Fiber Link Anomaly Detection and Estimation Based on Signal Nonlinearity

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Abstract *A fiber link anomaly detection and estimation approach is proposed. Using signal nonlinear distortion, signal power profile anomaly and passband narrowing anomaly can be recognized with high quantitative and position accuracy. This approach does not require additional device and can support online working.*

Introduction

In the widely deployed fiber communication network, due to man-made excavations, natural disasters, equipment aging, etc., abrupt network performance deterioration often occurs. Optical time-domain reflectometer (OTDR) is the most common measuring instrument when establishing the link or positioning the anomaly. By analysing the Rayleigh scattering and Fresnel reflection of the OTDR probe light propagating in the fiber, the fiber attenuation and breakpoint can be measured[1]. However, the high power of the probe light and the resulting strong nonlinearity limit its ability to work online. Another possible way to detect signal power evolution is to utilize its correlation with fiber nonlinear noise[2]-[4]. It could be based on a similarity comparison between distance-wise nonlinear noise waveform and the signal waveform[2] or an overall fiber link parameter inference[3]-[4] via learn digital back propagation (LDBP) algorithm[5]. Such approaches could tell the power longitudinal profile online, but the quantitative measurement and precise localization of the anomaly are still lacked.

In this paper, we propose to use Volterra nonlinear equalizer (VNLE)[6] based algorithm to estimate the variation of fiber nonlinear noise intensity along the propagation. VNLE allows to use simple Least Squares (LS) or Least Mean Squares (LMS) adaptation methods to make overall estimation[7]. Quantitative detection of fiber attenuation, abnormal loss and EDFA amplification gain are demonstrated in simulations. Through calculating signal energy imbalance, detection of passband narrowing caused by frequency offset of in-line optical filters (e.g. wavelength selective switching, WSS) is also achievable.

Method description

Fiber nonlinearity can be described with Manakov system of equations[8] which can be modified with attenuation, EDFA gains and abnormal losses:

$$\begin{aligned} &\frac{\partial \boldsymbol{X}}{\partial z} - \beta\frac{\partial^2 \boldsymbol{X}}{\partial t^2} - i\gamma \boldsymbol{X}\boldsymbol{X}^H\boldsymbol{X} + \alpha(z)\boldsymbol{X} = 0, \\ &\boldsymbol{X}(z = b_k + 0) = \alpha_k \boldsymbol{X}(z = b_k - 0), \\ &\boldsymbol{X}(z = z_n + 0) = G_n \boldsymbol{X}(z = z_n - 0), \end{aligned} \quad (1)$$

where $\boldsymbol{X} = \boldsymbol{X}(z,t) = \left(X(z,t), Y(z,t)\right)^T$ is the vector of the electric field envelope of the optical signal in two polarizations, $z \in [0, L]$ is the propagation distance, β is the second-order dispersion parameter, γ is the nonlinear coefficient, $\alpha(z)$ is the fiber attenuation coefficient, $\alpha_k, k \in [0, K]$ is abnormal losses which appear at distance $z = b_k$ along the fiber, G_n is the gain of EDFA at the end of each span $z = z_n, n \in [0, N]$, K – number of abnormal loss points, N – number of EDFA. Linear approximation is a common way to simplify Eq. 1, it is also known as chromatic dispersion compensation (CDC)

$$\tilde{\boldsymbol{X}}_z \equiv \boldsymbol{X}(z,t) = \hat{H}_{z-L}\boldsymbol{X}(L,t), \quad (2)$$

where $\hat{H}_{z-L}$ is the linear operator of CD evolution for signal from distance L to distance z. While VNLE based solution add an extra compensation term $\Delta\boldsymbol{X}_0$ to $\tilde{\boldsymbol{X}}_0$,

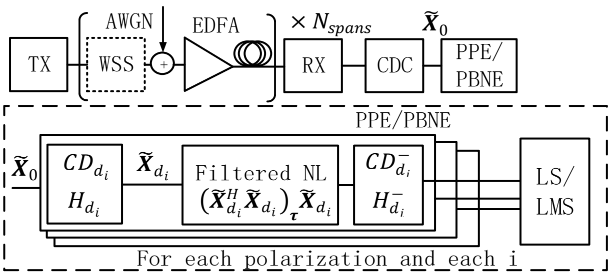

Fig.1: Block diagram of VNLE-based PPE/PBNE.

