Experimental Demonstration of Monitoring PDL Value and Location Using DSP-Based Longitudinal Power Estimation with Linear Least Squares

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Abstract *We experimentally demonstrate fiber-longitudinal monitoring that visualizes polarization-wise signal powers. The method is based on linear least squares and successfully estimates the position and amount of PDL in a multi-span optical link. Results show accurate PDL estimation with errors below 0.5 dB at 1-km granularity.*

Introduction

In polarization-multiplexed digital coherent systems, polarization dependent loss (PDL) is a dominant factor limiting the capacity and distance of fiber transmission systems [1-4]. PDL appears in various link components such as fiber couplers, wavelength selective switches (WSS), and erbium-doped fiber amplifiers (EDFA) [5-7].

The power imbalance at the PDL component output depends on the incident state-of-polarization (SOP). Thus, the PDL behaves as a stochastically varying loss and results in stochastic variations in the system performance. Hence, to ensure reliability over its operational lifetime and avoid system outages, a network needs to be designed with margins assuming the worst case [2]. The accumulated margins of individual PDL components increase the ambiguity of the estimated signal quality, thus limiting the transmission rate. If distributed PDLs that occur randomly and simultaneously in a multi-span link can be accurately monitored, such worst-case designs can be avoided and the transmission rates can be maximized.

Therefore, monitoring the physical parameters of optical links has attracted much attention as a very important technique for estimating network failures and reducing excess operating margins, and various monitoring techniques have been proposed [8-10]. One technique, the transceiver-based longitudinal power profile estimation (PPE) [11-17], can estimate signal power evolution over multiple spans using a single coherent receiver without additional measuring equipment. PDL localization was recently demonstrated using PPE [18, 19], but the correlation method used in the demonstration does not estimate the true power, as noted in [16]. Thus, the true value of the PDL is difficult to estimate without hardware-based calibration [19]. In addition, the spatial resolution of the correlation method is limited, as shown in [16].

In this work, we experimentally demonstrate a fiber-longitudinal PPE that can both locate PDL positions with high spatial resolution and estimate PDL true values. The method is based on linear least squares and accurately estimates polarization-wise signal power [20], achieving reliable PDL estimation and localization. The experiment was performed using dual-polarization transmission over a 3-span × 50-km link, with a PDL resolution of 0.5-3 dB and a spatial step size of 1 km. All estimated PDL values agree with actual values with estimation errors of < 0.5 dB.

Method

Our monitoring method for estimating PDL is based on [20], which uses linear least squares to estimate the polarization-wise power profile on the basis of the Manakov equation. The optical signal $\boldsymbol{A}(z,t) = \left[A_x(z,t), A_y(z,t)\right]^{\mathrm{T}}$ at position z and time t is governed by Manakov equation with loss (amplification) coefficients for x and y signals $\alpha_x(z)$ and $\alpha_y(z)$, the group velocity dispersion β_2, and the nonlinear coefficient γ. By transforming variables $A_{x/y}(z,t) = E_{x/y}(z,t)\exp\left(-\frac{1}{2}\int_0^z \alpha_{x/y}(z')\,dz'\right)$, the loss and nonlinear coefficients can be merged as $\frac{\partial \boldsymbol{E}}{\partial z} = j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}\boldsymbol{E} - j\left(\gamma_x'(z)|E_x|^2 + \gamma_y'(z)\left|E_y\right|^2\right)\boldsymbol{E}$, where

$$\gamma_{x/y}'(z) = \frac{8}{9}\gamma P(0)\exp\left(-\int_0^z \alpha_{x/y}(z')dz'\right). \quad (1)$$

Note that the power of $\boldsymbol{E}$ is normalized to 1. From (1), if $\gamma_x'(z)$ and $\gamma_y'(z)$ are obtained, the polarization-wise signal powers $P_x(z)$ and $P_y(z)$ can be estimated, assuming γ is constant. PDL can then be estimated as the power difference between $P_x(z)$ and $P_y(z)$. Therefore, our estimation target is $\boldsymbol{\gamma}'(z) = \left[\gamma_x'(z), \gamma_y'(z)\right]^{\mathrm{T}}$.

