A Generalized Method for Fiber-longitudinal Power Profile Estimation

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Abstract *We propose a fiber-longitudinal monitoring method that generalizes the correlation method (CM) and least squares (LS). The proposed method balances the advantages of CM and LS, achieving both high noise robustness and power sensitivity. The results are experimentally validated using 800G signals from a DSP-ASIC.*

Introduction

Monitoring physical parameters of optical links is crucial for minimizing redundant operational margins and detecting soft network failures. In particular, signal power in transmission links is a dominant factor in determining the generalized signal-to-noise ratio and thus should be monitored to achieve the maximum capacity for a given link.

To address this need, fiber-longitudinal power profile estimation (PPE) has been developed [1-5]. PPE estimates signal power evolution in the signal-propagation direction by extracting fiber-nonlinearity from received signals. It also offers several advantages, such as: (i) end-to-end characterization of a multi-span link at a single coherent receiver, (ii) the capability to locate loss and gain anomalies, (iii) no need for additional probing light and optical configuration, and (iv) wide applications such as locating excessive polarization dependent loss [6] and filter anomalies [2, 3].

However, in existing PPE methods, either power sensitivity or noise robustness is sacrificed. Correlation methods (CMs) [1,4,7] provide stable performance under noise and distortions; however, their sensitivity to power-related events (e.g., loss anomalies) and spatial resolution are limited due to the convolution effect related to chromatic dispersion (CD) [7]. In contrast, least-squares methods (LSs) [2,3,5] achieve high sensitivity and spatial resolution but suffer from noise enhancement due to the deconvolution (or more generally, the inverse matrix) operation [6,7]. Although it was discussed in [8] that the sensitivity and spatial resolution of CMs can also be enhanced by applying deconvolution, this operation is a special case of the LS algorithm [7], which means the noise enhancement is also accompanied.

In this paper, we propose a fiber-longitudinal PPE method that generalizes both the CM and LS by using the Tikhonov regularization [9]. This method achieves both high sensitivity and high noise robustness, balancing the strength of CM and LS. We first show that by setting a regularization parameter $\lambda \to \infty$, the proposed method converges to CM, whereas it approaches LS when $\lambda \to 0$. The results are experimentally validated using an 800G signal from a transceiver plug-in unit (PIU) with a DSP-ASIC, demonstrating that the proposed method enhances the feasibility of PPE even in noisy environments with practical transceivers.

Conventional PPEs: Correlation-based Method (CM) and Least-Squares-based Method (LS)

First, let us revisit a CM in [4,7] and a LS in [5,7], and then introduce the proposed method in comparison with them. All the PPE method estimates an averaged nonlinear phase rotation $\gamma'(z) = \gamma P(z)$, where γ and $P(z)$ denote the nonlinear constant of a fiber and the signal power at position z. One can estimate the power $P(z)$, assuming γ is known.

In the CM, power profiles $\gamma'(z)$ are estimated by correlating a received signal $\mathbf{E}[L]$ with a reference signal called a nonlinear template [4], where L is the link distance. To obtain the reference signal, CD $\widehat{D}_{0z_k}$ from 0 to z_k km ($k = 0, \dots K-1$) is first applied to the transmitted signal $\mathbf{E}[0]$ as $\widehat{D}_{0z_k}\mathbf{E}[0]$. Subsequently, a nonlinear operation $\widehat{N} = -j|\cdot|^2(\cdot)$, and residual CD are applied to obtain the reference signal $\mathbf{E}_k^{ref}[L]$ as

$$\mathbf{E}_k^{ref}[L] = \widehat{D}_{z_k L}\widehat{N}\widehat{D}_{0z_k}\mathbf{E}[0]. \tag{1}$$

Then the signal power at position z_k is estimated by correlating received signals with $\mathbf{E}_k^{ref}[L]$ as

$$\widehat{\gamma'_{CM,k}} = \mathrm{Re}\left[\mathbf{E}_k^{ref\dagger}[L]\mathbf{E}[L]\right], \tag{2}$$

where $\mathrm{Re}[\cdot]$ is a real part and $(\cdot)^\dagger$ is the Hermitian transpose. By performing (2) for all the positions z_k, power profiles are reconstructed as

$$\widehat{\boldsymbol{\gamma}}'_{\mathrm{CM}} = \mathrm{Re}\left[\mathbf{G}^\dagger\mathbf{E}[L]\right], \tag{3}$$

where

$$\mathbf{G} = \left[\mathbf{E}_0^{ref}[L], \dots \mathbf{E}_k^{ref}[L], \dots \mathbf{E}_{K-1}^{ref}[L]\right]. \tag{4}$$