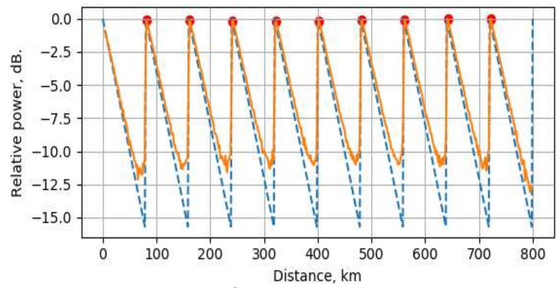

Fig.2: PP estimation. Solid line is the estimated PP and dashed line is the real transmitted PP.

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$$\Delta \boldsymbol{X}_{\mathbf{0}} = \sum_{z} \widehat{H}_{-z} \left[\widetilde{\boldsymbol{X}}_z \sum_{\tau} c_{z,\tau} \left(\widetilde{\boldsymbol{X}}_z^H \widetilde{\boldsymbol{X}}_z \right)_\tau \right], \quad (3)$$

where $(\cdot)_\tau$ represents delay operation, $c_{z,\tau}$ is model coefficient at position z and delay τ. Such coefficients could be solved by LS/LMS method with known or post-forward error correction (FEC) signal $\boldsymbol{X}_0$ as convergence target. In addition, signal attenuation is implicitly included in Eq. 3. Proportional relationship between $c_{z,0}$ and power profile (PP) can be considered,

$$\left|c_{z,0}\right| \sim P(z)^{3/2}, \quad (4)$$

where $P(z)$ is the signal power at distance z. Therefore, after using LS/LMS to obtain $c_{z,\tau}$ from VNLE-based algorithm, the relative power change and the link quality information contained therein can be extracted.

Fig.1 demonstrates the block diagram of the proposed power profile estimator (PPE) and passband narrowing estimator (PBNE), which are placed after the full length CDC. Besides, post-FEC signal also needs by PPE/PBNE in order to construct the loss function of LS/LMS.

Branch with different forward and backward CD filters are used to calculate spacially localized nonliearity as shown in Eq. 3. For PPE, 50 uniformly distributed branches without memory ($\tau = 0$) are adopted for each span, where d_k means different distances. According to Eq. 4, signal PP can be extracted from absolute value of coefficients c_{d_k}. Fig. 2 demonstrates that the interpreted PP (solid orange line) has a good consistance with real power evolution (dashed blue line) in the simulation. Further analysis of $\left|c_{d_k}\right|$ can help to determine other fiber link parameters like: span quantity and length, fiber attenuation, abnormal power loss and gain loss of EDFAs. For PBNE, only one branch with memory range $\tau \in [-64, +64]$ is adopted for each span. For a specific span, $\left|c_{z,\tau}\right|$ will change with τ and is symmetrical about $\tau = 0$ if there is no PBN. Therefore the passband frequency offset can be reflected by the variation in curve symmetry.

Simulation results

For PPE and PBNE simulations, 10- and 15-spans fiber link is chosen, respectively. Each span has 80 km length and 16.89 ps^2/km chromatic dispersion coefficient. 130 GBaud, 16 QAM signal is transmitted with 1550 nm central wavelength and 8 dBm launch power. At each span, additive white Gaussian noise (AWGN) is added to simulate amplified spontaneous emission (ASE) noise. In abnormal fiber attenuation detection simulation, attenuations from 0.18 to 0.22 dB/km are set at 6th span fiber instead of 0.2 dB/km for normal fiber. In abnormal loss detection simulation, 1dB power loss is added at distance 520 or 550km. And 0.5~2.0 dB extra loss is given to EDFA at the end of 6th span in EDFA gain loss detection simulation. For PBNE simulations, two WSSs with frequency offset from -16 to 16 GHz are considered.

After obtaining the PP plot, the number of peaks in it allows to know the span number directly. For a complete detection, fiber attenuation should be check first. Otherwise the influence of abnormal fiber attenuation to the peak position will be confused with that of the abnormal EDFA gain. Attenuation can be determined by the slope of the PP line in logarithm domain if length of each span is provided. Linear regression are used to fit the line by LS method. Determined slope could be converted to the attenuation coefficient with expression: $\alpha = m\beta_1 + \beta_0$, where β_0, β_1 are coefficients that estimated on training data sets. In Fig.3 (a), the simulation result for attenuation change in 6th span shows a good accuracy with a relative error less than 5%. Besides, for launch power p_{in} in the range of 4 to 11 dBm, detection result of attenuation coefficients is robust, which means the PPE result is still credible even if the system works in the weak nonlinear regime with lower launch power.

