Transmission Link Status Estimation Based on Phase Information for Long-Haul Optical Networks

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***Abstract*—A phase-correlated method (PCM) for monitoring link power evolution is proposed. Compared to traditional MCM, it breaks the restriction of constant modulus signals and is applicable to any MQAM signals.**

***Keywords*—Longitudinal power monitoring, Digital signal processing, Phase information.**

I. Introduction

The growing network size and user traffic increase network complexity and link failure probability. A cost-effective and easy-to-deploy technology to monitor large-scale optical networks is crucial for building autonomous optical networks [1]. While optical time-domain reflectometers (OTDRs) are known for their ability to accurately measure link fibers, their deployment in optical links requires additional optical components for monitoring the link status. This can become impractical and not cost-effective in large-scale optical networks that require monitoring of multiple points for fault detection. Due to this reason, many techniques for longitudinal power monitoring (LPM) based on the receiver have been proposed in recent years. An instance of successful application in this regard is presented in [2], the authors presented an in-situ power profile estimator (PPE) based on modulus correlation method (MCM), which employs a low-complexity signal processing algorithm, i.e., it does not require iterative optimization of parameters to find the optimal values, and utilizes minimal prior information about the link to reconstruct the power evolution of the channel on the link. In addition, it achieves a fault location accuracy within a range of 1 km [3, 4]. However, this monitoring method cannot be applied to constant modulus signals, which continue to constitute a significant portion of backbone networks.

This paper presents a novel approach, the phase correlation method (PCM), for estimating the power evolution status of a transmission link. The proposed method achieves accurate monitoring of power evolution for any MQAM modulation signals, including QPSK, by extracting the phase information of the received signal and performing correlation calculations. In order to evaluate the performance of the proposed method, we conducted different power evolution status at a 56G-Baud coherent transmission system using two different modulation formats, i.e., DP-QPSK and DP-16QAM, over 360 km standard single-mode fiber (SSFM). The simulation results demonstrate that our proposed PCM algorithm overcomes the limitations of the MCM method in estimating power evolution status of transmission links carrying constant-modulus signals and performs well in achieving LPM for high-order modulation signals.

II. Operation Principle

In the MCM method, the power status of each monitoring point in the link is reflected by calculating a specific correlation value for the corresponding point. The formula for calculating this correlation value is as follows:

$$correlation(i) = \frac{\sum_i (\|U_i\| - \|\overline{U}\|)(\|L\| - \|\overline{L}\|)}{\sqrt{\left(\sum_i (\|U_i - \overline{U}\|)^2\right)\left(\sum_i (\|L - \overline{L}\|)^2\right)}} \quad (1)$$

The MCM method calculates a correlation value for each monitoring point in the link based on the power status of the signal before and after link propagation. The U_i variable is obtained by applying a digital backward propagation (DBP) chain, which varies for different points in the link and contains the corresponding power status information for the i-th point in the link [5, 6]. The L variable is acquired through a standard receiver DSP chain to closely represent the transmitted signal before link propagation. According to formula 1, it can be observed that for constant-modulus modulation signals, the matrix $\|L\|$ obtained after decision and the corresponding mean matrix $\|\overline{L}\|$ is always equal, leading to a correlation value of zero. This is a critical point as it clarifies why MCM cannot achieve LPM for constant-modulus signals in transmission links. In such case, the MCM method that calculates the correlation value from the signal modulus to reflect the power evolution of each point in the link is rendered ineffective.

To overcome this obstacle and enable effective monitoring of the transmission state for constant modulus signals, we propose a novel link monitoring method based on signal phase. The PCM method, depicted in the upper part of Figure 1, can be described as follows. Firstly, after the optical signal is received by a coherent receiver, the chromatic dispersion present in the link is blindly estimated and then fully compensated using a chromatic dispersion compensator (CDC) block. Then, the resulting signal is subject to polarization demultiplexing with the adaptive equalizer (AEQ). In contrast to MCM, the carrier phase recovery (CPR) operation is placed before splitting the signal into tributaries. The reason for this approach is to maintain consistency of the phase information extraction among different branches, which allows for effective monitoring of PCM performance. For the upper branch, the signal is reloaded with dispersion to reconstruct a signal that contains both dispersion and damage. It is important to ensure that the amount of dispersion reloaded is consistent with the amount of dispersion compensated for by the CDC module, as previously mentioned. Afterwards, the signal undergoes a three-step iterative processing, which includes:

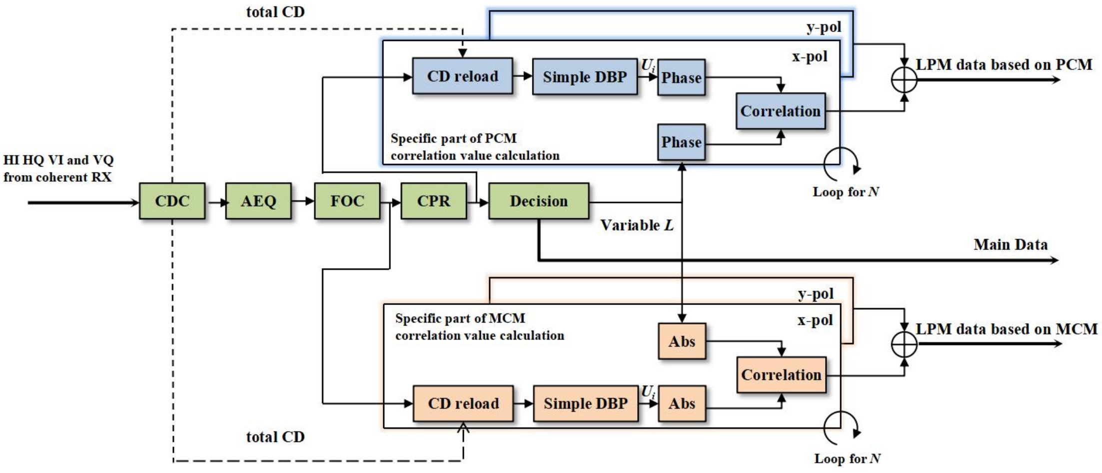

Fig. 1 The detailed structure of PCM and MCM scheme for LPM, CDC: chromatic dispersion compensator, AEQ: adaptive butterfly structured filter, FOC: frequency offset compensator, CPR: carrier phase recovery, FOC: frequency offset compensation

1) Partial chromatic dispersion compensation;2) Nonlinear remediator;3) A residual chromatic dispersion compensation; Since these three steps are similar to the DBP process. To facilitate the discussion, we will use the term "Simplified DBP" to refer to the three-step iterative process as a whole [7]. The variable U_i corresponds to the output signal of the Simple DBP module. As for the other variable L, it is obtained in the same way as in MCM. By extracting phase information from both variables and calculating their correlation, the power status information of the corresponding monitoring points in the link can be obtained. The calculation formula is as follows:

$$correlation(i)=\frac{\sum_i(\theta(U_i)-\theta(\overline{U}))(\theta(L)-\theta(\overline{L}))}{\sqrt{\left(\sum_i(\theta(U_i-\overline{U}))^2\right)\left(\sum_i(\theta(L-\overline{L}))^2\right)}} \quad (2)$$

For any quadrature amplitude modulation (QAM) signal, the distribution of symbols on the constellation diagram after decision cannot be concentrated at one point. Combining this with the formula, we can conclude that when calculating the correlation values that reflect the power status information of the link, the calculation result will not always be zero due to the equality of the variable and its mean.

III. Results and Discussion

To demonstrate the feasibility of the proposed PCM method for monitoring constant-mode signals, and compare the performance of PCM and MCM in calculating the LPM of non-constant-mode signals, the extensive simulations have been carried out in the 56GBd DP-QPSK and DP-16QAM optical coherent systems, respectively, which is built by the VPI transmission Maker and MATLAB software, as shown in Fig. 2.

