Optical Performance Monitoring in Elastic Optical OFDM Networks

Calvin C K Chan, Kam-Hon Tse, Tianwai Bo, and Shuang Gao
Department of Information Engineering,
The Chinese University of Hong Kong
Shatin, Hong Kong
ckchan@ie.cuhk.edu.hkm

***Abstract*—Optical performance monitoring (OPM) is a crucial element in network management, in order to assure the quality of the optical signals at various intermediate and destination nodes. In future elastic optical network, the network operation is more adaptive and reconfigurable. The OPM monitoring information retrieved at each intermediate node would be useful for optimal network control. Common OPM parameters in an optical transmission system, include optical signal-to-noise ratio (OSNR), accumulated chromatic dispersion (CD) and polarization mode dispersion (PMD). In this paper, we present our OPM techniques for these three parameters, based on signal correlation procedures on one or a few pilot subcarriers inserted in the spectrum of an optical OFDM signal, which is one of the promising signal format to support the future elastic optical networks.**

Keywords—optical performance monitoring; elastic optical networks; OFDM.

I. INTRODUCTION

Recently, elastic optical network has been widely recognized as a promising approach to support future high-speed heterogeneous data traffic [1]. Optical orthogonal frequency division multiplexing (OFDM) is one of the feasible candidates to enable such flexible network, for its flexible bandwidth and high spectral efficiency [2]. To date, there are two mainstreams of optical OFDM systems, in terms of the signal detection technique, namely coherent optical OFDM (CO-OFDM) [3] and direct detection optical OFDM (DDO-OFDM) [4]. In medium/short distance transmission, such as metro/access networks, DDO-OFDM is more preferred because of its low requirement for transmitter's laser linewidth. It employs a cost-effective photodiode, instead of expensive coherent receivers, to achieve high speed transmission, though at certain expense of sensitivity. However, it suffers from a critical drawback of power fading induced by the various optical impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD) of the fiber link. In order to assure the quality of the optical OFDM signals over an optical network, low-cost and effective in-line optical performance monitoring (OPM) techniques are highly desirable to be incorporated at the intermediate network nodes, such that the network control plane can be kept updated of the optical signal quality, for the subsequent network control and signal compensation.

In [5-7], we have recently proposed to apply a simple signal correlation technique on one or a few pilot subcarriers inserted to the signal spectrum of the single-sideband (SSB) modulated optical OFDM signal in a DDO-OFDM system, and the three OPM parameters, including optical signal-to-noise ratio (OSNR), CD and PMD, of the optical OFDM signal can be accurately estimated. The proposed schemes offer robust and effective solutions to realize in-line OPM for future high-speed elastic optical networks.

II. OPM TECHNIQUES

A. OSNR monitoring [5]

Consider an SSB modulated DDO-OFDM signal, the received signal r on the pilot subcarrier can be expressed as

$$r = H \cdot s + n \tag{1}$$

where s is the transmitted original signal on the pilot subcarrier, n is the electrical noise on the pilot subcarrier after FFT and H is the channel function related to frequency responses of the transmitter, fiber CD, optical filters and receiver. The calculation of the electrical noise power requires the knowledge of the channel function. Let s' represent the signal, which is recovered based on the estimated channel function H' ($s' = r/H'$), by definition, the ESNR is expressed as

$$ESNR_{Def} = \frac{E[|s|^2]}{E[|n|^2]} = \frac{E[|s|^2]}{E[|s' - s|^2]}, \tag{1}$$

where $E[\cdot]$ is the expectation operator. It is clear that the estimation of $ESNR_{Def}$ requires the prior estimation of the channel response. A poor channel estimation would probably result in a poor $ESNR_{Def}$ estimation, especially under the large power of ASE noise case. Here, we propose an alternative ESNR estimation method based on the correlation to estimate the signal and noise powers, that is,

$$\rho = \frac{|E[r^* \cdot s]|^2}{E[|r|^2]E[|s|^2]} = \frac{E[|s|^2]}{E[|s|^2] + E[|n|^2/|H|^2]}, \tag{2}$$

$$ESNR_{Corr} = \frac{\rho}{1-\rho}, \tag{3}$$

where r^* is the complex conjugate of r, and ρ is defined as the cross correlation at the zero point of the received signal and the original signal divided by the product of the auto correlation at the zero point of r and s, respectively. It is assumed that the modulus of channel function H to be constant or slowly varying within the time period of all received signals. For DDO-OFDM systems, the channel function for one subcarrier satisfies this condition. Therefore, with the proposed ESNR estimation method, by removing the extra channel estimation, the estimation process can be simplified. After the ESNR is estimated, the OSNR value can be derived through a calibrated curve between OSNR and ESNR.