In our method, $\widehat{\boldsymbol{\gamma}'}$, the estimation of $\boldsymbol{\gamma}'(z)$, is formulated as the following linear least squares problem:

$$\begin{aligned}\begin{bmatrix}\widehat{\boldsymbol{\gamma}'_x}\\ \widehat{\boldsymbol{\gamma}'_y}\end{bmatrix} &= \underset{\boldsymbol{\gamma}'_x,\boldsymbol{\gamma}'_y}{\operatorname{argmin}}\, I \\ &= \underset{\boldsymbol{\gamma}'_x,\boldsymbol{\gamma}'_y}{\operatorname{argmin}}\, \mathbb{E}\left[\left\|\boldsymbol{E}[L]-\boldsymbol{E}^{\mathrm{ref}}[L]\right\|^2\right],\end{aligned} \tag{2}$$

where $\boldsymbol{E}[L]$ is the received digitized signals and $\boldsymbol{E}^{\mathrm{ref}}[L]=\left[\boldsymbol{E}_x^{\mathrm{ref}}[L],\boldsymbol{E}_y^{\mathrm{ref}}[L]\right]^{\mathrm{T}}$ is the reference signal obtained as an output of an digitally emulated optical link. Here, we model both received and reference signals by the first-order regular perturbation such as $\boldsymbol{E}[L]=\boldsymbol{E}_0^{\mathrm{ref}}[L]+\boldsymbol{E}_1^{\mathrm{ref}}[L]$. Then, the cost function in (2) becomes

$$I=\mathbb{E}\left[\left\|\boldsymbol{E}_1[L]-\boldsymbol{E}_1^{\mathrm{ref}}[L]\right\|^2\right], \tag{3}$$

assuming linear terms satisfy the Nyquist theorem. The perturbation term $\boldsymbol{E}_1^{\mathrm{ref}}$ can be expressed as

$$\begin{pmatrix}\boldsymbol{E}_{1,x}^{\mathrm{ref}}\\ \boldsymbol{E}_{1,y}^{\mathrm{ref}}\end{pmatrix}=\boldsymbol{G}\begin{pmatrix}\boldsymbol{\gamma}'_x\\ \boldsymbol{\gamma}'_y\end{pmatrix}=\begin{pmatrix}\boldsymbol{G}_{xx} & \boldsymbol{G}_{xy}\\ \boldsymbol{G}_{yx} & \boldsymbol{G}_{yy}\end{pmatrix}\begin{pmatrix}\boldsymbol{\gamma}'_x\\ \boldsymbol{\gamma}'_y\end{pmatrix}, \tag{4}$$

where the k-th columns of $\boldsymbol{G}_{pq}$ $(p,q\in\{x,y\})$ are $\left(\boldsymbol{G}_{pq}\right)_k=(-j\Delta z)\cdot\boldsymbol{D}_{z_kL}\cdot\left(\left|\boldsymbol{E}_{0,q}[z_k]\right|^2\boldsymbol{E}_{0,p}[z_k]\right)$. $\boldsymbol{D}_{z_kL}$ is the matrix that represents a chromatic dispersion (CD) operation from z_k km to L km. Therefore, (3) becomes

$$I=\mathbb{E}\left[\left\|\boldsymbol{E}_1-\boldsymbol{G}\begin{pmatrix}\boldsymbol{\gamma}'_x\\ \boldsymbol{\gamma}'_y\end{pmatrix}\right\|^2\right], \tag{5}$$

which can be solved by linear least squares. Since $\boldsymbol{\gamma}'_x$ and $\boldsymbol{\gamma}'_y$ are real vectors, the solution of (2) can be obtained as

$$\widehat{\boldsymbol{\gamma}'}=\left(\mathrm{Re}[\boldsymbol{G}^\dagger\boldsymbol{G}]\right)^{-1}\cdot\mathrm{Re}[\boldsymbol{G}^\dagger\boldsymbol{E}_1]. \tag{6}$$

Finally, the signal power profile for each polarization can be obtained using (1).

