# Automated Mitigation of Quality of Transmission Fluctuations Induced by PDL Anomalies

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***Abstract*—We propose a closed-loop automation to mitigate quality of transmission fluctuations due to polarization dependent loss (PDL) anomalies. We experimentally demonstrate stabilization of $Q^2$ within +/-0.2 dB despite 5 dB of PDL.**

***Index Terms*—optical networks, netowrk optimization, polarization dependent loss, automation**

## I. Introduction

In optical transmissions, polarization dependent loss (PDL) occurs in many components such as wavelength selective switches and amplifiers. For standard polarization-multiplexed (PM) coherent communications, PDL elements cause a dependence between their input states of polarization (SOP) and the quality of transmission (QoT) [1], e.g. the $Q^2$ or pre-FEC BER measured at Receiver (Rx). Thus, natural SOP fluctuations [2] combined with PDL leads to QoT fluctuations. When one faulty component induces abnormally large PDL, e.g. of several dB, this PDL anomaly dominates over normal PDL from other components and can lead to QoT fluctuations with ranges exceeding 1 dB [1], [3]. This phenomenon is consistent with the large QoT fluctuations observed in Fig.1 from available field data [4]. Large QoT fluctuations cause technical problems, from confusion in network management to an increased failure probability due to the transient and unexpected margin erosion. Thus, there is a need to compensate for this effect.

PDL-induced QoT fluctuations dominantly stem from the QoT mismatch between the two orthogonal tributaries created when a PDL component is located before an amplifier [1]. Thus, QoT fluctuations from PDL may not be fully mitigated at Rx through digital signal processing [5]. In parallel, substantial research showed that PDL and associated QoT fluctuations can be largely mitigated through spatiotemporal coding [6]. Our alternative and possibly lower-complexity solution tackles large PDL anomalies, where high QoT gains can be expected from the mitigation. It consists in controlling the SOP at the transmitter (Tx) to permanently maintain the QoT at its optimal level. In the following, we start by revisiting the physics behind large PDL-induced QoT fluctuations observed in field data. Then, we present our closed-loop automation and explain how it can be deployed in any optical network. Finally, we show simulation and experimental results demonstrating our solution's ability to stabilize the QoT in presence of PDL despite SOP fluctuations.

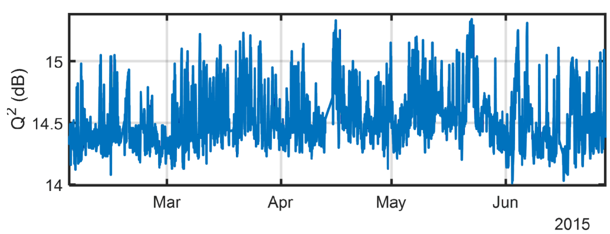


Fig. 1. Observation of large QoT fluctuations on a selected channel (#2252) in a large optical network backbone [4], consistent with the combination of a PDL anomaly with natural SOP fluctuations.

## II. QoT fluctuations induced by PDL elements

In [1], Duthel *et al* studied the impact of a single PDL element on PM coherent transmissions. The authors specifically studied how the QoT varies depending on the angle between the PDL axis and the orthogonal, linearly polarized Tx lasers of both H and V tributaries. As extension, we performed numerical simulations of large chains of PDL elements closely emulating arbitrary optical connections. We simulated a typical 100G PM-QPSK transmission as described in Fig. 2(a). The *SOP control* block is a rotation of angle $\theta_0$ in the polarization plane for controlling the SOP at Tx output. It is coded as a pure rotation matrix in Jones space. Note that throughout the paper, we do not account for the ellipticity of the SOP as this parameter does not impact the QoT. Similarly, the repeated *ROP* blocks are rotations of angle $\theta_i$, i from 1 to N; N stands for the total number of chained *PDL* blocks. These ROP blocks emulate the SOP fluctuations between two

