Pilot-Aided Optical Signal-to-Noise Ratio Estimation for Direct-Detection OFDM Systems

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***Abstract*— We propose an optical signal-to-noise ratio (OSNR) estimation method for direct-detection optical orthogonal frequency division multiplexing (DDO-OFDM) systems by calculating the electrical SNR of one pilot subcarrier based on correlation. Simulation and experiment are conducted to verify this OSNR estimation method in a 15-Gb/s DDO-OFDM system. The maximum OSNR estimation error is 0.8 dB within an OSNR range of 8–28 dB for 100- and 200-km transmission distances.**

***Index Terms*— OSNR, optical performance monitoring, direct-detection optical OFDM.**

I. Introduction

ORTHOGONAL frequency division multiplexing (OFDM) is a promising technique for future elastic optical networks enabled by its high spectral efficiency, flexibility and high robustness against the linear impairments in fiber transmission. Based on the detection technique, optical OFDM can be categorized as coherent optical OFDM (CO-OFDM) with relatively complicated detection devices, coherent receiver and local oscillator (LO) at the receiver end [1], and direct detection optical OFDM (DDO-OFDM) with a single photo-detector for detection [2], [3]. Recently, DDO-OFDM is proposed for elastic optical networks [4], especially the metro network scenario [5], since it has the advantages of low-cost receiver, simple digital signal processing (DSP), as well as high granularity and flexibility. With the adoption of single sideband (SSB) modulation and super-channel aggregation, DDO-OFDM can achieve high bit rate transmission over several hundreds, or even thousands of kilometers [6], [7], and thus, is a promising solution for metro and medium distance networks.

In optical networks, dynamic network management is enabled by optical performance monitoring (OPM). OPM assures the reliable delivery and routing of the optical signals. Optical signal-to-noise ratio (OSNR) has been widely recognized as one of the most significant parameters to characterize the signal quality. Thus, OSNR monitoring is indispensable for the DDO-OFDM based elastic

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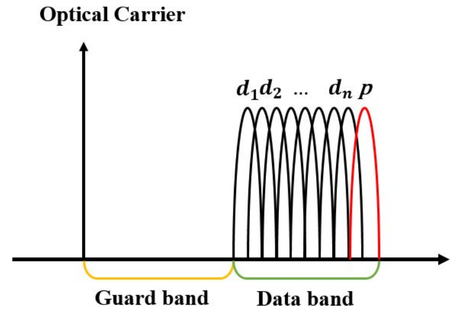

Fig. 1. Spectrum of the DDO-OFDM signal, where d_i $(i = 1, 2, \ldots, n)$ are the data subcarriers and p is the pilot subcarrier (in red) for ESNR estimation.

optical networks. OSNR monitoring can be realized by the optical power measurement or RF spectrum analysis techniques, enabled by the high resolution optical spectrum analyzer (OSA) or narrow bandwidth filters or interferometer or RF spectrum analyzer [8]. In [9], for intensity-modulated DDO-OFDM systems, an all-optical in-band OSNR measurement method with 0.08pm bandwidth resolution Brillouin scattering assisted OSA is proposed. OSNR monitoring can also be realized by digitally processing the detected signal. In [10] and [11], for CO-OFDM systems, electrical SNR (ESNR) is calculated with the coherently detected OFDM signals based on complete demodulation and polarization state analysis, respectively.

In this letter, a pilot-aided OSNR monitoring method is proposed for the SSB modulated DDO-OFDM systems. One designated pilot subcarrier is adopted adjacent to the OFDM data band. The correlation method is employed to estimate the ESNR of the pilot subcarrier. With the established relationship between OSNR and ESNR, the signal OSNR can be calculated. Note that this method is valid for all the SSB modulated DDO-OFDM systems.

