Training Symbol Assisted Optical Signal-to-Noise Ratio Monitoring Technique for DDO-OFDM Systems

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Abstract: A high-accuracy training symbol assisted optical signal-to-noise ratio (OSNR) monitoring technique for DDO-OFDM systems is proposed and demonstrated with less than 0.42dB estimation error in an 8.87Gb/s QPSK-OFDM system over 40km SSMF transmission.

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1. Introduction

Direct-detection optical orthogonal frequency division multiplexing (DDO-OFDM) system is considered as one of the promising solutions to cope with the bottleneck of the last-mile bandwidth for its simple implementation, high spectral efficiency, flexible coding and system robustness against fiber dispersion [1]. Based on its modulation technique, DDO-OFDM can be categorized as single sideband modulated OFDM (SSB-OFDM) with relatively complicated and expensive modulators or optical filters [2], and double sideband modulated OFDM (DSB-OFDM) with a cost-efficient intensity modulator or directly modulated laser (DML) [3]. In both scenarios, optical signal-to-noise ratio (OSNR) monitoring is indispensable for the DDO-OFDM based elastic optical networks, especially in metro and medium distance networks [4]. OSNR monitoring can be realized based on the optical power measurement or RF spectrum analysis, using the high resolution spectrum analyzer or narrow bandwidth filters [5]. OSNR monitoring in coherent optical OFDM can also be implemented with the help of digital signal processing (DSP) technique using error vector magnitude (EVM) based or polarization state analysis methods[6, 7], in which electrical SNR (ESNR) of the received signal is calculated after channel estimation and massive tedious DSP operations. Recently, a pilot-aided OSNR estimation approach for SSB modulated DDO-OFDM systems using correlation method was demonstrated in [4]. However, one additional designated pilot subcarrier has to be adopted, which not only sacrifices the spectral efficiency but also aggravates the burden on coding and decoding. Moreover, the pilot subcarrier located at the upper spectral edge adjacent to the data band is susceptible to the filtering effects caused by bandwidth-limited components and dispersion induced power fading. Besides, it is more valuable to measure the OSNR in DSB modulated DDO-OFDM systems, which are widely used in short range optical transmission for its simplicity and cost-efficiency.

In this paper, we proposed a training symbol assisted OSNR monitoring technique for the DSB modulated DDO-OFDM system. Correlation operations are used to extract the ideal signal from the noise contaminated signal and then derive the ESNR of the training symbol after frame synchronization. With the prior information of the established relationship between OSNR and ESNR, the OSNR of the DDO-OFDM signal can be calculated. As the same training symbol designed for frame synchronization based on Schmidl and Cox method, can be directly used for ESNR estimation without introducing any redundancy, the spectral efficiency is not affected. Moreover, the ESNR can be calculated only employing several subcarriers within the training symbol without the need of channel estimation and equalization, which means lower computation complexity.

2. OSNR Monitoring Principle

In our proposed OSNR estimation method for DDO-OFDM system as depicted in Fig. 1, as in conventional OFDM systems before IFFT operation, training symbols are inserted into the mapped data at the beginning of each frame, one of which is used for Schmidl and Cox based frame synchronization and the others are for channel estimation. After direct detection at the receiver, the training symbols can be extracted with proper synchronization, cyclic prefix (CP) removing, and FFT operation. Then the k^{th} subcarrier of the first received training symbol can be expressed as: $R(k) = H(k) \bullet T(k) + n(k)$, where $H(k)$ represents the channel response at the location of k^{th} subcarrier, $T(k)$ is the known training data on the k^{th} subcarrier and $n(k)$ is the electrical noise on the k^{th}

subcarrier in frequency-domain. As the transmitted training data sequence T is uncorrelated with the noise n, the autocorrelation with zero delay of the received symbol R can be simplified into:

$$R_{R,auto}(0)=|H|^2 \bullet R_{T,auto}(0)+R_{n,auto}(0) \tag{1}$$

where $R_{R,auto}(0)$, $R_{T,auto}(0)$, $R_{n,auto}(0)$ are the autocorrelation with zero delay of the received training symbol, transmitted training symbol, and noise, respectively. The cross correlation with zero delay between the received training symbol R and the transmitted training symbol T is:

$$R_{RT,xcorr}(0)=H \bullet R_{T,auto}(0) \tag{2}$$

It should be pointed out that we assumed the channel response $|H|$ to be constant or slowly varying in frequency domain. This scenario is actually not suitable for the whole bandwidth in practical DDO-OFDM systems, however, the channel response can keep flat within the range of a few adjacent subcarriers. Based on the relationship between autocorrelation function and signal power, we can derive the training symbol's ESNR from (1) and (2) as following:

$$ESNR=\frac{|H|^2 P_S}{P_n}=\frac{R^2_{RT,xcorr}(0)}{R_{R,auto}(0) \bullet R_{T,auto}(0)-R^2_{RT,xcorr}(0)} \tag{3}$$

where P_S and P_n are power of training symbol sent in the transmitter side and noise, respectively. According to [4], the ESNR relates to OSNR by the following equation,

$$\frac{1}{ESNR}=A\frac{1}{OSNR^2}+B\frac{1}{OSNR}+C \tag{4}$$

where the coefficients A, B and C depend on the OFDM signal bandwidth, optical or electrical filter, subcarrier allocation, and modulation index. These system determined parameters can be calibrated using optical back to back (OB2B) system measurements. Obviously, the OSNR estimation accuracy is determined by the ESNR estimation and with our proposed method, OSNR monitoring can be accomplished without channel estimation, which reduces complexity and improves the accuracy.

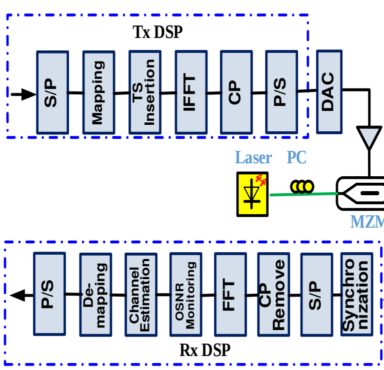

Fig.1. Schematic of the proposed OSNR monitoring technique for DDO-OFDM system using training symbol.

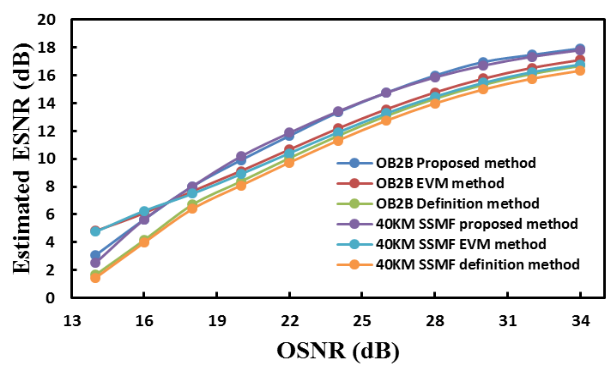

Fig.2. Simulation results of estimated ESNR Vs OSNR using different ESNR estimation methods in OB2B and 40km SSMF link

3. Simulation Results

To verify the proposed OSNR monitoring method, we performed simulations based on the system setup shown in Fig. 1 using MATLAB® and VPI Transmission Maker version 9.0. In our simulation, the baseband OFDM signal generation and DSP for OFDM de-multiplexing are almost the same with that we used in [8], even without any modification on training symbol. The modulation format we used is QPSK-OFDM, and the OSNR monitoring based on aforementioned process is inserted after FFT operation. The sampling rate of the DAC is 10GSa/s leading to a net data rate of 8.87Gb/s excluding the CP and training symbols. The wavelength of laser is set to 1550.12nm while the linewidth is 1MHz in our DDO-OFDM system. The EDFA we used to compensate the 40km SSMF loss is ideal so that we can set the OSNR using an off-the-shelf module in VPI. The modulation index and the received optical power are fixed at 0.23 and -15dBm, respectively. As the current noise, shot noise and thermal noise are considered in our simulation system, a 4th order Bessel electrical low-pass filter (LPF) with 3dB bandwidth of 7.5GHz is used after the photo-detector (PD) and electrical amplifier (EA). To ensure a flat frequency response and accurate estimation, 20 subcarriers located from 11th to 30th are selected to estimate the ESNR of the first training symbol while the ESNR is averaged over all the 13 frames of OFDM signals.