Fig. 1 shows the estimated OSNR values and the estimation error results after calibration of the experimentally measured data, for 100-km and 200-km transmission spans. It could be observed that the proposed correlation method showed smaller estimation error than the definition method. Within the OSNR range of 8 to 28 dB, the maximum estimation errors for the correlation method and the definition method were 0.8 dB and 1.1 dB, respectively.

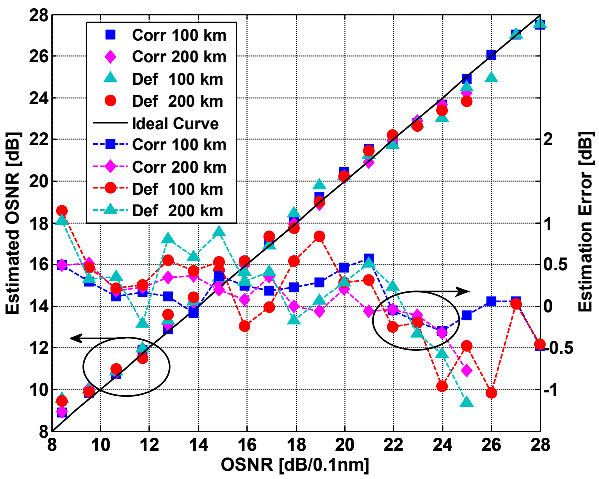

Fig. 1. Experimental results: estimated OSNR results with calibration at different transmission spans for two ESNR methods with respect to the left vertical axis; dashed curves are the OSNR estimation error results for two ESNR methods with respect to the right vertical axis.

B. PMD monitoring [6]

Consider the first-order PMD effect, the differential group delay (DGD) induces misalignment of the state of polarizations (SOPs) among the optical carrier and the optical subcarriers of a DDO-OFDM signal. This creates destructive interference among themselves during the signal beating at the receiving photodiode, and leads to power fading over the entire power spectrum of the detected signal. Assume the input optical signal is equally split into two orthogonal principal states of polarization (PSPs), the PMD-induced power fading over the whole signal's spectrum exhibits a cosine function relationship. By inserting a pair of pilot subcarriers, each loaded with distinct pilot sequences, as the first and the last subcarrier of the SSB-DDO-OFDM signal, their respective amplitudes can be retrieved by applying simple signal correlation procedure with the respective pilot sequences, respectively. These two pilot amplitude can be used to derive the DGD value ($\Delta\tau$), according to the following expression:

$$\cos(\pi f_1 \Delta\tau) = \left(A_1 / A_2\right) \cdot \cos(\pi f_2 \Delta\tau) \qquad (5)$$

where f_1 and f_2 are the frequency values of the two inserted pilot subcarriers, and A_1 and A_2 are their corresponding amplitudes, estimated by correlation. Fig. 2 shows the DGD monitoring results in the optical transmission experiments of 50 km and 100 km. The standard deviations of monitoring errors were below 1.5 ps over the whole monitoring range.

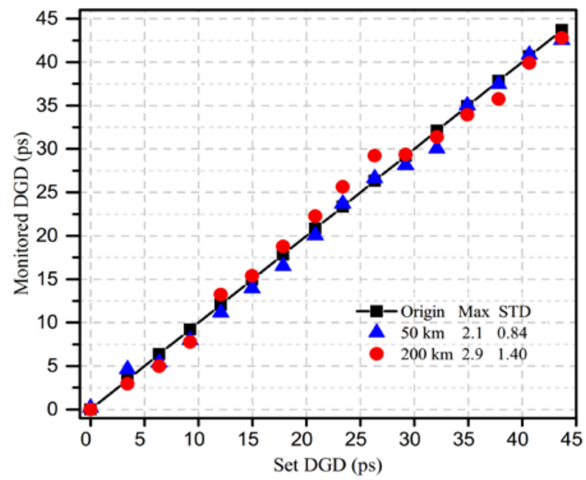

Fig. 2. Monitored DGD versus DGD value in the fiber link, with transmission length of 50 km and 100 km