II. OSNR Monitoring Principle

Consider a DDO-OFDM system with SSB modulation, the optical signal spectrum can be modelled as the combination of optical carrier, guard band and data band, as shown in Fig. 1. One designated pilot subcarrier is inserted at the upper spectral edge adjacent to the data band without breaking the integrity and continuity of the whole data band, as depicted. This pilot subcarrier is loaded with a known pseudo-random bit sequence (PRBS) to facilitate ESNR estimation. After detection at the receiver, with proper synchronization and fast Fourier transform (FFT), the pilot subcarrier can be extracted. The ESNR of the pilot subcarrier is then estimated based on the cross correlation between the extracted received pilot sequence and the original pilot sequence loaded at the transmitter. The OSNR is then derived based on the obtained ESNR value, via their relationship, discussed as follows.

A. Relationship Between OSNR and ESNR

Considering the white Gaussian amplified spontaneous emission (ASE) noise in the optical channel, OSNR is defined as

$$OSNR = \frac{P_s}{P_n}, \tag{1}$$

where P_s is the optical signal power and P_n is the optical noise power within 0.1-nm measurement bandwidth. With the square-law detection property of the photo-detector, beating noise is generated. Both the signal-noise beat interference and the noise-noise beat interference would spread over the whole signal spectrum with complicated distributions [12], [13]. The electrical signal power P_{es} and noise power P_{en} of the pilot subcarrier are related to the optical signal power P_s, as follows

$$P_{es} = A_1 P_s^2, \tag{2}$$
$$P_{en} = B_1 P_n^2 + C_1 P_s P_n + D_1 P_s^2, \tag{3}$$

where A_1, B_1, C_1 and D_1 are the coefficients of various power terms. For systems with large enough guard band, the signal-signal beating term P_s^2 falls within the guard band, thus the coefficient $D_1 = 0$. However, in a practical system, due to inadequate SSB filtering or imbalance of the optical IQ modulator, signal-signal beating spreads beyond the guard band, which also introduces interference ($D_1 \neq 0$). For systems with reduced guard band, the signal-signal beating falls in the data band, thus the coefficient $D_1 \neq 0$. The ESNR is defined as the electrical power ratio of the signal P_{es} to the noise P_{en}. It relates to OSNR by the following equation,

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

where the coefficients B, C and D depend on the OFDM signal bandwidth, optical filter bandwidth and the pilot subcarrier position. These coefficients can be calibrated based on back to back (BTB) system measurements. Obviously, the OSNR estimation accuracy is determined by the ESNR estimation.

B. ESNR Estimation

For a SSB modulated DDO-OFDM system as shown in Fig. 1, the received signal r on the pilot subcarrier can be expressed as

$$r = H \cdot s + n, \tag{5}$$

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 chromatic dispersion, optical filters and receiver [14]. 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

$$ESNR_{Def} = \frac{E[|s|^2]}{E[|n|^2]} = \frac{E[|s|^2]}{E[|s' - s|^2]}, \tag{6}$$

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 [15], [16], that is,

$$\rho = \frac{|E[r^* \cdot s]|^2}{E[|r|^2]E[|s|^2]} = \frac{E[|s|^2]}{E[|s|^2] + E[|n|^2/|H|^2]}, \tag{7}$$
$$ESNR_{Corr} = \frac{\rho}{1-\rho}, \tag{8}$$

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. From the derivation in Eq. (7) with substitution of Eq. (5), it should be noted that the modulus of channel function H is assumed 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. Meanwhile, the estimation accuracy can also be improved.

III. NUMERICAL SIMULATIONS & EXPERIMENTS

The proposed OSNR estimation method was studied via simulation and experiment, based on the RF-tone-assisted DDO-OFDM system [14]. The OFDM signals were generated by MATLAB offline. The "optical carrier" was generated by setting one subcarrier with a constant value. The Inverse FFT (IFFT) size was set to 256. Among them, 83 subcarriers carried payload with 16-quadrature amplitude modulated (QAM) symbols. One pilot subcarrier was loaded with designated 16-QAM symbols in the proposed ESNR estimation. One subcarrier was treated as the "optical carrier" and the rest were padded with zero. The power of the carrier was optimally set to be equal to the total power of all the subcarriers in both simulation and experiment [14]. The pilot subcarrier was located at the upper edge of the signal spectrum as shown in Fig. 1. The CP length was set to ten points.