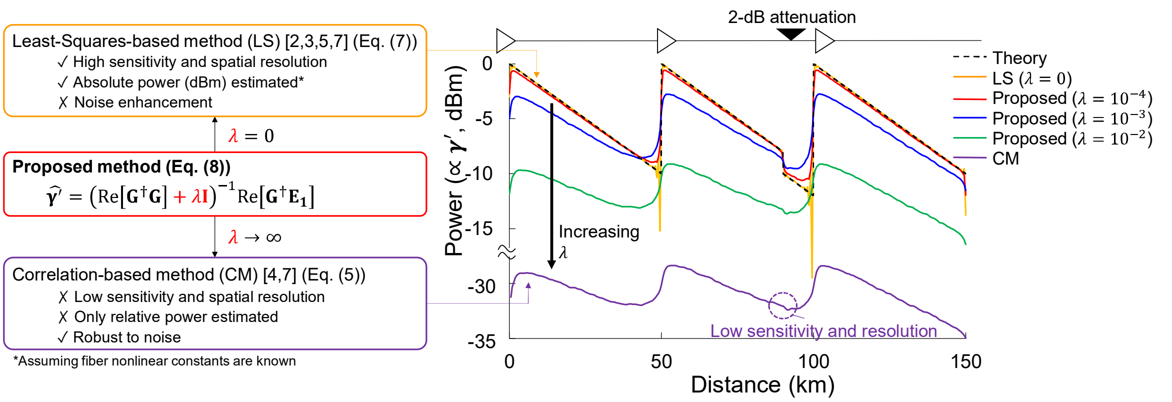

Fig. 1. Simulation results of power profiles estimated by proposed method (red and blue), LS(yellow), and CM(purple). Proposed method approaches LS under λ = 0 and CM under $\lambda \to \infty$.

According to [7], (3) can be transformed under assumptions that the transmitted signals are

1. modelled by the first order regular perturbation (RP1) such that $\mathbf{E}[L] = \mathbf{E}_0[L] + \mathbf{E}_1[L]$, where $\mathbf{E}_0[L]$ and $\mathbf{E}_1[L]$ are linear and t nonlinear terms, respectively [10].
2. a stationary circular complex Gaussian process.

Then the terms related to $\mathbf{E}_0[L]$ vanish and (3) becomes

$$\hat{\gamma}'_{\mathrm{CM}} = \mathrm{Re}\left[\mathbf{G}^\dagger\mathbf{E}_1[L]\right]. \quad (5)$$

This is the power profile of the CM [4,7]. The purple line in Fig. 1 shows a simulation result of (5). In the simulation, a PCS64QAM 128-GBd signal with a Nyquist roll-off of 0.1 was used and transmission link was emulated by the split-step method with α = 0.20 dB/km, β_2 = -21.8 ps^2/km, γ = 1.3 W^{-1}km^{-1}, and the step size Δz = 50 m. No noise and distortion were added. PPE was performed with a spatial granularity of 0.5 km. Note that the vertical axis is the absolute value of power, assuming the nonlinear constant is known. The CM successfully estimates power tendencies but offers a sub-optimal solution in that its spatial resolution and accuracy are limited, and it does not estimate the absolute power. Additionally, the sensitivity to a 2-dB loss event inserted in the second span is also limited. It was shown in [7] that these limitations of CM arise from the fact that the estimated power profile of CM can be understood as a convolution between the true power profile and a smoothing function related to CD.

In the LS, power profiles are obtained by solving the following least squares problems:

$$\hat{\gamma}'_{\mathrm{LS}} = \underset{\gamma'}{\mathrm{argmin}}\, \mathbb{E}[\|\mathbf{E}[L] - \mathbf{E}^{ref}[L]\|^2], \quad (6)$$

where $\mathbf{E}^{ref}[L]$ is a complete emulation of the received signals, obtained by either the full SSM [2], Volterra [3], or RP1 [5]. According to [5], (6) can be solved simply under the RP1 assumption as:

$$\hat{\gamma}'_{\mathrm{LS}} = (\mathrm{Re}[\mathbf{G}^\dagger\mathbf{G}])^{-1}\mathrm{Re}\left[\mathbf{G}^\dagger\mathbf{E}_1[L]\right] \quad (7)$$

This is the power profile of the LS [5,7]. Interestingly, (7) implies that power profiles of LS are that of CM (5) applied by the inverse matrix $(\mathrm{Re}[\mathbf{G}^\dagger\mathbf{G}])^{-1}$. It was noted in [7] that this inverse matrix is a general expression for deconvolving the smoothing function accompanied in CM. The yellow line in Fig. 1 shows an example of (7). The LS successfully estimates the absolute power, and its spatial resolution and accuracy are high under noise-less and distortion-less conditions. Moreover, the inserted 2-dB loss is clearly detected, demonstrating the LS's high sensitivity to loss events. However, as implied in (7), the inverse matrix $(\mathrm{Re}[\mathbf{G}^\dagger\mathbf{G}])^{-1}$ (or deconvolution) enhances noise and distortions in received signals (or in $\mathbf{E}_1[L]$,) which means that LSs are more vulnerable to noise than CMs. This point is clearly observed in the experimental section.