C. CD monitoring [7]

For an optical OFDM signal, a pair of pilot subcarriers is inserted as the first and the last subcarriers of the signal spectrum. Each of them is loaded with a distinct code sequence. At the receiver, by correlating with the respective code sequences individually, we obtain two sets of correlation results, one for each code sequence. As the first and the last coded subcarriers suffer from different amount of walk-off, due to the fiber chromatic dispersion, the code sequences, modulated on those two edge label subcarriers, will experience different amount of temporal spread, accordingly. Such phenomena will lead to larger difference between the temporal positions of the two obtained correlation peaks, when the optical OFDM signal is suffered from a higher value of accumulated chromatic dispersion. Hence, by examining the temporal positions of the correlation peaks of the two edge optical label subcarriers, the accumulated chromatic dispersion value as well as the dispersion sign of the optical OFDM signal can be derived and monitored. Fig. 3 illustrates temporal differences between the measured correlation peaks of the two coded pilot subcarriers (denoted as label1 & label2) in a DDO-OFDM signal, after transmission of 800 km (top), and 1600 km (bottom). Such temporal differences will be translated into their respective accumulated chromatic dispersion values.

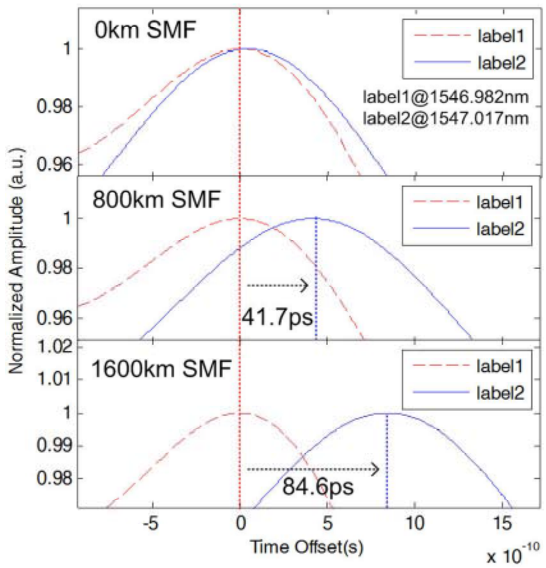

Fig. 3: Measured correlation results, showing temporal differences between the correlation peaks of the two coded pilot subcarriers (labels), after 800-km and 1600-km transmissions.

Fig. 4 shows the experimental measurement of the accumulated chromatic dispersion when the optical OFDM signal passed through the fiber ranged from 0 km to 1800 km. The obtained accumulated chromatic dispersion values increased linearly and agreed well with dispersion specification of the SSMF.

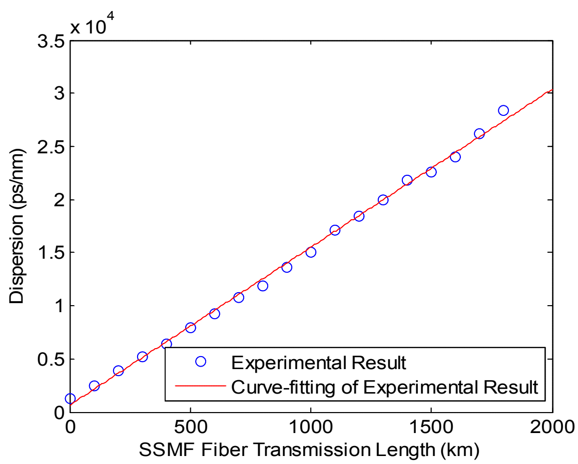

Fig. 4: Accumulated chromatic dispersion of the optical OFDM signal with different lengths of SSMF fiber transmission.

III. Summary

Optical OFDM is a promising enabling signal format for future elastic optical networks. By applying a simple signal correlation technique on one or a few pilot subcarriers inserted to the signal spectrum of the optical OFDM signal in an up-converted DDO-OFDM system, the three common OPM parameters, including OSNR, CD and PMD, of the DDO-OFDM signal can be estimated accurately. The proposed schemes offer robust and effective solutions to realize in-line OPM for future high-speed elastic optical networks. This work was partially supported by a grant from Hong Kong Research Grants Council (General Research Fund: CUHK410512).

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