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Statistical Assessment of System Margin in Metro Networks Impaired by PDL

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Abstract: We experimentally justify the need of analyzing stochastic PDL insertion in optical metro network nodes. Consequently, we assess conservative OSNR margin comparing different approaches to the case with maxwellian-distributed PDL, through Monte Carlo simulation. © 2025 The Author(s)

1. Introduction

As 5G and future 6G networks, Artificial Intelligence, and Data Center Interconnects continue to evolve, the convergence of metro and access networks emerges as a critical enabler for achieving seamless, intelligent, and high-capacity transparent end-to-end (E2E) connectivity, transforming the traditional boundaries of network architecture [1]. Driven by the increasing demand for E2E data traffic, optical network operators are seeking innovative, cost-effective solutions, including software-defined, open, and disaggregated network architectures [2]. From this perspective, to maximize deployable capacity, the adoption of a vendor-neutral quality of transmission (QoT) estimator enables light-path computation [3]. In metro networks, characterized by topologies containing several optical switches, reconfigurable add/drop multiplexers (ROADMs), leveraging wavelength selective switches (WSSs), are crucial for dynamic and automated traffic routing. However, WSSs, introduce significant polarization-dependent loss (PDL). PDL is time-varying due to random polarization rotations caused by fiber spans, which are influenced by temperature fluctuations and mechanical stress. In addition, PDL is also frequency and port dependent. This time-varying random process impacts the optical signal-to-noise ratio (OSNR), particularly in relation to the location of amplified spontaneous emission (ASE) noise within the network [4]. Metro-access network convergence requires the seamless integration of high-capacity metro networks with lower-capacity access networks. Assessing the system margin, based on out of service (OOS) probability, helps ensure that OSNR fluctuations caused by PDL do not impair transmission quality. Worst-case scenarios assuming a significant PDL penalty are highly conservative due to the distributed nature of ASE noise and the low probability of extreme PDL events. Consequently, a detailed analysis is required to prevent PDL-induced service outages.

In past works, the impact of PDL in term of OSNR penalty has been experimentally investigated for a cascade of WSS, considering each WSS to introduce a constant amount of PDL for fixed frequency channel and port [5]. In such experiments, the statistic of received PDL-induced OSNR distributions has be proven to be gaussian, in accordance to [6], due to the random polarization rotations caused by fibers connecting the WSSs. The statistical characterization of PDL impairment on OSNR has been performed in disaggregated manner in [7], considering both increasing and decreasing deterministic PDL insertion along the link. In case of deterministic PDL for each ROADM, standard deviation and difference between maximum and minimum values of the PDL-induced OSNR distributions can be computed in closed form [7]. However, the PDL value introduced in each WSS in real systems is not deterministic, due to its port and frequency dependence. It has been proven that, in addition to the stochastic polarization rotations, PDL introduced by each WSS is stochastic itself, and it can be modeled as maxwellian-distributed [8, 9]. For instance, frequency dependency of PDL, observed when characterizing single devices [4], has an impact also on the received OSNR distribution of a cascade of PDL devices, as concluded in the preliminary experimental analysis provided in this work. An extensive experimental analysis of PDL impact on OSNR, when PDL is stochastic, is not feasible, requiring to change signal input and output port and signal frequency, in additon to polarization alignment between each ROADM, in order to replicate the maxwellian PDL insertion in each WSS. Moreover, there are no closed formulas to evaluate the final OSNR distribution standard deviation and difference between maximum and minimum when PDL is random-distributed. Therefore, there is the need to analyze which deterministic deployment of PDL can be chosen to evaluate conservatively the system margin, exploiting existing formulas. The novelty of this work is the investigation of maxwellian-distributed PDL case, by means of Monte Carlo analysis, which allows to simulate hundred of thousands of possible PDL realizations and polarization alignments. Simulations are replicated also for some cases in which PDL is deterministic, to compare the margin given by them to the realistic random PDL case. The Monte Carlo analysis is carried taking as a reference metro networks scenario, where PDL effect is significant, due to the presence of an high number of ROADMs.

2. Preliminary Experimental Analysis

The experimental setup considered to observe the frequency dependency of PDL-induced OSNR degradation is provided in Figure 1. The commercial transceiver generates a 32 GBd DP-QPSK channel with 25% roll-off at three

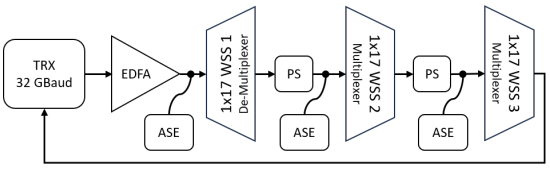


Fig. 1: Experimental setup scheme.

f [THz]	EDFA [dB]	WSS_1 [dB]	WSS_2 [dB]	WSS_3 [dB]	σ_{OSNR} [dB]
191.5	0.11	0.20	0.31	0.28	0.060
194.5	0.20	0.37	0.22	0.14	0.041
195.5	0.17	0.20	0.19	0.18	0.033

Table 1: (1st col.)Transmitted signal frequency values; (2-5th col.) PDL values for each device for each frequency; (6th col.) Received OSNR distributions standard deviations for each frequency .

