PAPR Reduction and Nonlinear Impairment Mitigation by Frequency Guard Band-Tone Reservation for DD-OFDM

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Abstract: A novel OFDM PAPR reduction scheme by exploiting frequency guard band (FGB) is proposed and experimentally demonstrated. Effective mitigation of nonlinear impairments is validated and BER improvement of 2.6 dB is achieved over 50-km fiber transmission without sacrificing data rate.
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1. Introduction

Combining the merits of robust dispersion tolerance and low optical hardware complexity, optical orthogonal frequency division multiplexing (OFDM) along with directed detection (DD) (DD-OFDM) has been recognized as a promising solution for cost-effective applications [1]. However, OFDM signals usually suffer from a high peak-to-average power ratio (PAPR) [2-7], which introduces nonlinear effects and clipping distortions in power amplifiers and digital-to-analog converters (DACs). In addition, high-peak signals could also result in nonlinear impairment during fiber-link transmission, which is difficult to compensate by electronic linear equalizers [2,4].

To reduce OFDM PAPR and improve transmission performance, diverse schemes have been investigated, such as companding [2], partial transmit sequences (PTS) [3], and tone reservation (TR) [5,6]. Among them, PAPR reduction based on TR is attractive as a distortion-free method. In this scheme, signal peaks can be minimized by adding an iterative peak-canceling signal to an original signal [6]. The peak-canceling signal is generated exclusively by reserved tones that are not dedicated to carrying information, thus a loss of data rate is inevitable. A method of TR-assisted PAPR reduction (TR-OFDM) with deeply attenuated subcarriers was proposed for directly modulated lasers [5] to reduce inter-carrier noise, but it may not be suitable for external modulation methods, and it lacks of experimental demonstration for improvements on transmission performance.

In this paper, for the first time to the best of our knowledge, we propose and experimentally demonstrate a PAPR reduction scheme based on TR by utilizing frequency guard band (FGB). In general, the FGB in DD-OFDM systems is reserved to accommodate the subcarrier-to-subcarrier beating interference (SSBI) caused by the square-law detection of photo detectors (PDs) [1]. In our proposed scheme, by inserting PAPR-reduce tones (PRTs) in the reserved FGB, a peak-canceling signal can be iteratively generated, therefore, minimizing the peaks of the original signal. Owing to the exploitation of the reserved FGB, the data rate is not sacrificed. The reduction of signal peaks also leads to effective mitigation of nonlinear impairments in fiber-link transmission. Experimental demonstration with a 8.62-Gb/s OFDM signal is performed. A PAPR reduction of 2.8 dB is obtained at a complementary cumulative distribution function (CCDF) of 10^{-4} for 20 iterations. The bit error rate (BER) performance is improved by ~2.6 dB over 50-km standard single mode fiber (SSMF) transmission for a ~10-dBm launch power. Furthermore, better improvements are observed for increased launch powers, which confirms effective mitigation of nonlinear impairments. The experimental results verify the feasibility of the proposed scheme as a data-rate loss-free solution to reduce PAPR for DD-OFDM systems.

2. Operation principal

For PAPR reduction based on TR, the constellation symbols of an original OFDM signal block are mapped onto certain assigned subcarriers, while other subcarriers are reserved as PRTs to build an iterative peak-canceling signal. As depicted in Fig. 1(a), a TR-OFDM signal is the sum of the original signal and the peak-canceling signal, whose relation can be expressed as follow [5,6]:

$$\begin{cases} x_{TR}^{i+1} = x_{OFDM} + c^{i+1} \\ c^{i+1} = c^{i} + \alpha_i p^{i} \end{cases}, \tag{1}$$

where i is the iteration index and x_{OFDM} is the original OFDM block. ${x_{TR}}^{i+1}$ and c^{i+1} denote the PAPR-reduced OFDM block and the peak-canceling signal with i+1 iterations, respectively. p^i refers to a peak-canceling element, which is generated by PRTs and serves to eliminate one or several peaks of ${x_{TR}}^{i}$. The factor α_i, which quantifies the difference between the largest peak in ${x_{TR}}^{i}$ and the desired maximum magnitude T, is defined as:

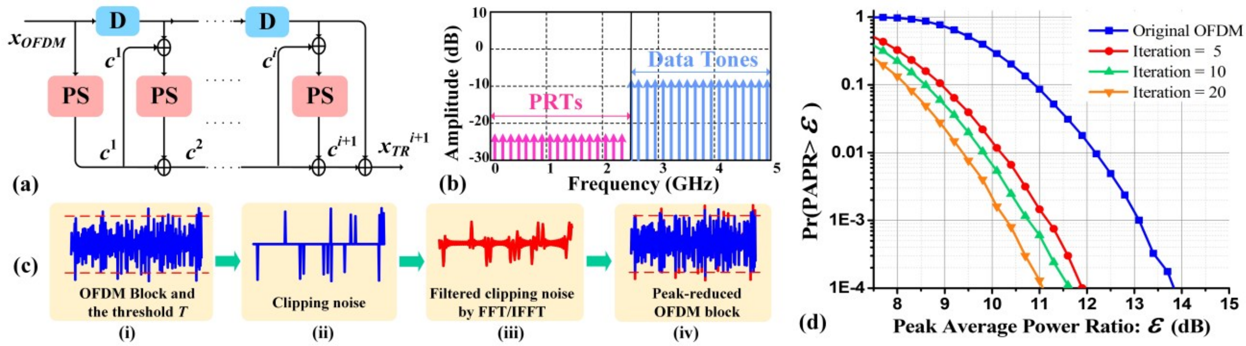

Fig. 1. (a) Algorithm of generating TR-OFDM signal. D: step delay, PS: peak search. (b) PRT allocations. (c) Waveforms in different steps of the proposed algorithm. (i) and (ii) Clipping step. (iii) Filtering step. (iv) Peak cancellation step, in which present the OFDM block (red) and the PAPR-reduced block (blue). (d) PAPR CCDFs for the original OFDM signal and the proposed TR-OFDM signal for various iterations.

$$\alpha_i = -\frac{2}{3}\left|T - \max(\left|x_{TR}^i\right|)\right|, \tag{2}$$

where –2/3 is the optimal coefficient obtained in simulations.

