0.77-dB Anomaly Loss Localization Based on DSP-Based Fiber-Longitudinal Power Estimation Using Linear Least Squares

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Abstract: We experimentally demonstrate that DSP-based fiber-longitudinal power estimation achieves good agreement with OTDR with a root-mean-square error of 0.18 dB and thus localizes a 0.77-dB anomaly loss, which may occur as a connector loss.

1. Introduction

To achieve the highest transmission capacity on a given transmission link with minimized margins, link parameters such as fiber losses need to be accurately characterized before system operation starts. It was reported [1] that nearly 40% of dark fibers do not meet the requirements for fiber loss coefficients, splice loss, connector loss, etc; thus, testing and remediation of such fibers are mandatory. Optical fibers are usually tested using dedicated hardware such as an optical time domain reflectometer (OTDR), often with human intervention. However, such a manual and hardware-based approach will be extremely costly for future highly fiber-parallelized systems.

As an alternative, novel link monitoring solutions that reveal fiber-longitudinal signal power evolution over multi-span links from a coherent receiver have emerged [2-4]. This longitudinal power estimation (LPE) has the potential to revolutionize conventional hardware-based testing since (i) it can characterize the entire multi-span link in receiver (Rx) side digital signal processing (DSP) and (ii) other link parameters, such as chromatic dispersion (CD) maps [3], amplifier gains [3,6], polarization dependent loss [7], and filter frequency responses [3], can be estimated. However, measurement accuracy of LPE has been insufficient for reliable fiber characterization. It was theoretically shown [8] that correlation-based methods (CMs) [2,5] inherently have limited measurement accuracy. The gradient descent optimization of the split-step method [3] suffers from many local minima; thus, the accuracy is limited. Consequently, experimental demonstrations of LPE thus far [2,3,5,7] required a 'normal state reference' to localize the loss event, which means that a more reliable approach (i.e., an OTDR) is still required to ensure the link is in a normal state.

In this paper, we experimentally demonstrate an Rx-DSP-based LPE method that achieves excellent agreement with OTDR results with a root-mean-square (RMS) error of 0.18 dB. The method is a linear least squares method for estimating the nonlinear parameter in the Manakov equation, which guarantees the global optimum solution and thus achieves significantly high measurement accuracy. Consequently, even a 0.77-dB anomaly loss in a 3-span link is successfully localized without any normal state reference. The amount of anomaly losses is also accurately estimated with an error of < 0.35 dB. These results indicate that a coherent transponder can localize poor conditions of splices or connectors in multi-span links without OTDR.

2. Linear Least Squares for Longitudinal Power Estimation (LPE)

The accuracy of LPE has been limited since the estimation of nonlinear phase rotation (thus signal power) is a *nonlinear* least square problem [3], in which the global optimum is difficult to find. We have shown theoretically [4,8] that such a problem can reduce to a *linear* least square problem, which enables an accurate LPE since it guarantees the global optimum. The contribution of this paper is to experimentally demonstrate the predicted results in [4,8].

Our estimation target is the nonlinear coefficients $\gamma'(z)$ in the Manakov equation $\frac{\partial \mathbf{A}}{\partial z} = j\frac{\beta(z)}{2}\frac{\partial^2}{\partial t^2}\mathbf{A} - j\gamma'(z)\|\mathbf{A}\|^2\mathbf{A}$, where $\mathbf{A} \equiv \left[A_x(z,t), A_y(z,t)\right]^T$ is the polarization-multiplexed optical signal, β_2 is the dispersion and $\gamma'(z) \equiv \frac{8}{9}\gamma P(z) = \frac{8}{9}\gamma P(0)\exp\left(-\int_0^z \alpha(z')\,dz'\right)$. Here, γ, $P(z)$, and $\alpha(z)$ are the nonlinear constant, signal power, and fiber loss at distance $z \in [0, L]$, respectively. Note that in this formalism, $\|\boldsymbol{A}\|^2$ is normalized to 1 and in turn, the signal power is only governed by $\gamma'(z)$. Thus, the signal power $P(z)$ can be obtained by estimating $\gamma'(z)$. The estimation of $\gamma'(z)$ is an inverse problem of the Manakov equation, in which $\gamma'(z)$ is estimated from boundary conditions, i.e., transmitted (Tx) and Rx signals. This problem can be formulated as the following least-squares problem:

$$\widehat{\gamma'}_k = \underset{\gamma'_k}{\mathrm{argmin}}\, I = \underset{\gamma'_k}{\mathrm{argmin}}\, E\left[\left\|\begin{bmatrix}\mathbf{A}_x[L]\\ \mathbf{A}_y[L]\end{bmatrix} - \begin{bmatrix}\mathbf{A}_x^{ref}[L]\\ \mathbf{A}_y^{ref}[L]\end{bmatrix}\right\|^2\right] \tag{1}$$