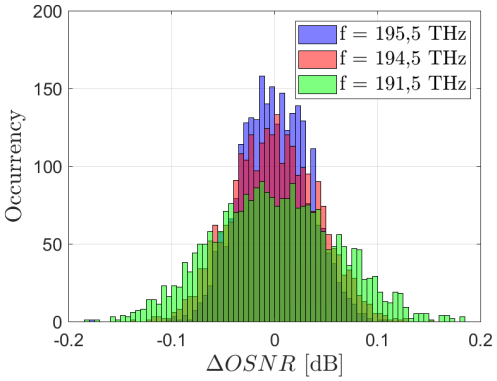


Fig. 2: Received OSNR distributions for each frequency.

frequencies of interest: 191.5 THz, 194.5 THz and 195.5 THz. The transmitted signal crosses an erbium doped fiber amplifier (EDFA) and a cascade of three WSSs. The presence of the amplifier was necessary due to power budget reason. All the devices have been separately characterized in term of introduced PDL for the specific ports and for the selected frequencies, as it is summarized in Table 1. Between the WSSs, 2 polarization scramblers (PS) are responsible of changing the polarization state of the signal and consequently the PDL alignment between the WSSs. Three ASE noise sources are distributed along the link. The amount of injected ASE noise has been calibrated to obtain a fixed overall OSNR value of 12.7 dB at the receiver. The received OSNRs, corresponding to the two main polarization axes, have been obtained by converting the bit error rate (BER) on x-polarization and y-polarization, provided by the linecard. Since equivalent results were obtained for both the polarization axes, only one polarization has been considered, and the corresponding metric called for simplicity OSNR. The received distributions of the frequency-dependent PDL-induced OSNR variations (referenced as $\Delta OSNR$) with respect to the reference value of 12.7 dB are provided in Figure 2. Observing the distributions, it can be noticed the dependency of PDL-induced OSNR variation on the transmitted signal frequency, as expected. The standard deviations of OSNR distributions in correspondence of the frequencies of interest are provided in column number 6 of Table 1. Such result underlines the need to treat the inserted PDL statistically for system margin assessment, and it allows to understand the importance of Monte Carlo analysis based on maxwellian PDL insertion, which constitutes the core of the present work.

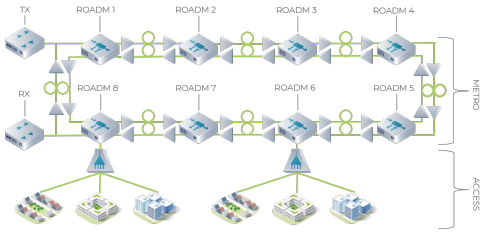


Fig. 3: Reference system for Monte Carlo Simulations.

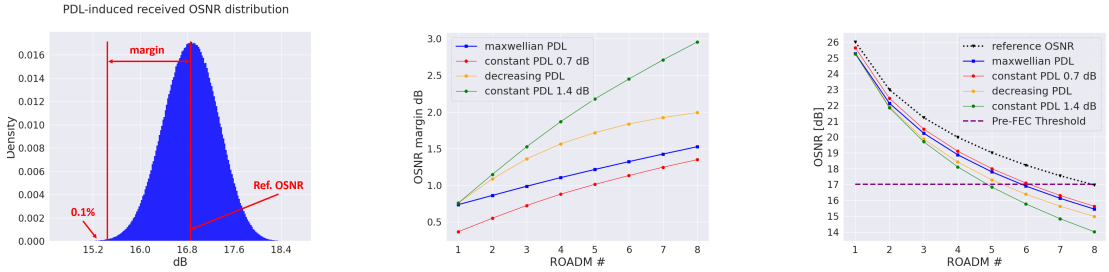
ROADM #	unif. 0.7 dB	decr.	unif. 1.4 dB
1	0.7	1.4	1.4
2	0.7	1.2	1.4
3	0.7	1.0	1.4
4	0.7	0.8	1.4
5	0.7	0.6	1.4
6	0.7	0.4	1.4
7	0.7	0.2	1.4
8	0.7	0	1.4

Table 2: PDL value in dB for each ROADM considering deterministic PDL insertion.