Generalized PPE

Our proposal is the following algorithm:

$$\hat{\gamma}' = (\mathrm{Re}[\mathbf{G}^\dagger\mathbf{G}] + \lambda\mathbf{I})^{-1}\mathrm{Re}\left[\mathbf{G}^\dagger\mathbf{E}_1[L]\right], \quad (8)$$

where λ is a regularization parameter. This method corresponds to solving (6) using the Tikhonov regularization [9]. When $\lambda = 0$, (8) becomes the LS (7). In contrast, it also converges to the CM (5) under $\lambda \to \infty$, since the second term $\lambda\mathbf{I}$ in the inverse matrix becomes dominant and $\mathrm{Re}[\mathbf{G}^\dagger\mathbf{G}] + \lambda\mathbf{I}$ approaches to the identity matrix. This is illustrated in Fig. 1. By adjusting λ, the proposed method (red and blue) can balance between the CM and LS. When $\lambda = 10^{-4}$ (red), the proposed method is close to the LS, showing good estimation of the true power and high sensitivity to an inserted 2-dB loss. By increasing λ (blue), it gradually approaches the CM, deviating from true power and losing the sensitivity to the loss. In this way, the proposed method is a generalized method of the CM and LS. The impact of noise and distortion on these

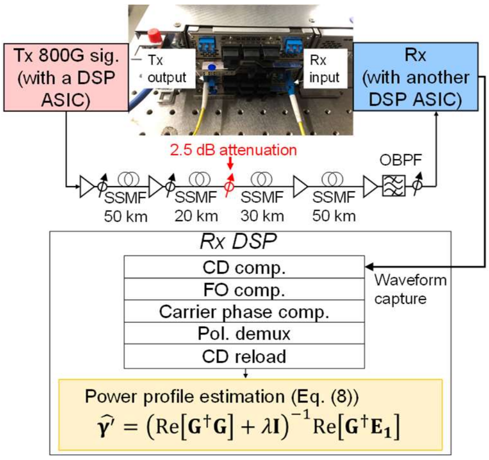

Fig. 2. Experimental setup and DSP function blocks

PPE methods is investigated in the following section.

Experiment

Fig. 2 shows the experimental setup. An 800G signal was generated from a transceiver PIU with a 5-nm CMOS DSP ASIC. After OE conversion with a high-baudrate coherent driver modulator (HB-CDM), the signal was launched into a 150-km 3-span standard single mode fiber (SSMF) link with an average fiber loss coefficient of 0.184 dB/km. A center frequency of the signal was 1547.72 nm and the fiber launch power was set to 8 dBm. An intentional 2.5-dB attenuator was inserted at 70 km. The signal was then captured by an intradyne coherent receiver (ICR) and another DSP-ASIC. The captured waveform was processed offline. CD, frequency offset, carrier phase, and polarization rotation were first compensated, and the compensated CD was then reloaded to the signal to obtain $\mathbf{E}[L]$. Then PPE was performed using Eq. (8). The obtained power profiles were averaged 20 times.

Fig. 3(a) shows the experimental results of PPEs using CM, LS, and the proposed method. Although the LS fits the true powers well, it shows noisy profiles, which originates from the deconvolution effect due to the inverse matrix in Eq. (7). The CM is more stable than the LS but does not estimate the true power, and its sensitivity to the loss event is limited. The proposed method at $\lambda = 2 \times 10^{-4}$ (red) achieves good noise suppression while maintaining agreement with the true power. By increasing λ (e.g., $\lambda = 1 \times 10^{-4}$ with blue line,) the power profile becomes less noisy but it gradually deviates from the true power profile and loses the sensitivity, implying it approaches that of CM. Thus, there is an optimum λ, which best balances the trade-off between noise robustness and sensitivity as well as the true power estimation.