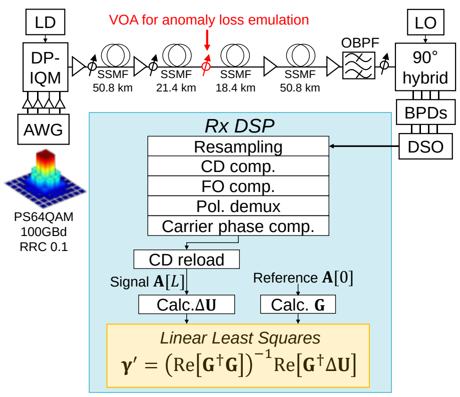

Fig. 1. Experimental setup and DSP-function blocks for longitudinal power estimation.

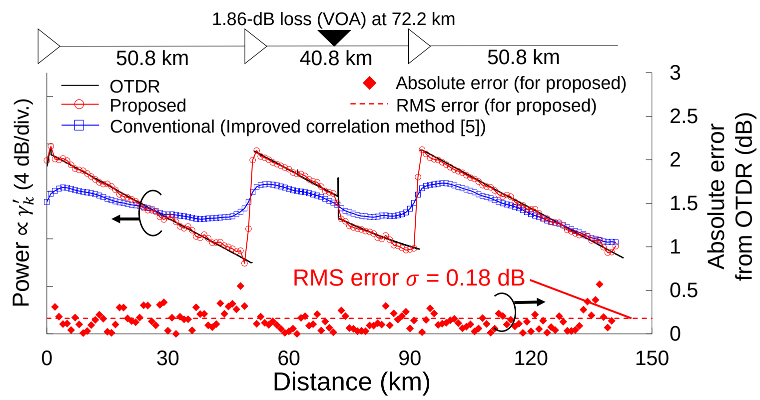

Fig. 2. Longitudinal power estimation with proposed linear least squares (red) and conventional improved correlation-based (blue) methods. Absolute error from OTDR (diamond) and RMS error (dashed line) are shown for proposed method.

where γ'_k are the discretized $\gamma'(z)$ at position z_k $(k \in \{0, \ldots, K\})$, $E[\cdot]$ is the expectation, and $\mathbf{A}_{x/y}[L] = \left[A_{x/y}[L,0], \ldots, A_{x/y}[L,N-1]\right]$ is the digitized Rx signals at the link end $z = L$ with N samples. $\mathbf{A}^{ref}_{x/y}$ is the emulated Rx (reference) signals obtained from the Tx signals and is a function of γ'_k. That is, γ'_k are estimated as the optimum parameters such that $\mathbf{A}^{ref}_{x/y}$ best emulates the Rx signals $\mathbf{A}_{x/y}$. We approximate both $\mathbf{A}_{x/y}$ and $\mathbf{A}^{d}_{x/y}$ using the first-order regular perturbation [9] such as $\mathbf{A}_{x/y}[L] = \mathbf{U}_{x/y}[L] + \Delta\mathbf{U}_{x/y}[L]$, where $\mathbf{U}_{x/y}$ is the linear term and $\Delta\mathbf{U}_{x/y}$ is the first-order nonlinear term. If the sampling rate satisfies the Nyquist theorem for linear terms, $\mathbf{U}_{x/y} = \mathbf{U}^{ref}_{x/y}$ holds, then the cost function reduces to the comparison of the nonlinear terms only:

$$I \simeq E\left[\left\|\begin{bmatrix}\Delta\mathbf{U}_x\\ \Delta\mathbf{U}_y\end{bmatrix} - \begin{bmatrix}\Delta\mathbf{U}^{ref}_x\\ \Delta\mathbf{U}^{ref}_y\end{bmatrix}\right\|^2\right]. \tag{2}$$