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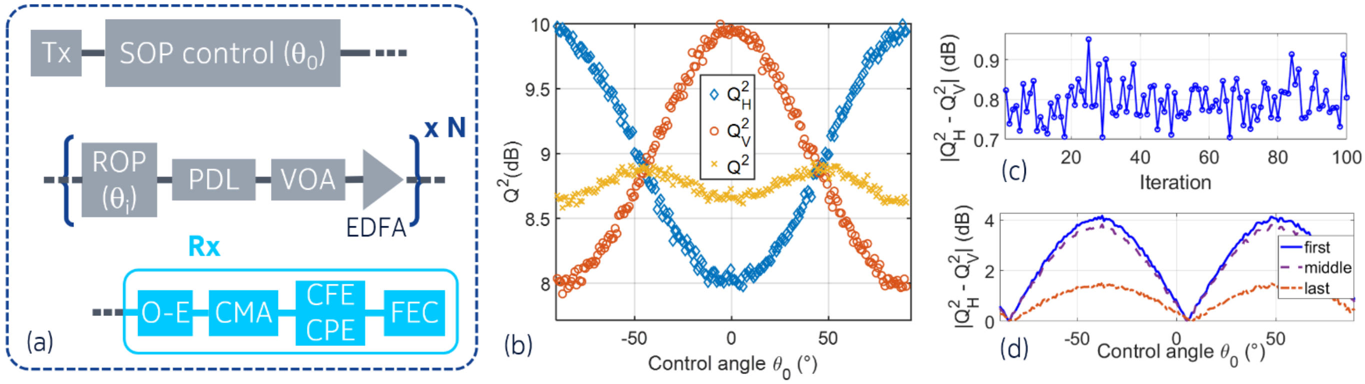


Fig. 2. (a) Simulation and experimental setup. The noise added in each of the N spans is controlled through a variable optical attenuator (VOA) before optical amplification (EDFA). (b) QoT vs $\theta_0$ for N=1 ($\theta_1$=0), $|Q^2_H - Q^2_V|$ for N=10 with (c) all PDL at 0.4 dB and (d) one PDL at 4 dB and nine at 0.4 dB

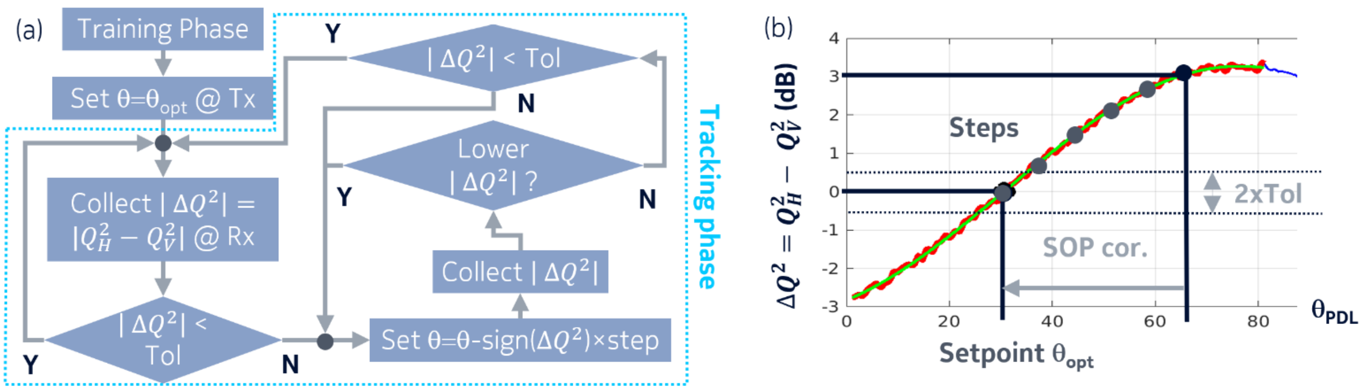


Fig. 3. (a) Flowchart of the closed-loop SOP control loop for mitigating PDL-induced QoT fluctuations over a single lightpath and (b) example of calibration curve obtained during training phase to determine SOP setpoint $\theta_0$ and convergence parameters.