Abnormal power loss may be caused by fiber damage, fiber aging or sudden fiber curvature change at some point. PP can also be used to locate the loss position and its value. Difference in log-domain Δ_k between coefficients at neighbor distances d_k and d_{k-1} can be calculated

$$\Delta_k = \log\left(\left|c_{d_k}\right|\right) - \log\left(\left|c_{d_{k-1}}\right|\right) \quad (5)$$

Fig.3 (b) and (c) show the estimation result for 1 dB abnormal loss at 520 km and 550 km, respectively. All curves are smoothed with a short sliding window to remove spurs and decrease statistic noise. The dotted blue lines show a bias

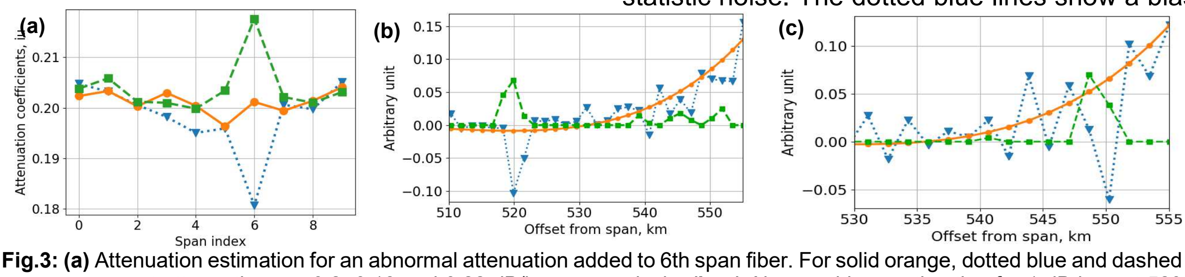

Fig.3: (a) Attenuation estimation for an abnormal attenuation added to 6th span fiber. For solid orange, dotted blue and dashed green curve, set attenuation are 0.2, 0.18 and 0.22 dB/km, respectively. **(b, c)** Abnormal loss estimation for 1 dB loss at 520 km **(b)** and 550 km **(c)** point. Dotted blue, solid orange and dashed green curves present $\boldsymbol{\Delta}$, $\boldsymbol{\zeta_{est}}$ and bias corrected estimation, respectively.

from constant value at the end of the span, which can be fitted accurately by LS using forth-order polynomial $\boldsymbol{\zeta}_{\mathrm{est}}(z)$ (solid orange lines Fig. 3 (b, c)). Therefore, such fitting can help to eliminate the bias from $\boldsymbol{\Delta}$(dashed green lines Fig. 3 (b, c)), which will also increase the detectable distance. This method can determine abnormal loss as low as1 dB and locate the abnormal losses within the initial 70 km of 80 km span with good accuracy. The increase of launch power or test data can further increase the detection distance.

EDFA gain loss is determined by peak values in the PP plot. The difference between peak values of adjacent spans represents total relative power loss which is the sum of fiber attenuation loss, in-line abnormal loss and EDFA gain loss. After the first two factors are detected, the gain loss in EDFAs could be identified. Simulation results for 0.5, 1.0, 2.0 dB EDFA gain loss at the end of 6th span is shown in Fig.4. In this case there is no other anomaly and the estimation error is less than 0.1dB.