$\Delta\mathbf{U}^{ref}_{x/y}$ can be expressed in a matrix form such as $\Delta\mathbf{U}^{ref}_x = \mathbf{G}_x\boldsymbol{\gamma}'$, where $\boldsymbol{\gamma}' = [\gamma'_0, \ldots, \gamma'_{K-1}]^T$. The k-th column of $\mathbf{G}_{x/y}$ is

$$(\mathbf{G}_x)_k = -j\Delta z \mathbf{D}_{z_k L}\left[\left(\mathbf{U}^*_x[z_k] \odot \mathbf{U}_x[z_k] + \mathbf{U}^*_y[z_k] \odot \mathbf{U}_y[z_k]\right) \odot \mathbf{U}_{x/y}[z_k]\right] \tag{3}$$

where $\odot$ denotes the element-wise multiplication, Δz is spatial step size, $\mathbf{D}_{z_1 z_2}$ is the matrix that represents a CD operation corresponding to the distance from z_1 to z_2, and $\mathbf{U}_{x/y}[z_k] = \mathbf{D}_{0 z_k}\mathbf{A}_{x/y}[0]$. The cost function can then further be transformed as follows:

$$I \simeq E\left[\left\|\begin{bmatrix}\Delta\mathbf{U}_x\\ \Delta\mathbf{U}_y\end{bmatrix} - \begin{bmatrix}\mathbf{G}_x\\ \mathbf{G}_y\end{bmatrix}\boldsymbol{\gamma}'\right\|^2\right]. \tag{4}$$

This can be solved by linear least squares. If we denote $\Delta\mathbf{U} = \begin{bmatrix}\Delta\mathbf{U}_x\\ \Delta\mathbf{U}_y\end{bmatrix}$ and $\mathbf{G} = \begin{bmatrix}\mathbf{G}_x\\ \mathbf{G}_y\end{bmatrix}$, then the real-valued solution is

$$\widehat{\boldsymbol{\gamma}'} = (\mathrm{Re}[\mathbf{G}^\dagger\mathbf{G}])^{-1}\mathrm{Re}[\mathbf{G}^\dagger\Delta\mathbf{U}]. \tag{5}$$

3. Experimental Setup

Fig. X shows the experimental setup. We used A PS-64QAM (H=4.347, IR=3.305 21% FEC OH) 100 GBd signal with a roll-off factor of 0.1 as the Tx signal. The frequency response of the transmitter was estimated in advance and compensated for. The transmitter was composed of a 4-ch 120GSa/s arbitrary waveform generator (AWG), driver amplifiers, and a DP IQ-modulator (IQM). The Tx and Rx lasers had a 1-Hz linewidth at 1547.31 nm. The tested link was composed of a 142.4-km 3-span standard single-mode fiber (SSMF) link with α = 0.180 dB/km β_2 = -20.26 ps^2/km, and γ=1.11 1/W/km. To emulate the fiber anomaly loss, a variable optical attenuator (VOA) was inserted at 72.2 km. The fiber launch power was set to 15 dBm. This power is prohibitive in wavelength division multiplexing scenarios but acceptable for green field applications (initial deployment of fiber links). The optical signals were detected by a 90° hybrid, balanced photodetectors (BPDs), and a 256-GSa/s digital sampling oscilloscope (DSO). In Rx DSP, after signals were resampled to 2 samples/symbols, CD, frequency offset (FO), polarization rotation, and carrier phase were compensated for. The compensated CD was reloaded to obtain $\mathbf{A}_{x/y}[L]$, and $\Delta\mathbf{U}[L]$ was calculated