consecutive PDL elements. In the following, we describe the QoT through the Q$^2$ metric deriving from the pre-FEC BER, as $Q^2 = 2\left[\text{erfc}^{-1}\left(2\text{ BER}\right)\right]^2$. Similarly, we describe the QoT of both H and V tributaries with $Q^2_H$ and $Q^2_V$ deriving from $BER_H$ and $BER_V$ through the same equation. For a single PDL element - i.e. N=1 - we plot in Fig. 2(b) $Q^2$, $Q^2_H$ and $Q^2_V$ as functions of $\theta_0$ with $\theta_1 = 0$. Due to the PDL, $Q^2$ varies with $\theta_0$ between two extremes [1]. The maximum $Q^2$ is achieved for $\theta_0 = \pi/4 + k\pi/2$ when $Q^2_H = Q^2_V$, while the minimum is obtained for $\theta_0 = 0 + p\pi/2$ when $|Q^2_H - Q^2_V|$ is maximal; k and p are integers. Indeed, PM tributaries are interleaved in standard coherent communications. Thus, BER = 0.5 $BER_H$ + 0.5 $BER_V$ so that $Q^2$ is not the average but a nonlinear function of $Q^2_H$ and $Q^2_V$. Consequently, the varying QoT penalty is due to the PDL-induced mismatch between $Q^2_H$ and $Q^2_V$. Next, we simulate a chain of N=10 PDL elements, first with same 0.4 dB magnitude and random, uniformly distributed, $\theta_i$ angles renewed between each of the 100 iterations and $\theta_0 = 0$. The result in Fig. 2(c) shows that the arbitrary SOP fluctuations between the cascaded PDL elements tend to randomize $|Q^2_H - Q^2_V|$ so that $Q^2$ may only slightly vary in time in typical configurations. We then emulate the presence of single PDL anomaly by introducing a 4 dB-PDL amongst nine 0.4 dB-PDL elements, in first, middle and last position. The $\theta_i$ angles are randomly selected while $\theta_0$ is scanned from $-\pi/2$ to $+\pi/2$. Result is plotted in Fig. 2(d). We notice that regardless of the position of the PDL anomaly, its impact largely dominates the variations of $|Q^2_H - Q^2_V|$ and thus $Q^2$, and can be controlled though the angle $\theta_0$ at Tx despite random fluctuations of the polarization states between consecutive PDL elements.

## III. Automated Mitigation of PDL-Induced QoT Fluctuations through SOP Control

To mitigate PDL over an entire optical network, our solution consists in controlling the SOP at Tx for each lightpath (LP) through independent instances of the same control algorithm running in parallel. The solution can be implemented with a centralized control plane or by direct signaling between paired transponders. The SOP can be adjusted at Tx with minimal added complexity, either at digital-to-analog conversion, or through polarization control of the outgoing optical signal. For each LP, correction of the SOP are occasionally triggered so that the measured $Q^2_H$ and $Q^2_V$ are maintained approximately equal, leading to a maximized QoT. As depicted in the flowchart of the control loop in Fig. 3(a), the automated

