Advanced Data-Analytics-Based Fiber-Longitudinal Monitoring for Optical Transport Networks

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Abstract *We present a novel monitor that estimates distance-wise optical power profile along a transmission-line-longitudinal axis throughout multiple spans by using signal at the link end only. This monitor can localize anomaly point caused by unexpected optical attenuation with sub-km resolution.*

Introduction

Optical monitoring and analysis technologies that recognize physical status of fiber-optic networks is one of the essential modules to build future optical networks with both high capacity and low operational expense [1].

One technical issue in monitoring and analyzing whole optical transport networks is how to monitor the possible failure points that are distributed over nationwide optical networks in a cost-effective and easily deployable manner. The most straightforward approach is to deploy massive number of optical monitors at various places in the networks. This approach however would face serious issues in its implementation cost and operation, especially for large networks.

A recently developed approach to address the above issue is to leverage a potential of digital coherent receivers to be deployed for every path in networks. This digital coherent-based monitoring can estimate various physical parameters of optical transmission links by digital signal processing (DSP) and/or machine learning techniques designed for monitoring[2-7]. Although these techniques are indispensable when it comes to constructing a system for recognizing optical links, conventional digital coherent-based monitors can only estimate cumulative parameter values for the end-to-end wavelength path.

Complementary alternative to the approach is to use multiple optical monitors and auxiliary light paths for span-by-span monitoring[8,9], however, realization of much finer resolution over end-end multi-span links still remains an issue.

In this paper, we review a recently proposed data processing algorithm designed for estimating the fiber-longitudinal optical power profile, which is a set of optical power values at each distance, by using a single digital coherent receiver at the link-end. The proposed method provides an instantaneous and point-wise optical power at any location on a multi-spans transmission link. The method enables that a digital coherent receiver determines not only the cumulative value of physical parameters but also the longitudinal profile of such parameters in a distance-resolved manner. Such functionality should help the network operator to identify where, which, and how much the physical layer anomalies are generated without deploying dedicated monitoring equipment everywhere.

Algorithm for Fiber-Longitudinal Monitoring

How can we develop such a fiber-longitudinal monitor solely by using the receiver? A key is to utilize the non-commutative property between chromatic dispersion (CD) and self-phase modulation (SPM) operators in fiber-optic propagation. In fact, the first trial of DSP-based fiber-longitudinal monitor was investigated in a context of automatic optimization for back propagation-based nonlinear equalizer back in 2010, which had a potential to mirror the nonlinear fiber-optic channel in a digital (back-propagating) domain [10]. More sophisticated demonstration was also presented in 2020[11]. Although this method was demonstrated to be operable in several link conditions, this proposal faces a serious problem of computational complexity in realizing sub-km distance resolution: when we aim to monitor a fine-details of link such as a meter-order resolved information by this method, we must solve massive multidimensional optimization problem that is usually (computationally) hard to solve.

A newly proposed DSP-based fiber-longitudinal monitor by us in 2019, which will be discussed in this paper, overcomes this problem by a deterministic formula to estimate a value of optical signal status at a specific point on the link[12,13]. The concept of the above-mentioned DSP-based fiber-longitudinal monitor is depicted