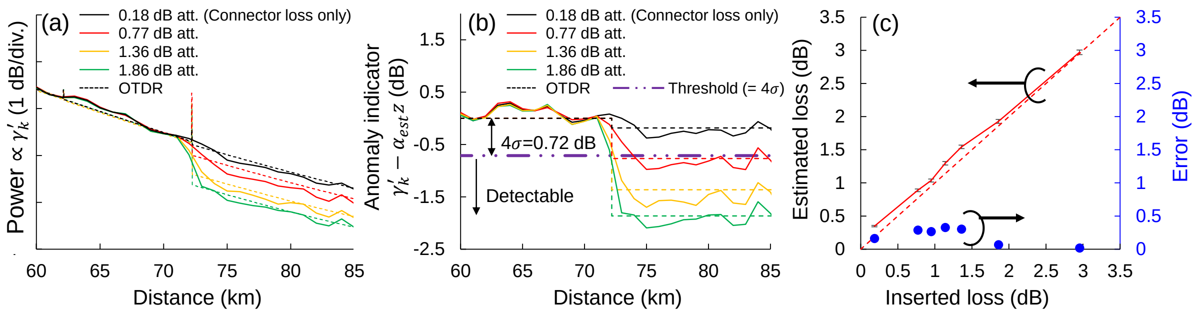

Fig. 3. (a) Estimated power profiles from 60 to 85 km with various VOA levels. (b) Anomaly indication by subtracting tilt ($-\alpha_{est}z$) from power profiles. Threshold for loss detection was set to 4σ = 4 × 0.18 = 0.72 dB. (c) Estimated loss as function of inserted loss (n = 100).

by subtracting the linear solution from the CD reloaded signals. $\mathbf{G}$ was calculated from the Tx (reference) signals $\mathbf{A}_{x/y}[0]$ using (3). Finally, we obtain $\widehat{\boldsymbol{\gamma}}'$ from (5) using these $\Delta\mathbf{U}$ and $\mathbf{G}$. 125000 samples were used to calculate $\widehat{\boldsymbol{\gamma}}'$.

4. Results and Discussion

Fig. 2 shows the estimated longitudinal power profile over a 142.4-km 3-span link, and 1.86 dB attenuation (VOA) was inserted at 72.2 km to emulate anomaly loss. For reference, OTDR loss profiles are shown. The power profile obtained with the conventional method (improved correlation-based method [5]) is also shown. The power profiles were averaged ten times. Though the conventional method reflects the global tendency of the true power, the deviation from the OTDR results is significantly large. Thus, detecting the inserted loss as well as estimating the true link parameters, such as the fiber loss coefficients and amount of inserted loss, is challenging. The proposed method, however, showed excellent agreement with the OTDR results with a root-mean-square error of 0.18 dB and a maximum absolute error of 0.57 dB. The loss event was clearly detected and localized without any normal state reference. Note that measurement dead zones of ± 1 km from fiber ends were eliminated from the error calculation.

To determine the detectable limit of anomaly losses, the VOA level was changed to 0.18, 0.77, and 1.36 dB. Fig. 3(a) shows the enlarged power profiles from 60 to 85 km, obtained by the proposed method. The estimated power profiles showed very good agreement with OTDR results for all VOA levels. To quantitatively evaluate the detectable limit of anomaly losses, we subtracted tilts (i.e., $-\alpha z$) from the power profiles to indicate anomalies as shown in Fig. 3(b). The fiber loss coefficient α_{est} of the second span was estimated from the obtained power profiles as 0.179 dB/km, which matches the actual fiber loss coefficient of 0.180 dB/km. Recalling that the RMS error of the power profiles was $\sigma = 0.18$ dB, we selected the threshold for detecting inserted anomaly losses as 4σ = 4 × 0.18 dB = 0.72 dB. Since the estimated power profile for a 0.77-dB anomaly loss (red) exceeded the threshold of 0.72 dB, the 0.77-dB loss was successfully detected and localized. Furthermore, the amount of inserted losses can also be estimated since the power profile fits the OTDR results well. Fig. 3(c) shows the estimated loss as a function of inserted loss. The amount of loss was estimated by simply averaging the obtained power from the point that exceeded the threshold (74 km) to the amplifier position (91 km). We tested 100 power profiles (without power profile averaging) and found that the estimated losses were very stable with a standard deviation of < 0.03 dB. A good accuracy for the loss estimation was observed with a maximum error of < 0.35 dB, which demonstrates the reliability of the proposed method.

5. Conclusion

We presented a linear least squares method for Rx-DSP-based fiber-longitudinal power monitoring, which had good agreement with the OTDR results with a root-mean-square error of 0.18 dB. Thus, a 0.77-dB anomaly loss was successfully localized without a normal state reference or hardware-based calibration. Furthermore, the amount of anomaly loss was estimated with an error of 0.35 dB. These results indicate that a coherent transponder can characterize even splice or connecter losses in multi-span links without an OTDR.

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