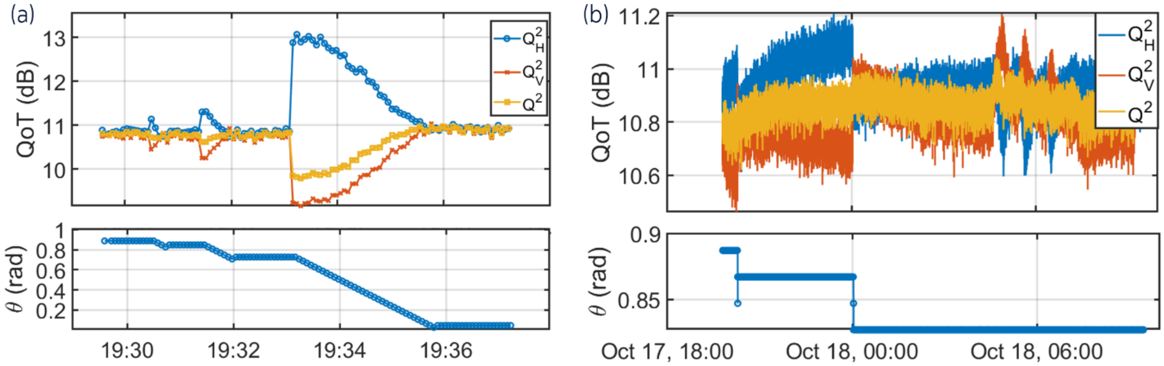


Fig. 4. PDL mitigation experiments with (a) large and instantaneous perturbations of the SOP and (b) continuous SOP perturbations from Rayleigh statistics

cancellation of PDL-induced QoT fluctuations can be decomposed into two phases, training and tracking. The training is a calibration step meant to adjust every instance of the algorithm to the unique LP it controls. It consists in scanning the SOP at Tx output $\theta$ to characterize $\Delta Q^2 = Q_H^2 - Q_V^2 = f(\theta_{PDL})$ for the LP, as depicted in Fig. 3(b) where $\theta_{PDL}$ represents the input SOP for the PDL anomaly. The SOP $\theta = \theta_{opt}$ achieving $\Delta Q^2 = 0$ becomes the setpoint of the automation. During the tracking phase, the SOP is corrected to maintain $\left|\Delta Q^2\right|$ within tolerance, hence the QoT in the vicinity of the optimum value. Effective SOP correction is triggered when $\left|\Delta Q^2\right|$ exceeds the tolerance. The SOP correction is applied step-by-step, where the angular step is determined based on the training phase to ensure that the variation of $\left|\Delta Q^2\right|$ between steps is significantly higher than measurement noise. A correction cycle ends when $\left|\Delta Q^2\right|$ cannot be further reduced and is back within bounds. The algorithm is notably designed to function even if the training curve collected at startup becomes obsolete due to major SOP drifts or network reconfigurations. In such rare events, the control angle will be continuously modified until $\left|\Delta Q^2\right|$ is reduced and eventually returns within bounds.

## IV. Experimental results

Our experimental testbed is based on an offline back-to-back transmission of a typical 100G PM-QPSK where we inserted a SOP controller, a SOP scrambler and a PDL element between the Tx and the VOA. It corresponds to the representation in Fig. 2(a) with N=1. The PDL is set at approximately 5 dB. In a first experiment, we test the robustness of the automation under large and fast SOP variations. As explained in the previous section, we start by the training phase where we measure $\Delta Q^2$ as a function of the control angle $\theta$ applied through the SOP controller. Based on the collected data, we set the angular step to 0.02 rad. After training, we impose increasingly large step-like variations of the SOP at the input of the PDL through manual control of the SOP scrambler. The result is plotted in Fig. 4(a). For each of the three step-like perturbations, the solution manages to recover the initial point corresponding to an optimal $Q^2$ around 11 dB. Expectingly, the larger the SOP perturbation, the longer it takes for the step-by-step mitigation to converge. This illustrates the necessary limitation from the response time of the closed-loop when it comes to counteracting fast and large SOP variations. To test the automation with SOP perturbations closer to the typical rates observed in deployed optical networks, we set in a second experiment the SOP scrambler so that it continuously modifies the SOP on Poincaré sphere following Rayleigh statistics, which best reproduces natural SOP fluctuations in optical fibers[2]. We plot the result in Fig. 4(b) obtained after overnight measurements. With realistic SOP fluctuations, our solution manages to maintain the $Q^2$ within +/-0.2 dB despite the large PDL anomaly in the experimental setup.

## V. Conclusion

We proposed an automated and low-complexity solution to mitigate the impact of PDL anomalies from faulty components on the QoT of PM coherent optical transmissions. Through experiments, we demonstrated the robustness of the proposed solution through its ability to counteract large step-like SOP perturbations as well as stabilizing the $Q^2$ within +/-0.2 dB despite 5 dB of PDL and realistic SOP fluctuations.

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