The rest of this section describes how to extract the PDL. The algorithm described above can estimate the polarization-wise power profiles. However, this does not mean that the correct PDL can be estimated because the power loss in each polarization depends on the incident SOP. To model PDL, we use the following Jones formulation to represent the electric field of the signal after the PDL element, as

$$\begin{aligned}&\begin{pmatrix}E_{x,\mathrm{out}}\\ E_{y,\mathrm{out}}\end{pmatrix}\\ &=R(\theta,\phi)^{-1}\begin{pmatrix}1 & 0\\ 0 & \rho\end{pmatrix}R(\theta,\phi)\begin{pmatrix}E_{x,\mathrm{in}}\\ E_{y,\mathrm{in}}\end{pmatrix},\end{aligned} \tag{7}$$

where θ and ϕ are the rotation and retardance angles between the signal axes and PDL element axes, respectively, i.e., $R(\theta,\phi)=\begin{pmatrix}e^{j\frac{\phi}{2}} & 0\\ 0 & e^{-j\frac{\phi}{2}}\end{pmatrix}\begin{pmatrix}\cos(\theta) & \sin(\theta)\\ -\sin(\theta) & \cos(\theta)\end{pmatrix}$. The loss induced by PDL element is given as $\rho=10^{\frac{-\mathrm{PDL\,[dB]}}{20}}$ for one polarization only. According to (7), the power loss of each x- or y-polarization depends on θ and ϕ. Therefore, the coordinate system of the received and reference signals needs to be aligned with that of the PDL to accurately estimate PDL values. To do so, we change the SOP, specifically by sweeping (θ,ϕ) of the received and reference signals. We then obtain the SOP that maximizes the power difference of two polarizations, and the PDL is estimated.

Experimental Setup

Fig. 1 shows the experimental setup and DSP algorithm. The transmitted signal was a single-channel 100-GBd dual-polarization probabilistic constellation-shaped (PCS) 64QAM signal (IR = 3.305, 21% FEC OH). The signal was Nyquist-shaped by a root-raised-cosine filter with a roll-off factor of 0.1. The transmitter was composed of a 4-ch 120-GSa/s arbitrary waveform generator (AWG), driver amplifiers, and a DP IQ modulator (DP-IQM). The transmission link consisted of three optical repeater sections each with 50-km fiber span length. Standard single-mode fiber was used, with a fiber loss of 0.18 [dB/km]. The fiber input power was set to 15 dBm. PDL loading values ranging from 0.5 to 3.0 dB were inserted

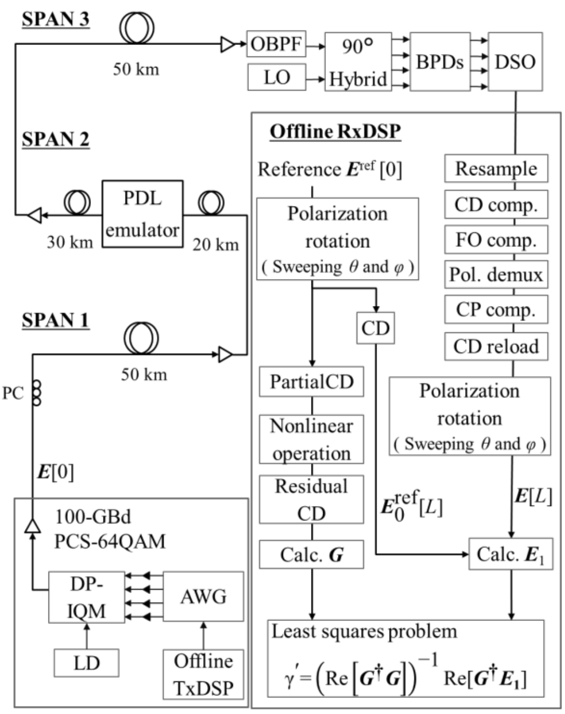

Fig. 1: Experimental setup and algorithm for polarization-wise PPE and PDL estimation.