In the transmitter, the optical signal is modulated by driving two I/Q optical modulators with electrical signal and applied a root-raised cosine filter with a roll-off factor of 0.18 to pulse-shape the signals. After being amplified by the EDFA, the signal is transmitted into a 360 km-long standard single-mode fiber (SSMF) transmission link consisting of 5 spans. To better demonstrate the effectiveness of the proposed method for monitoring the link performance, we employ two different span length configurations in an interleaved manner. Specifically, the lengths of the 1st, 3rd, and 5th spans are set to 80 km, while the lengths of the 2nd and 4th spans are set to 60 km. All spans are terminated with an optical amplifier with a fixed output power of 4 dBm and a noise figure of 5 dB to compensate for the power loss. Here, other parameters in the link are set as predetermined constants, including the attenuation coefficient of the fiber at $0.2dB/km$, the dispersion coefficient of $16.75\,ps/nm/km$, and the nonlinearity coefficient of $1.3w^{-1}km^{-1}$, respectively. Additionally, the linewidth of both the transmitter and receiver lasers is set to 100 kHz, and a frequency offset of 1 GHz is taken into consideration. After coherent detection, the signal is subjected to DSP processing as described in section 2. For

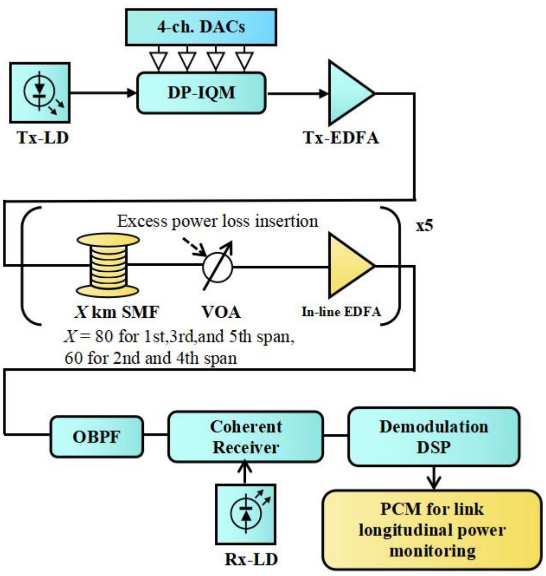

Fig. 2 Simulation setup for 56GBd using DP-QPSK/16QAM. DP-IQ Modulator: dual polarization in phase and quadrature-phase modulator, SMF: single-mode fiber, LD: laser diode, EDFA: erbium doped fiber amplifier, attenuator, OBPF: optical band-pass filter,

