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PDL Localization and Estimation through Longitudinal Power Monitoring: a Comparison between Least Squares and Correlation Methods

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***Abstract*—In this work, we compare two Longitudinal Power Monitoring (LPM) techniques (Least-Squares and Correlation Method) for localizing and measuring Polarization-Dependent Loss (PDL) in a multi-span optical transmission link. We consider situations with different PDL values in the link and multiple PDL sources.**

***Index Terms*—Longitudinal Power Monitoring, Optical Communications**

I. Introduction

The accurate monitoring of optical links plays a crucial role in ensuring the reliable operation and effective management of an optical network. Recently proposed Longitudinal Power Monitoring (LPM) algorithms [1]–[4] exploit the digital data available inside standard coherent receivers, which eliminates the need for external devices and represents a cost-effective solution for the monitoring of the optical link. These LPM algorithms can be divided into two main families, namely correlation-based methods (CM) [1], [4] and Least Squares (LS)-based methods [2], [3].

Traditionally, LPM has been employed mainly for power profile estimation. However, additional parameters have successfully been estimated in recent research, such as chromatic dispersion coefficient for fiber type identification [5], Multi-Path Interference (MPI) [4], and Polarization-Dependent Loss (PDL) [3], [6], [7]. In particular, a precise monitoring of PDL is critical, since it can introduce a significant penalty in terms of link performance. Moreover, since its effect is closely related to the location of the PDL source in the system, accurate localization is also required. To this end, two methods have been proposed to estimate and localize PDL, based on linear LS (LLS) [3], [6] and correlation methods [7]. However, no direct comparison between the two methods has been carried out so far. For this reason, in this work we perform a detailed comparison between the two approaches, analyzing their performance under varying PDL conditions. We consider two scenarios: first, different PDL values within the link, and second, multiple PDL sources distributed across a simulated optical link consisting of ten 50-km single mode fiber (SMF) spans.

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II. Simulation setup

The simulation setup is reported in Fig. 1. The transmitted signal consists of a PM-64QAM channel having square-root raised-cosine spectral shape with roll-off 0.15, modulated at 128 GBaud and with a channel power $P_{\text{ch}} = 5\,\text{dBm}$. The link is composed of 10×50-km identical SMF spans, with attenuation $\alpha_{\text{dB}} = 0.2\,\text{dB/km}$, CD coefficient $\beta_2 = -21.28\,\text{ps}^2/\text{km}$ and non-linearity coefficient $\gamma = 1.3\ 1/\text{W/km}$. Each span is followed by an EDFA with noise figure $5\,\text{dB}$, working in constant output power mode to fully compensate for both the span loss and the average PDL loss. The PDL sources have been modeled according to the Jones formalism as:

$$\mathbf{E}_{\text{out}} = \mathbf{R}^{-1} \begin{pmatrix} 1 & 0 \\ 0 & \rho \end{pmatrix} \mathbf{R}\mathbf{E}_{\text{in}} \tag{1}$$

where $\mathbf{R}$ is a random unitary matrix, $\rho = 10^{-\frac{\text{PDL}_{\text{dB}}}{20}}$ and $\mathbf{E}_{\text{in/out}}$ are the input and output optical signals, respectively. Fiber propagation has been simulated using the split-step Fourier Method (SSFM) to implement the Manakov equation. The SSFM step has been set as described in [8]. After propagating, the received signal enters a standard coherent receiver, where it is resampled at a rate of 2 samples per symbol and processed by several DSP blocks, which perform CD compensation, data-aided LMS-based fractionally-spaced adaptive equalization and blind-phase search (BPS) carrier phase recovery. The output of this last stage is extracted and used as input of the LPM algorithms, briefly described in the following.