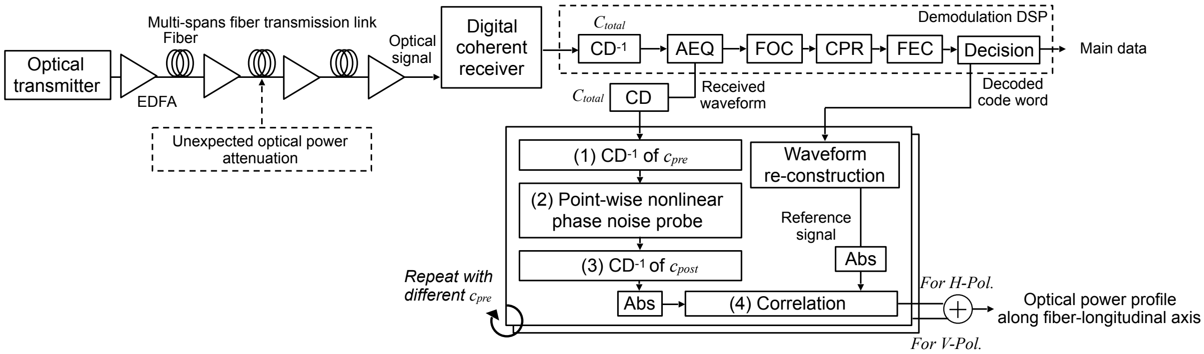

Fig. 1: Schematic diagram of proposed fiber-longitudinal monitor. DSP: digital signal processing, CD: chromatic dispersion, AEQ: adaptive butterfly structured filter, FOC: frequency offset compensator, CPR: carrier phase recovery, FEC: forward error correction, Abs: taking absolute value of complex number, Diff.: differentiator, EDFA: erbium doped fiber amplifier.

in Fig. 1. First, a digital coherent receiver placed at the link-end converts the incoming optical signal into a data as a set of numerical values of time-sampled and digitalized amplitude and phase of both polarizations of the signal. Note that we assume the receiver measures the signal propagating in a CD-uncompensated link with cumulative CD value of c_{total}. This is a limitation of the proposed method.

Then an optical power at a distance of $d = c_{post}/D = (c_{total} - c_{pre})/D$ on the transmission link is estimated by the following procedure, where c_{pre} and c_{post} are parameters of the method, and D is the dispersion of fiber per unit length.

1. Digitally compensate for CD of c_{pre} on the received optical signal, which corresponds to linear fiber back-propagation from the receiver for a distance of c_{pre}/D.
2. Impose a point-wise nonlinear phase shift for the output signal of (1). The point-wise nonlinear phase shift is a DSP as $u_{out}(t) = u_{in}(t)\ \exp(-j\ p\ |u_{in}(t)|^2)$, where p is a parameter for nonlinear phase probe, u_{in} and u_{out} are the input and output complex-valued electric field. Note that the parameter p is a small fixed constant, not a variable to be optimized.
3. Compensate for CD of $c_{post} = c_{total} - c_{pre}$ on the signal after (2).
4. Calculate the correlation the signal of (3) with the reference signal modulated with the same data but without imposing the nonlinear phase shift. The reference signal is reconstructed from the received symbol information after demodulation, forward error correction, and symbol decision.

The resulting correlation is an indicator of the point-wise nonlinear power at d, which consists of instant optical power and the nonlinear refractive index of the fiber at that point. In this paper, assuming that the nonlinear refractive index along the fiber is constant where we used the typical value of nonlinear refractive index of a standard single mode fiber was used for calculating all location points.

To obtain whole optical power profile over the entire link, parameter c_{pre} is swept with a step size of Δc to cover the entire transmission link. Note that Δc can be adaptively chosen for each estimation process. With this advantage, we can reduce the overall computational complexity for some applications. For example, an application to determine the location of 'anomaly' in optical power, the method first scans the entire fiber link with a coarse step size (e.g., 1 km) to detect the rough anomaly area, and then re-scan only this anomaly area with a finer step size (e.g., 5 m) to identify the exact anomaly location.

Experimental verification

We implemented the proposed method and evaluated it with 63.25GBd DP-16QAM signal over 260-km long DWDM transmission line consisting of five spans of standard single mode fiber (SSMF), each having a length of either 40 or 60 km. Details of the setup is described in Ref. [13].

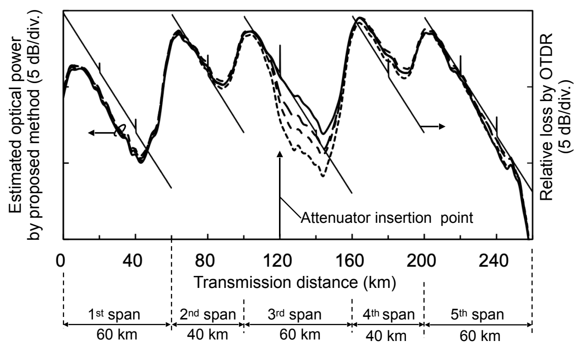

Fig. 2: Estimated power profile in 'normal' (no excess loss, solid line) and 'anomaly' cases with three different insertion losses (dotted, dashed, and long-dashed lines) with measured relative loss by OTDR corresponding to the solid line.

