, depending on the number of WSSs in the OLS, transmission scenarios involving the same amount of Σ_{PDL} may be affected by an overly large OSNR penalty, preventing lightpath deployment. In any case, in most realistic scenarios, where the high value of accumulated PDL is given by a large number of WSSs that each introducing a reasonable PDL, the OSNR penalty remains limited.

4. Conclusion

In this work, the complex interplay between PDL and transmission impairments is investigated and its effect on the OSNR degradation is experimentally observed. The large difference between the PDL-induced OSNR penalties, either in the worst case scenarios on in most probable realizations, highlights the need of precise modeling. A Monte Carlo simulator has also been tested using experimental measurements and exploited for a simple investigation of the PDL-induced OSNR penalties in some characteristic reference use cases. In future works, both the experimental and simulation campaigns will be extended, providing a further insight of the PDL effects, along with an accurate analytical expression of the PDL-induced OSNR penalties.

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