Firstly, we compare the ESNR estimation performance using our proposed method with that of EVM based method [8] and definition based method [4] in OB2B configuration and 40km SSMF link. As shown in Fig.2, the calculated ESNR of the training symbol using our proposed method or ESNR of OFDM signal using EVM and definition based approaches increases with the OSNR value in the range from 14dB to 34dB. It can be observed that the ESNR estimation shows similar performance in the high OSNR range while the EVM based method is badly-behaved in the lower OSNR region, which results from the deviation between EVM and ESNR in large noise case. The ESNR gap between our proposed method and definition based method is in consequence of non-ideal channel estimation and constellation reconstruction. Moreover, the dispersion induced ESNR penalty is small compared to the OB2B configuration in all the three cases. Subsequently, the relationship between 1/ESNR and 1/OSNR is investigated as illustrated in Fig. 3. We can see that the coefficients for every component of the parabola can be obtained using quadratic fitting for all ESNR estimation schemes based on the OB2B measurement results.

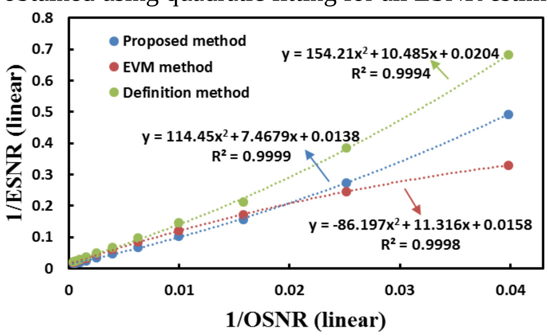

Fig.3. Fitting curves for 1/ESNR and 1/OSNR of OB2B results for different ESNR estimation methods

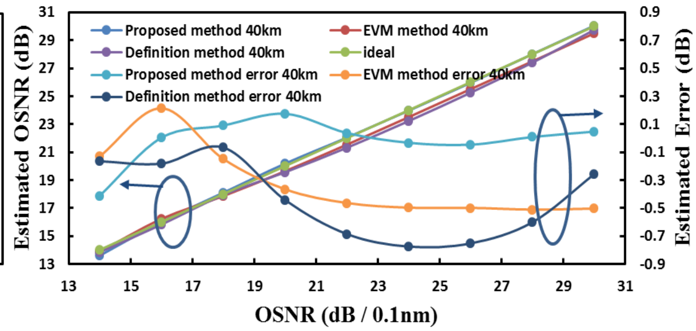

Fig.4. Estimated OSNR results after 40km SSMF transmission using OB2B fitting curve and the estimation errors for different methods

Finally, the fitting curve obtained in the OB2B case is used for calibration and estimating the OSNR in 40km SSMF transmission system. After calibration, the estimated OSNR values and the estimation error results are summarized in Fig.4. Compared with the other two estimation methods, our proposed training symbol assisted correlation based OSNR monitoring scheme has smaller estimation error. Within the OSNR range from 14dB to 30dB, our proposed method provides accurate estimation performance with maximum estimation error less than 0.42dB. Therefore, the capability of OSNR monitoring and the estimation accuracy of our proposed method are verified and demonstrated with better estimation performance. In principle, the estimation accuracy and robustness can be improved by averaging the ESNRs estimated by all the training symbols instead of only the first one we used in our simulation.

4. Conclusion

We have proposed a training symbol assisted OSNR monitoring method for DDO-OFDM systems without the need of channel estimation. We compared the OSNR estimation performances using three different ESNR calculating approaches, and simulation results show that our proposed method exhibits higher OSNR monitoring accuracy. In the 8.87Gb/s QPSK DDO-OFDM system, the estimation error after 40km SSMF transmission can be kept below 0.42dB within the OSNR range from 14dB to 30dB using our proposed OSNR monitoring method.

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5. References

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