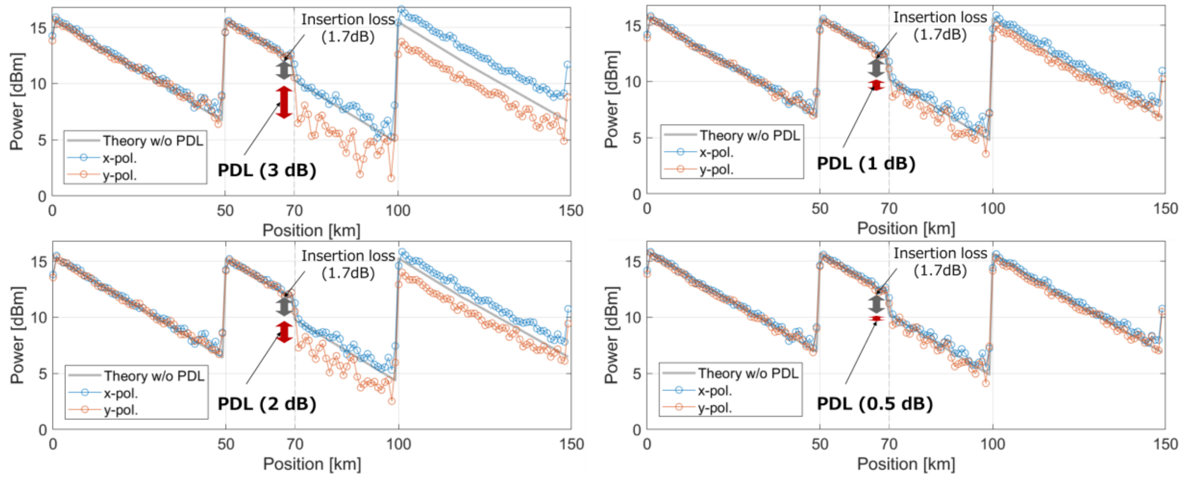

Fig. 2: Estimated polarization-wise longitudinal power with various PDL levels. PDLs were set to 3, 2, 1, and 0.5 dB. Theoretical lines are for single polarization and are based on actual measurements.

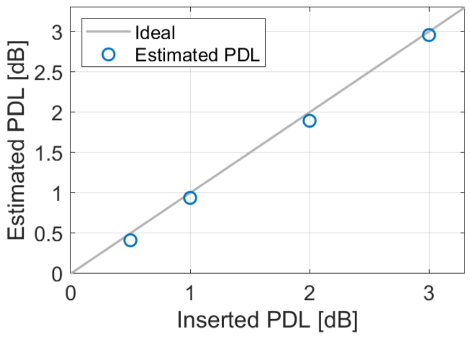

Fig. 3: Estimated PDL as a function of inserted PDL.

at the 70 km point of the 150-km transmission link to emulate a PDL-existing link. After propagation, the optical signals were detected by a 90° hybrid, balanced sampling oscilloscope (DSO). The received signal was down-sampled to two samples/symbol, and then CD and frequency offset were compensated for. After the polarization demultiplexing, carrier phases (CP) were recovered. CD was then reloaded to obtain $\boldsymbol{E}[L]$. $\boldsymbol{E}_1[L]$ was calculated as $\boldsymbol{E}_1[L] = \boldsymbol{E}[L] - \boldsymbol{E}_0[L]$. Polarization rotation was applied before PPE (6) with random θ and ϕ. The spatial step size was set to 1 km. Fifty profiles are averaged to reduce noise.

Experimental Results

Fig. 2 shows the results of polarization-wise power profiles for three spans with various PDLs of 3, 2, 1, and 0.5 dB. Note that we searched beforehand for the best SOP that maximized the power difference between polarizations, and only the best SOP case is shown in Fig. 2. From 0 to 70 km, the estimated power shows good agreement with the theoretical power without power difference between polarizations. Additionally, the power difference (PDL) was clearly observed at around 70 km, which matches the actual PDL insertion point, indicating that the PDL was successfully localized with a spatial granularity of 1 km even when the SOP of the signal changed in a link. The power difference also agrees with the actual PDL values when changing the PDL values from 3 to 0.5 dB. Note that the PDL emulator we used had an inherent insertion loss of 1.7 dB. The estimated power profiles also reflect this insertion loss, demonstrating that this method can clearly distinguish between polarization dependent and independent losses.

Next, we evaluated the PDL estimation accuracy. Estimated PDL values were obtained by averaging the power difference over 15 km after PDL location. Fig. 3 shows the estimated PDLs as a function of inserted PDLs. Estimated PDLs were 2.95, 1.89, 0.937, and 0.412 dB when set PDL loadings were 3, 2, 1, and 0.5 dB, respectively. Estimated PDL values thus had absolute errors under 0.5 dB. Our experimental results demonstrate that the monitoring technique can successfully provide PDL true values and locations with high accuracy in a multi-span optical link.

Conclusion

We experimentally demonstrated a linear least squares algorithm for estimating polarization-wise longitudinal power profiles in a coherent receiver, which enables the localization of PDL in multi-span optical links. The method also estimated the amount of PDL without any dedicated measurement equipment or calibration. Experimental results demonstrate that inserted PDLs ranging from 0.5 to 3 dB can be successfully localized with a spatial granularity of 1 km and estimated with an absolute error < 0.5 dB.

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