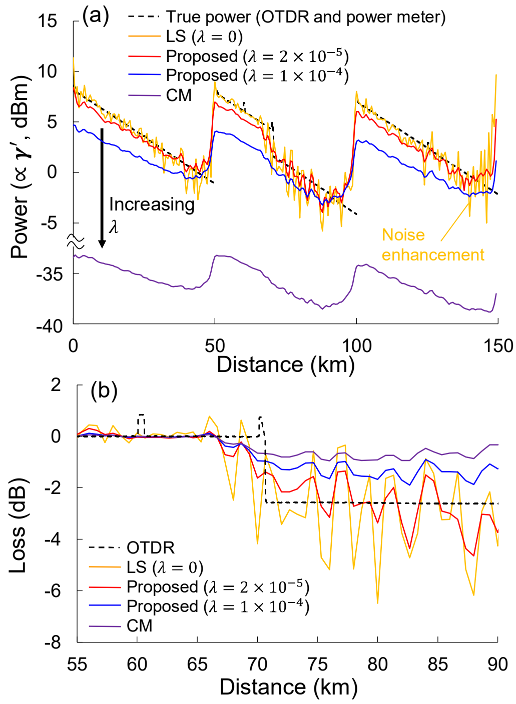

Fig. 3. (a) Experimental results of power profile estimation. (b) Loss anomaly indication by subtracting tilt ($-\alpha_{est}z$) from power profiles in (a)

To evaluate the sensitivity to the loss event, we subtracted tilts (i.e., $-\alpha_{est}z$) from the estimated power profiles, as shown in Fig. 3(b). α_{est} for each profile is estimated from a stable area ranging from 55 to 65 km. The LS tracks the true loss (OTDR) but shows noisy profiles, while CM shows less sensitivity to the loss anomalies. The proposed method (red) suppresses the noisy characteristic of LS well while maintaining the loss sensitivity and estimating the true value of the inserted loss.

Conclusions

We proposed and demonstrated a fiber-longitudinal PPE method that generalizes the CM and LS by using the Tikhonov regularization. The proposed method converges to CM under $\lambda \to \infty$, while it approaches LS under $\lambda \to 0$. By adjusting regularization parameter λ, the proposed method achieves both high noise robustness and sensitivity to the loss event. This method enhances the performance of PPE in practical environments with noise and distortions.

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References

[1] T. Tanimura, K. Tajima, S. Yoshida, S. Oda and T. Hoshida, "Experimental demonstration of a coherent receiver that visualizes longitudinal signal power profile over multiple spans out of its incoming signal," *European Conference on Optical Communication*, PD.3.4, 2019, DOI: 10.1049/cp.2019.1031

[2] T. Sasai, M. Nakamura, E. Yamazaki, S. Yamamoto, H. Nishizawa and Y. Kisaka, "Digital Longitudinal Monitoring of Optical Fiber Communication Link," *Journal of Lightwave Technology*, vol. 40, no. 8, pp. 2390-2408, 2022, DOI: 10.1109/JLT.2021.3139167

[3] S. Gleb, P. Konstantin, J. Luo, and B. Zheng, "Fiber link anomaly detection and estimation based on signal nonlinearity," *European Conference on Optical Communication,* Tu2C2.5, 2021. DOI: 10.1109/ECOC52684.2021.9606094

[4] C. Hahn, J. Chang, and Z. Jiang, "Localization of reflection Induced multi-path-interference over multi-span transmission link by receiver-side digital signal processing," *Optical Fiber Communications Conference and Exhibition*, Th1C.3, 2022, DOI: 10.1364/OFC.2022.Th1C.3

[5] T. Sasai, E. Yamazaki, M. Nakamura, and Y. Kisaka, "Proposal of linear least squares for fiber-nonlinearity-based longitudinal power monitoring in multi-span link," *OptElectronics and Communications Conference*, WB3-1, 2022. DOI: 10.23919/OECC/PSC53152.2022.9850175

[6] M. Eto, K. Tajima, S. Yoshida, S. Oda, and T. Hoshida, "Location-resolved PDL monitoring with Rx-side digital signal processing in multi-span optical transmission system," *Optical Fiber Communications Conference and Exhibition*, Th1C.2, 2022, DOI: 10.1364/OFC.2022.Th1C.2

[7] T. Sasai, E. Yamazaki, and Y. Kisaka, "Performance limit of fiber-longitudinal power profile estimation methods," *Journal of Lightwave Technology, (early access), 2023,* DOI: 10.1109/JLT.2023.3234534

[8] C. Hahn and Z. Jiang, "On the spatial resolution of location-resolved performance monitoring by correlation method," *Optical Fiber Communications Conference and Exhibition*, W1H.2, 2023.

[9] C. W. Groetsch, "Inverse problems in the mathematical sciences," 1st ed., Springer, 1993. DOI: 10.1007/978-3-322-99202-4

[10] P. Serena and A. Bononi, "An alternative approach to the Gaussian noise model and its system implications," *Journal of Lightwave Technology*, vol. 31, no. 22, pp. 3489–3499, 2013. DOI: 10.1109/JLT.2013.2284499.