Figure 2 shows the measured power profile by the proposed method. The power profile estimated by the proposed method visualized the amplification by EDFA and the attenuation by fiber propagation span-by-span. To demonstrate a capability of the method, three different excess optical attenuators (1.8, 3.3, and 5.0 dB, respectively) were inserted at the 20-km point in the third span, i.e., 120 km from the transmitter.

To investigate the spatial resolution of the above excess optical power attenuation ('anomaly loss') location, we plotted the power anomaly indicator value, which is defined by the differential coefficients of difference between the current power profile and the reference power profile that has no excess power attenuation points, as a function of equivalent transmission distance in Fig. 3. The anomaly location indicator serves as a useful information to locate unexpected optical attenuation points. Note that we test two step sizes of Δc (corresponding to 1 km and 5 m) in Fig. 3. The result shows that the proposed method can provide on-demand spatial resolution depending on the parameter and has potential to estimate the anomaly location within an error of less than one km.

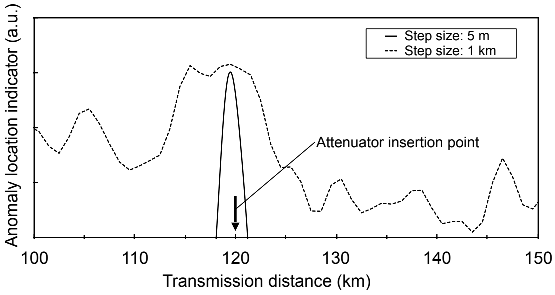

Fig. 3: Experimental results of anomaly location indicators.

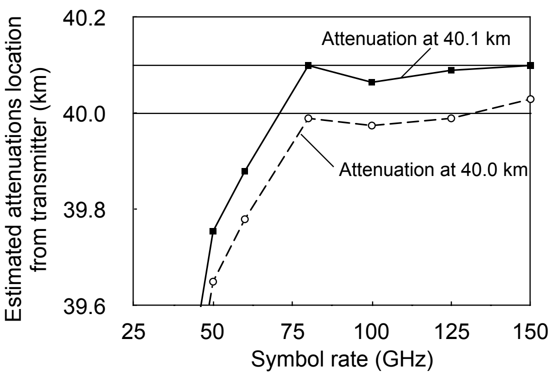

Fig. 4: Simulation results of symbol rate dependency of estimated location points.

For in-depth analyses of the longitudinal spatial-resolution of the anomaly localization by the proposed method, we performed additional simulation with a 80-km long single-span SSMF link. An excess optical power attenuator (3-dB bulk optical power loss) was inserted at two different locations at around the middle of the span (40 or 40.1 km points from the transmitter).

Figure 4 shows the estimated anomaly location point that is a maximum point of the anomaly location indicator with different symbol rate signals ranging from 25 to 150 GHz. The estimated anomaly locations converges to have a good agreement with actual value with the symbol rate of around 100 GHz and beyond: A higher symbol rate leads to a rapid spreading of the optical pulse by CD that is beneficial to distinguish the waveform states at different distances in the proposed method.

Figure 5 shows the anomaly location indicator by a 150 GBd DP-16QAM signal with the 5-m step size. The result indicates the method can distinguish one point from the other within an error of one hundred meters.

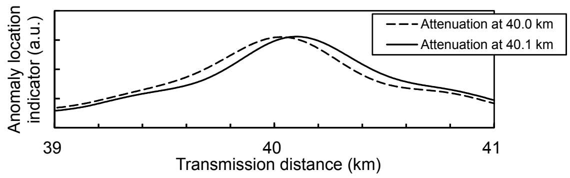

Fig. 5: Simulation results of anomaly location indicators.

Conclusions

We have developed a fiber-longitudinal monitor that visualizes distance-wise optical power throughout the entire multi-span link by using the signal waveform obtained by a coherent receiver placed at the link-end. This is an in-situ monitor that estimates power profile along the link-longitudinal axis from its incoming signal by a unique digital post-processing of coherent receiver data. Experimental results showed that our method successfully indicated unexpected excess losses on a 260-km-long 5-span SSMF link for a 63.25 Gbaud DP-16QAM signal transport.

Acknowledgements

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