Frequency shift of the WSS is one common reason for passband narrowing. With the help of signal nonlinearity, position and quantity of such frequency shift can be recognized. Signal energy imbalance caused by such offset at span z could be noticed through checking the difference between $c_z^- = \sum_{\tau=-1}^{-M} |c_{z,\tau}|$, the sum of negative part of coefficients and $c_k^+ = \sum_{\tau=1}^{M} |c_{z,\tau}|$, the sum of positive part of the coefficient, $\Delta c_z = c_z^+ - c_z^-$. Simulation results in Fig. 5 (a) show that the imbalance appears at the span with offset and could be used to quantitatively estimate this offset. To eliminate the bias (dashed-dotted orange line and dotted red line in Fig.5 (a)) after the span with offset, relative coefficients $c_{rel_z}^- = c_z^- \frac{c_{z-1}^+}{c_{z-1}^-}$ and $c_{rel_z}^+ = c_z^+ \frac{c_{z-1}^-}{c_{z-1}^+}$ could be used. And the relative imbalance $\Delta c_{rel_z} = c_{rel_z}^+ - c_{rel_z}^-$ (dashed green line in Fig. 5 (a)) is analyzed. The regression defined by $f_{off} = \mathrm{F}(\Delta c_{rel}, p_{in}, n_{span})$ was built to convert and normalize Δc_{rel} to real frequency value, where F is a quadratic form. In order to enhance the generalization ability of the regression formula F, training set from simulations with p_{in} between 4 to 11 dBm, frequency offset between -16 to 16 GHz are fed to the formula. Fig. 5(b) shows the frequency shift output of this regression formula from another test set with 7dBm p_{in} and 2, 6, 10 GHz frequency offset, respectively. Each point in Fig. 5(b) is a frequency offset estimation result for a simulation with only one WSS frequency offset in span index determined by x-axis value. Estimation error less than 0.5 GHz is demonstrated in this figure.

Conclusions

Digital signal compensation technologies for signal distortion caused by fiber nonlinearity can also be used in anomalies detection of optical fiber link without affecting to signal transmission. The VNLE nonlinear coefficients calculated by LS/LMS method can accurately reflect signal power evolution during the propagation. The proposed PPE, PBNE can achieve fiber link anomaly detection and localization quantatively. Estimation error of fiber attenuation is smaller than 5%. As low as 1 dB abnormal loss can be deteced with good positioning accuracy in the inital 70 km of 80 km span. The resolution of EDFA gain loss detection can be 0.5 dB. When the span length is know in the realistic link, this approach can also potentially distinguish the fiber type by detected features like attenuation coefficient, chromatic dispersion coefficient or nonlinear coefficient. Proposed PBNE can detect passband narrowing with accuracy up to 2GHz in 130Gbaud simulations.

With this approach, online fiber link monitoring can be realized to discover and forecase hidden dangers in time without any additional equipment. It will imporve the operating quality of the transmission network and reduce the complexity and the cost of link maintenance.

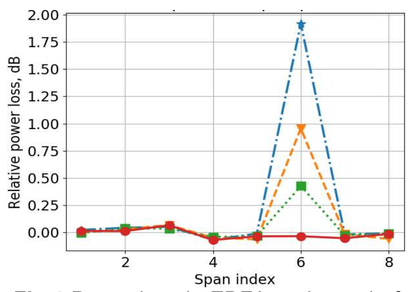

Fig.4 Power loss in EDFA at the end of 6th span. Set gain loss for solid red, dotted green, dashed orange and dashed-dotted blue line are estimation from the simulation with 0.0, 0.5, 1.0, 2.0 dB loss, respectively.

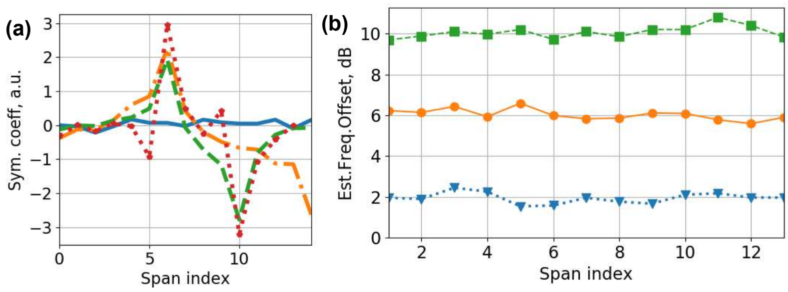

Fig.5 (a) PBNE simulation results. Solid blue line is $\Delta \boldsymbol{c}$ from a simulation without offset. Dashed-dotted orange line is $\Delta \boldsymbol{c}$ from a simulation with 10 GHz offset at the end of 6th span. Dotted red line and dashed green line are $\Delta \boldsymbol{c}$ and $\Delta \boldsymbol{c}_{rel}$ from a simulation with 10 GHz offset in 6th and -10 GHz offset in 10th span, respectively. **(b)** Estimated frequency offset from regression formula from simulations with 7 dBm launch power and 2, 6, 10 GHz offset, respectively.

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