3. Monte Carlo simulation and Results

The reference system for simulations is depicted in Figure 3, which represents a metro-access network scenario. The simulation results are obtained by propagating clockwisely a signal from ROADM number 1 to ROADM number 8, provided by TX and RX blocks, testing the worst case in which PDL is accumulated crossing all the ring nodes. The considered link is composed by 8 ROADMS, introducing PDL on both the propagated signal and the accumulated noise, which is injected by the optical amplifiers between each ROADM couple. A reasonable amount of ASE noise for metro networks, equal to -25 dBm, is injected due to optical amplification between each ROADM couple. It is assumed that, for each fiber link, a couple of amplifiers (booster and preamplifier) work with gain set to 15 dB, with noise figure equal to 8 dB, on a bandwidth of 64 GHz. The transmitted signal power is set to 1 dBm, considering a single propagating channel within the C-band, according to the input power per channel for state-of-the art ROADMs. An ideal receiver performing cross polarization power equalizing is assumed. The Monte Carlo simulator is equivalent to the software framework reproducing the PDL effect, which has been experimentally validated in [5], adding the feature to set the PDL in each ROADM to be extracted from a maxwellian distribution. Regarding the PDL that a ROADM could be responsible of, a maximum value of 1.4 dB has been chosen, assuming each WSS to introduce a maximum of 0.7 dB of PDL, since from each input and output port couple two WSSs are crossed by the signal. To be consistent with the previous assumption, when PDL is stochastic, the maxwellian probability density function has been adapted so that each realization is lower or equal than 1.4 dB, with a probability of 0.99, and then truncated. The optical amplifier PDL has been

neglected simplifying the system structure. As a target for the system margin to be estimated, an OOS probability of 0.1% has been taken as a reference. Applying such constraint to the received PDL-induced OSNR distribution, it is possible to determine a margin, setting the threshold when 0.1% of distribution area is covered in the left tail. An example of PDL-induced OSNR distribution after 8 ROADMs, considering maxwellian PDL insertion, with the corresponding margin is showed in Figure 4a. The Monte Carlo simulation has been executed first with maxwellian-PDL, replicating a real system scenario, and successively according to 3 deterministic-PDL scenarios, in order to compare the real case with them. Regarding the deterministic PDL insertion among the ROADMs, considered values are depicted in Table 2, in which PDL can be uniform equal to worst-case maximum value of 1.4 dB, uniform equal to mean case of 0.7 dB and uniformly decreasing from maximum value of 1.4 dB to 0 dB.



(a) (b) (c)

Fig. 4: (a) Margin computation based on the received OSNR distribution. (b) Margins for all the considered PDL insertion scenarios. (c) OSNR PDL-induced penalty vs number of ROADMS for all the considered PDL scenarios.

The margins computed based on the received OSNR distributions are shown in Figure 4b for all the PDL scenarios. Again, the results for both the polarizations axes were equivalent, therefore only one polarization is considered. First, the dummy choice of medium PDL value equal to 0.7 dB is not conservative with respect to the random PDL case, which represents the real system. Conservative margins are obtained when PDL is uniformly decreasing and when, as expected, it is set to the worst case for each ROADM. The situation depicted in Figure 4b suggests to adopt decreasing PDL as reference deterministic PDL displacement since it leads to conservative margin which is also closer to the real system one, rather than considering just the worst case of maximum PDL insertion along the link. Such consideration is confirmed looking at Figure 4c, in which the margin has been subtracted from the reference OSNR expected in absence of PDL. The reference OSNR is computed based on the transmitted power and the noise sources power as: $OSNR_{ref} = P_{TX,dBm} - P_{n,dBm} - 10log_{10}(N_{ROADM})$. Also the reference Pre-FEC threshold given by the 400 G transmission standard is provided, allowing to exploit the computed margins to design the maximum system length in term of ROADMs. Focusing on the PDL effect for real system with maxwellian PDL, it can be seen that its maximum reach is equal to 5 ROADMs, significantly lower than 8 ROADMs, given by the reference OSNR in absence of PDL. Considering the conservative margins given by deterministic PDL, the decreasing PDL assumption allows to dimension the system with 5 ROADMs, as the real system case, while the worst case assumption of PDL equal to 1.4 dB leads to waste resources, dimensioning a system composed by just 4 ROADMs. Such difference highlights the importance of finding conservative but at the same time efficient margin, when trying to select the opportune deterministic PDL displacement. According to such purpose, the simulation of maxwellian-distributed PDL plays a pivotal role.

4. Conclusion

In this work a statistical approach to margin assessment is explored for metro networks affected by PDL impairment. The findings of this study play a crucial role in ensuring that the optical infrastructure supporting metro-access networks convergence can maintain reliable performance while being optimized for efficiency. Conservative margin is selected, based on the comparison between the Monte Carlo simulation output for a realistic system, impaired by stochastic maxwellian PDL, and some deterministic PDL displacements along the link. The decreasing PDL approach is selected as the most effective among the considered ones. Further works will extend the simulation campaign, optimizing the deterministic PDL displacement, and will focus on the mathematical modeling of the PDL-induced OSNR penalties for maxwellian-distributed PDL.

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