A. Simulation Results

Numerical simulation was performed to emulate the DDO-OFDM system. The optical IQ modulator was set at the ideal null bias point. White Gaussian noise was added to vary the channel's OSNR with 0.1-nm reference bandwidth. The OSNR range was set from 5 to 30 dB. 360 OFDM symbols were generated as one packet with 30 symbols as the training symbols for channel estimation. Four packets were used to calculate the ESNR of the pilot subcarrier at different fiber distances with a dispersion coefficient of 16.4-ps/nm/km.

Fig. 2 shows the simulation results. Both $ESNR_{Corr}$ based on the proposed method Eqs. (7) & (8) and $ESNR_{Def}$ based on the definition (Eq. (6)), increased with the OSNR values. The fiber transmission distance had little influence on both

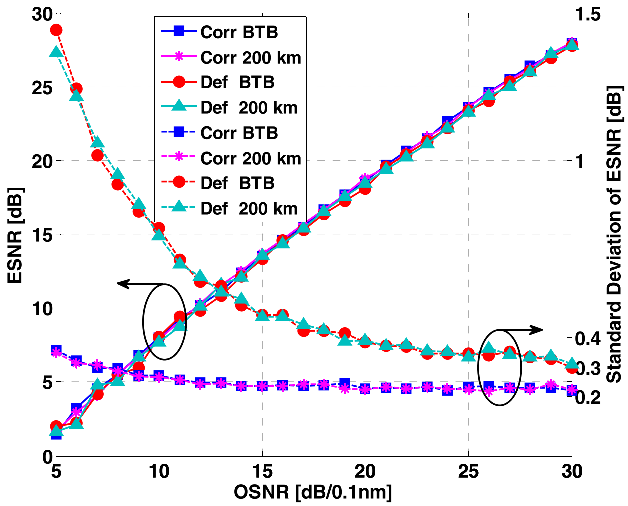

Fig. 2. Simulation results: solid curves are computed ESNR of the pilot subcarrier as a function of OSNR of the optical OFDM signal at different transmission spans for Corr (correlation) and Def (definition) based methods with respect to the left vertical axis; dashed curves are computed standard deviation of ESNR values for the two ESNR estimation methods with respect to the right vertical axis.

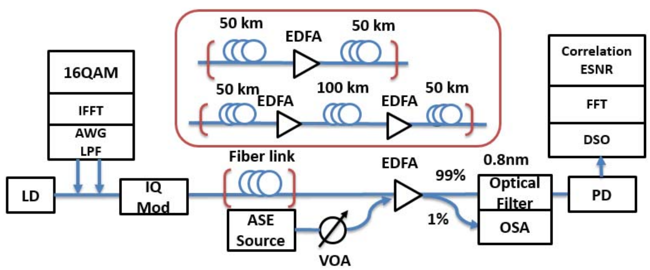

Fig. 3. System setup for characterization of the proposed OSNR estimation method, the insets are the link architectures for 100-km and 200-km transmissions, respectively.

methods. The standard deviation of the two estimation methods characterized by 1000 OFDM packets were compared. It was shown that the standard deviation of the estimation error of the correlation method $ESNR_{Corr}$ outperformed that of the definition method $ESNR_{Def}$ by at least 0.1 dB, over the whole OSNR range of 5 to 30 dB. At low OSNR values, $ESNR_{Corr}$ showed more significant estimation accuracy improvement. For instance, at an OSNR value of 5 dB, $ESNR_{Corr}$ exhibited about 1 dB smaller standard deviation than $ESNR_{Def}$. It could be attributed to the inaccurate channel estimation for $ESNR_{Def}$, while $ESNR_{Corr}$ did not require the knowledge of the channel response. The required minimum OSNR value was 14.8 dB, which corresponded to the BER limit of 2×10^{-2}.