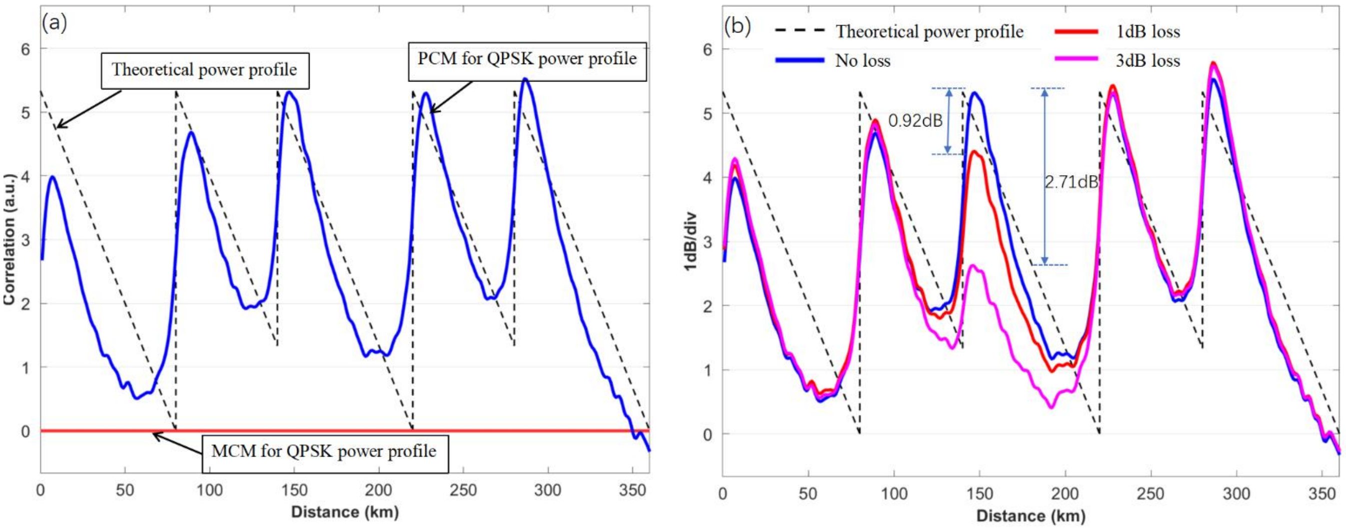

Fig. 3. (a) Comparison of two different LPM methods for link state monitoring of QPSK signals (b) Performance of PCM for QPSK signal transmission with link failures

the LPM calculation, we set the value of N=360, indicating that each "virtual" segment of the fiber in the algorithm had a length of 1 km.

To validate the proposed method for performing LPM calculations on constant-modulus signals, we first transmit QPSK signals. The LPM results obtained using the PCM and MCM algorithms on the QPSK signals are illustrated by the blue and red curves, respectively, in Figure 3(a). The MCM method is observed to be unresponsive to changes in signal power, indicating its inability to effectively monitor the power distribution of the signal in the link. In contrast, our proposed PCM method exhibits perfect consistency between the estimated power distribution curve and the theoretical curve of the QPSK signal, which demonstrates its capability for LPM of constant-modulus signals. Figure 3(b) illustrates the performance of the proposed PCM method for QPSK signal transmission in the presence of link failures. As shown in the figure, the PCM method effectively reveals information about the link failures at the corresponding points. To create this figure, we add 1 dBm and 3 dBm power attenuators at the second in-line amplifier and applied the proposed PCM algorithm. This results in a peak power difference of 0.92 dB and 2.71 dB between the blue and red curves and between the blue and magenta curves, respectively.

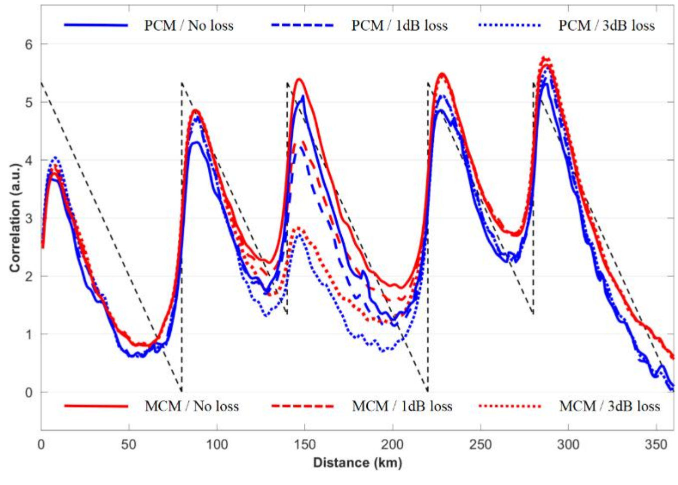

Fig. 4 Comparison of two different LPM methods for link state monitoring of 16QAM signal with different value of loss

Furthermore, we investigate and examind the effectiveness of our proposed PCM algorithm for monitoring high-order modulation formats. The results of comparative experiments in a 16QAM coherent transmission system are shown in Figure 4, where both MCM and PCM methods are employed to calculate the LPM of signals that experienced various link impairments. Different types of signal impairments are represented by different line styles in the figure and are located at the output power of the second-span EDFA. The red line indicates the LPM calculation of the link based on the MCM method, and the blue line represents the LPM calculation based on the proposed PCM method. Both methods exhibit comparable trends, demonstrating that our PCM algorithm can reliably monitor the power evolution of higher-order MAQM signals.

IV. Conclusion

In this study, we propose a PCM algorithm for LPM that overcomes the limitations of MCM in monitoring constant-modulus signals. The results demonstrate that the proposed PCM algorithm achieves accurate LPM monitoring of QPSK signals and provides reliable monitoring of power evolution for higher-order MAQM signals. It should be a promising solution for efficient and reliable LPM in future autonomous optical network transmission systems.

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