The CM method is implemented according to [1], with a nonlinear remediation parameter equal to $\epsilon = 0.01$ and introducing the modifications proposed in [7] to compute polarization-wise power profiles. Note that a calibration procedure [7] needs to be performed both on the transmission link and the estimated power profiles, since CM-based LPM

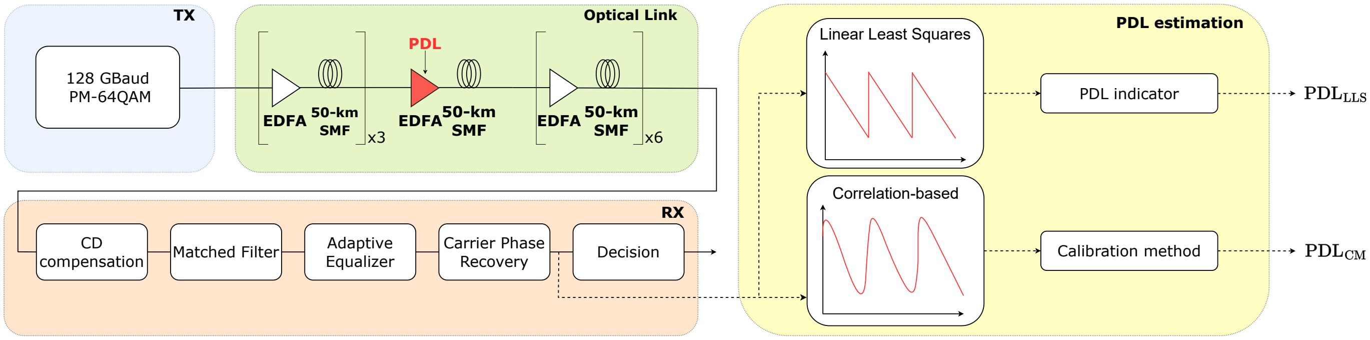

Fig. 1. Simulation setup (left) and PDL estimation schematic (right).

does not estimate real power values. In particular, an anomaly indicator $\mathrm{AI} = \mathrm{AI}_x + \mathrm{AI}_y$ is computed, where $\mathrm{AI}_{x/y}$ indicates the anomaly indicator of the individual polarizations, defined as the difference between a reference and a monitoring profile. Its peak is then mapped to a location on the link and to a PDL value through a calibration factor which relates correlation variations to power variations. The LLS-based LPM described in [2] is adapted for polarization-wise estimation, as well, as proposed in [3]. The LLS-based LPM outputs the real power evolution of the optical signal, hence PDL is estimated considering a PDL indicator computed as the difference – in logarithmic units – between the maximum and minimum values of the estimated power profiles for each position on the link. In both cases (CM and LS), the spatial step is fixed to $\Delta z = 2\,\mathrm{km}$.

III. Results and Discussion

The first comparison is performed by inserting a lumped PDL element at the beginning of the 4th span (corresponding to a distance of $z = 150\,\mathrm{km}$ from the transmitter side), whose value is varied between $0.25\,\mathrm{dB}$ and $3\,\mathrm{dB}$. For each PDL value, 10 estimations are performed leveraging both LPM algorithms, using $\sim 7 \cdot 10^5$ samples as input. In particular, calibration and reference profile estimation are performed before the estimation of the 10 monitoring profiles with the CM-based method. Afterwards, AI is computed and its peak is used to retrieve the inserted PDL value. In the case of LLS-based LPM, polarization requires rotation, either at the transmitter or receiver, to align the signal's polarization with the PDL element's axes. To achieve this alignment, 20 random rotations were performed at the transmitter for each estimated value, maintaining the polarization-rotating elements within the transmission link in a fixed position. This is in line with the assumption that, in a realistic scenario, the incident state of polarization at the PDL elements remains relatively stable over time. Finally, the PDL indicator allows to localize the span at which the PDL source is inserted and its value is estimated as the mean of such indicator over the first half of the span. In this region, the signal power is still relatively high and the LPM algorithm yields a more accurate power estimation. The mean estimated PDL values and their standard deviation σ_{PDL} are reported in Fig. 2.