B. Experimental Results

Fig. 3 shows the system setup of the experiment as well as the fiber link architecture. The OFDM signals were offline generated. The real and the imaginary parts of the OFDM signals were loaded to an arbitrary waveform generator (AWG) at 12-GSample/s sampling rate. As the amplitude response of the AWG was not flat, pre-emphasis was performed to ensure similar ESNR value for all subcarriers. The clipping ratio was set to 3.3. The OFDM symbol rate was 45.1Mb/s with

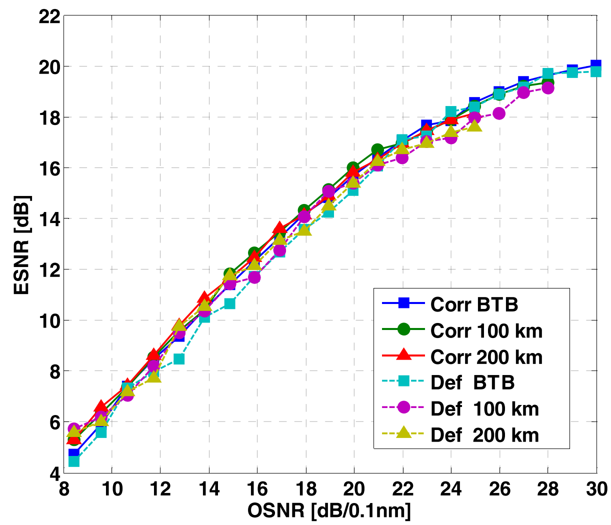

Fig. 4. Experimental results: computed ESNR of the pilot subcarrier as a function of OSNR of the optical OFDM signal at different transmission spans for two ESNR estimation methods, solid curves for Corr based method and dashed curves for Def based method.

266 (FFT+CP) samples in one OFDM symbol. The total bit rate was about 15 Gb/s. With two 5.5-GHz bandwidth analog LPFs, the two components of AWG output were sent into an optical IQ modulator, which was biased at the null point. The laser wavelength was 1550.06 nm. The launching power was −10dBm. The total transmission span was up to 200-km. The ASE noise was added to vary the OSNR value of the optical OFDM signal. At the receiver, 1% of optical power was tapped off for OSNR measurement by the optical spectrum analyzer (OSA) with 0.1-nm resolution bandwidth, while the rest of the optical power, after optical band pass filter, was fed into a photodiode. The electrical signals were then sampled and stored by a 25-Gsample/s real-time digital storage oscilloscope (DSO). After synchronization and FFT performed, the OFDM subcarriers were separated, of which the pilot subcarrier data was extracted. The ESNR of this subcarrier was estimated based on the correlation method ($ESNR_{Corr}$), compared to that based on the conventional ESNR definition ($ESNR_{Def}$) with extra channel estimation. The OSNR values of the optical OFDM signal was varied from 8 to 30 dB. With the use of 0.8-nm optical band pass filter to remove the out-of-band ASE noise, the required minimum OSNR value was 16 dB, which corresponded to a BER limit of 2×10^{-2}. 360 OFDM symbols were grouped into one packet with 30 training symbols and the ESNR value was estimated by taking the average of four packets.

Fig. 4 shows the ESNR results calculated based on the two methods when the OFDM system was operated with different transmission spans. From the curves, the ESNR of the pilot subcarrier increased as the OSNR of the optical OFDM signal increased, however, at a slightly decreasing rate. The relationship between them was independent of the transmission span, as the CP of the OFDM signal could combat the channel dispersion.

As illustrated in section II, the derived relationship between 1/ESNR and 1/OSNR has a quadratic component. Calibration has been performed so as to determine the coefficients in Eq. (4) based on the BTB experimental results. Fig. 5 shows

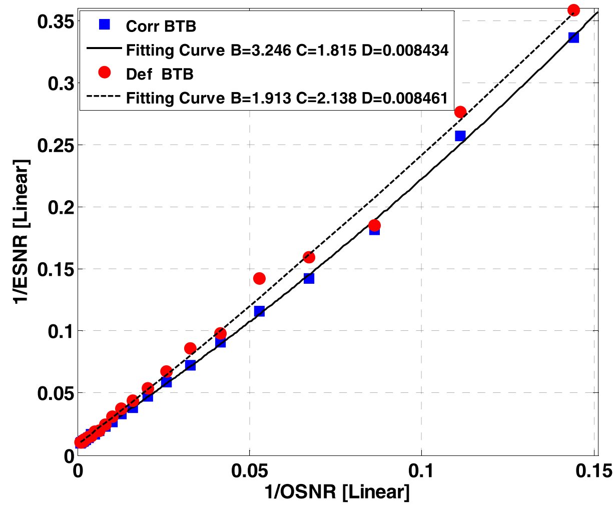

Fig. 5. Experimental results: fitting curves for 1/ESNR and 1/OSNR of experimental BTB results based on two ESNR estimation methods.

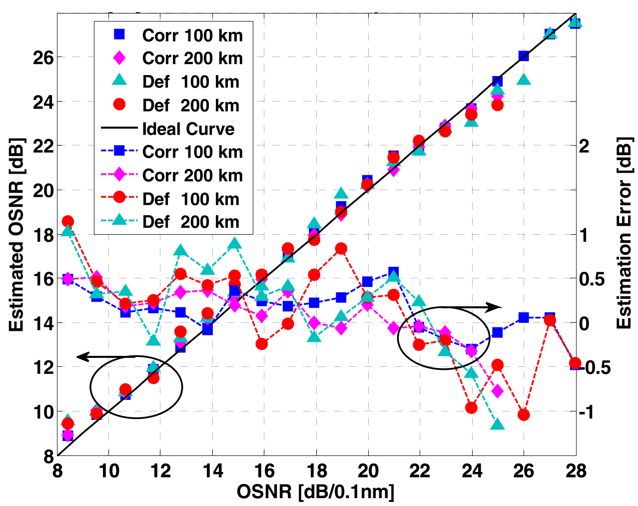

Fig. 6. Experimental results: estimated OSNR results with calibration at different transmission spans for two ESNR methods with respect to the left vertical axis; dashed curves are the OSNR estimation error results for two ESNR methods with respect to the right vertical axis.

the calibration fitting curves for 1/ESNR and 1/OSNR, as well as the coefficients B, C and D under the conventional and the proposed ESNR estimation methods. The expression of the fitting curve should be stored at the intermediate nodes in optical networks so as to facilitate OSNR monitoring.

Fig. 6 shows the estimated OSNR values and the estimation error results after calibration, 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. From the experimental results depicted in Fig. 4, it was noticed that the increasing rate of the ESNR curves was reduced when the OSNR value increased. At the high OSNR region, the ESNR was dominated by the background noise, instead of the ASE noise [10]. The purpose of calibration in Eq. (4) was to adjust the curves in Fig. 4 to become more linear, which were then used to derive the results shown in Fig. 6. Thus, the accuracy of calibration curve was very important. Since the proposed correlation based method gave more accurate ESNR results, the coefficients, B, C and D based on the calibration curves would be more accurate. Hence, the proposed OSNR estimation results in Fig. 6 exhibited smaller estimation error, compared with that using the definition method.

IV. Summary

A novel OSNR estimation method for DDO-OFDM systems has been presented and characterized. It is realized by calculating the ESNR of one pilot subcarrier based on the signal correlation. Simulation and experiment have been carried out in a 15-Gb/s DDO-OFDM system to verify this proposed OSNR estimation method. The OSNR estimation error is less than 0.8 dB, within an OSNR range of 8 to 28 dB, after 100-km and 200-km transmissions. Compared with the conventional definition based ESNR calculation method, the proposed correlation method can provide more accurate OSNR estimation and does not require channel estimation.

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