Both approaches manage to yield relatively accurate results. However, for PDL values below $1\,\mathrm{dB}$, which are also the typical values, the calibration method manages to yield very accurate estimations down to $0.25\,\mathrm{dB}$ with a standard deviation $\sigma_{\mathrm{PDL}} < 0.05\,\mathrm{dB}$ and a maximum estimation error of $0.058\,\mathrm{dB}$. On the contrary, the LLS-based approach provides less accurate estimations. This can be explained by considering that LLS-based power profiles are a deconvolved version of the CM-based ones, which causes noise and distortion enhancement. Hence, the intrinsic estimation noise of the algorithm does not allow to detect PDL values below a certain threshold. A confirmation of this aspect is given by the fact that the same estimation performed on the 4th span, when no PDL source is present, yields an estimation around $0.5\,\mathrm{dB}$, thus defining the minimum detectable PDL value of the algorithm under the considered conditions.

Nevertheless, the lower accuracy with respect to the calibration method is compensated by the lower complexity of the LLS-based approach. Indeed, LLS does not require any calibration procedure to be performed on the transmission link, nor a reference profile to be compared with the monitoring ones. In addition, calibration in the CM needs to be performed again if some transmission parameters are changed, e.g., the symbol rate. This of course adds more complexity and degrades the flexibility of the transmission system. Moreover, LLS-based LPM outputs the real signal power evolution, meaning that PDL can be directly computed using its definition, i.e., a simple difference between absolute power values, in logarithmic units.

Another scenario that has been considered is the one with multiple PDL sources within the link. To this end, two 2-dB PDL elements have been inserted in the same setup as in Fig. 1 at the beginning of the 4th and 7th span, i.e., at $z = 150\,\mathrm{km}$ and $z = 300\,\mathrm{km}$. Since the end-to-end PDL value depends on the relative orientation of the PDL axes of the single elements, they have been set so as to have a total PDL of $3\,\mathrm{dB}$. The PDL and anomaly indicators obtained with the two approaches are reported in Fig. 3.

While the LLS-based approach in Fig. 3a is able to clearly localize both PDL elements and yield the correct cumulated value, the CM-based approach in Fig. 3b simply manages to localize the PDL elements. However, it does not seem to

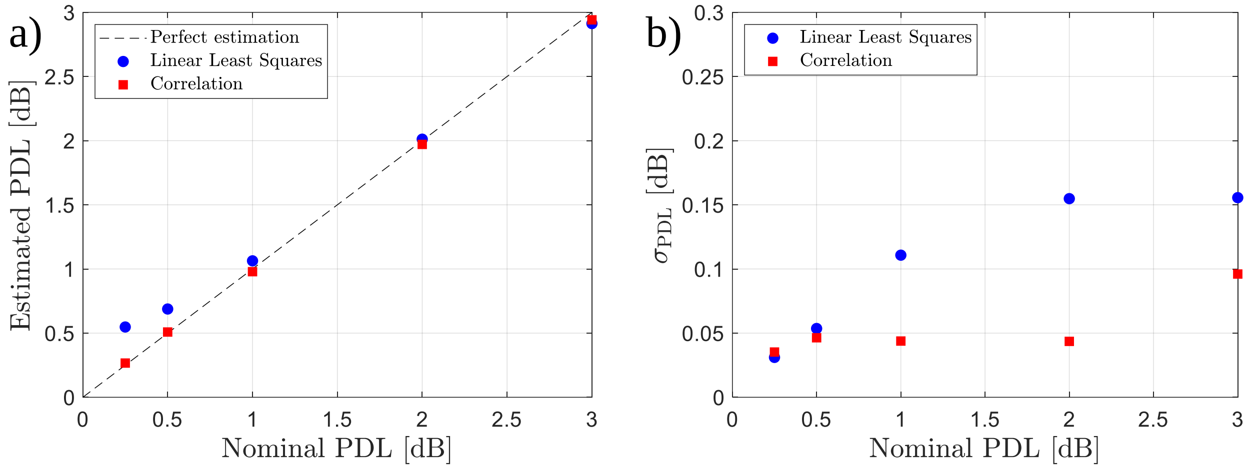

Fig. 2. a) Mean estimated PDL over 10 realizations, obtained with both LLS-based (blue) and CM-based (red) approaches. Dashed line represents perfect estimation. b) Standard deviation of estimated PDL values.

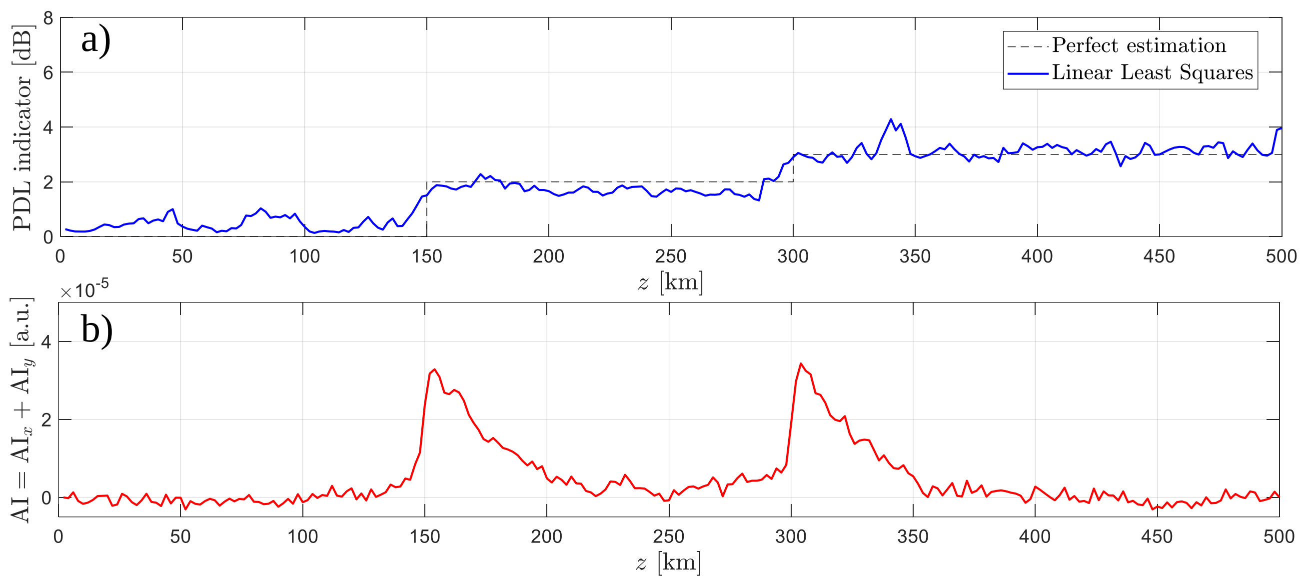

Fig. 3. Resulting a) PDL indicator and b) anomaly indicator AI when two 2-dB PDL elements are inserted on the link at $z = 150\,\mathrm{km}$ and $z = 300\,\mathrm{km}$. The end-to-end PDL is set to $3\,\mathrm{dB}$.

give any useful information on the cumulated value, since both estimated values are around $2\,\mathrm{dB}$. This represents a clear advantage of the LS-based approaches with respect to the CM-based ones.

IV. Conclusion

In this work, we performed a comparison between Least-Squares (LS) and Correlation (CM) LPM methods to localize and measure PDL in a single-channel multi-span optical transmission link. We found that CM-based methods are able to accurately detect and estimate values of PDL as small as $0.25\,\mathrm{dB}$ with a maximum estimation error of $0.058\,\mathrm{dB}$. However, the main trade-off is represented by the higher complexity of the calibration procedure. In the case of multiple PDL sources along the optical link, instead, only the LLS-based method succeeds in both detecting and estimating the correct end-to-end PDL value.

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