To efficiently generate the peak-canceling element p^i for each iteration, clipping and digital filtering are utilized [6]. For this technique, the element p^i can be simply deemed as a properly filtered clipping noise between the signal $x_{TR}{}^i$ and the desired maximum magnitude T. The filtering operation is required to limit the frequency components of the clipping noise within the assigned PRTs. Therefore, the data carriers would not be affected. In our proposed scheme, the PRTs are continuously located in low frequencies by utilizing FGB, as described in Fig. 1(b). The filtering can be realized by a digital low-pass filter through FFT/IFFT operations. For a clipping noise after FFT, the frequency components located outside of the PRTs are set to zeros, while those in PRTs remain unchanged. The element p^i can be obtained at the output of IFFT and then added with $x_{TR}{}^i$ to further reduce its peaks. Four insets provided in Fig. 1(c) depict the principle steps of this algorithm, in which the waveforms of a 256-subcarrier OFDM block are presented in one simple iteration. One can see from Eq. (1) that the PAPR reduction level is a function of iteration index, which is illustrated in Fig. 1(d). When T is set to 75% of the maximal peak value, the proposed TR-OFDM signal brings 1.9 dB, 2.2 dB and 2.8 dB gains in comparison with the original signal at the CCDF of 10^{-4} for iterations of 5, 10, and 20, respectively.

3. Experimental demonstration

We performed an experiment to test the transmission performance of the proposed scheme. The schematic diagram is shown in Fig. 2. A continue-wave (CW) light at 1551 nm from a distributed feedback (DFB) laser is fed into a Mach-Zehnder modulator (MZM) biased at the quadrature point of the transmission curve. The OFDM data are generated offline by Matlab. The total number of the subcarriers is 256. 16 QAM symbols are mapped onto 65~127 subcarriers, while 1~64 subcarriers remain empty as the FGB. To realize IM-DD OFDM, Hermitian symmetry is satisfied. After 256-point IFFT, the proposed TR-algorithm is implemented to search and clip the peak values. The iteration index is set equal to 20 and the desired maximal magnitude is set as 75% of the maximal peak value. A cyclic prefix (CP) of 16 samples is added to alleviate the inter-symbol interference. After parallel to serial

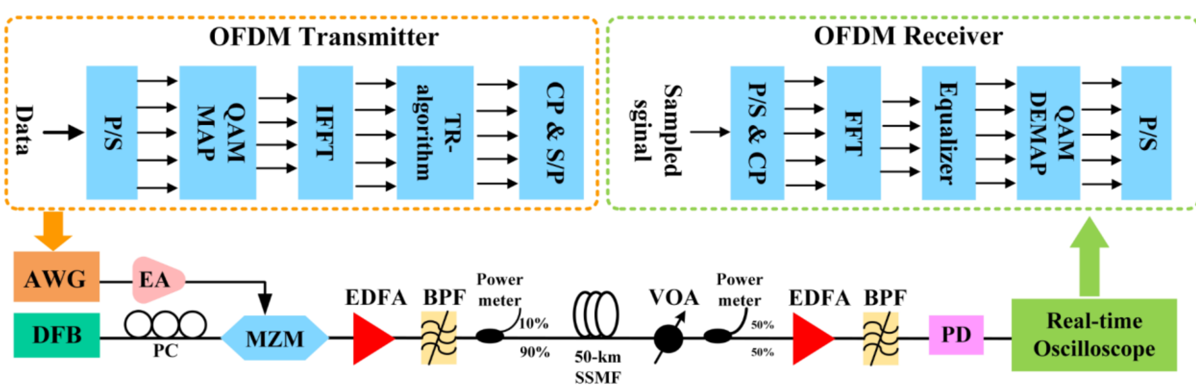

Fig. 2. Block diagram of the experimental setup for an intensity-modulated direct-detection (IM-DD) optical OFDM system with the proposed PAPR reduced method. EA: electrical amplifier, PC: polarization controller, VOA: variable optical attenuator, QAM: quadrature amplitude modulation, P/S: parallel to serial conversion, S/P: serial to parallel conversion.

conversion, the OFDM signal data are output by an arbitrary waveform generator (AWG) operating at 10-GSa/s sampling rate with 8-bit resolution. The proposed OFDM data have a bit rate of ~8.62 Gb/s, which is the same as the original OFDM data. After electro-optical modulation by the MZM, the optical signal is booted by an erbium-doped fiber amplifier (EDFA) followed by a tunable band pass filter (BPF) to suppress the amplified spontaneous emission (ASE) noise. A 90:10 fiber coupler and a power meter are employed to monitor the launch power. At the receiver, the optical signal is detected by a 10-GHz PD and then sampled by a real-time oscilloscope (LeCroy 806Zi-A) at 40-GSa/s sampling rate. Through down sampling, FFT, single-tap equalization, and 16-QAM symbol de-mapping, information on data subcarriers is recovered.

Figure 3(a) shows the BER curves of the original OFDM signal and the proposed TR-OFDM signal after 50-km fiber transmission for ~2.5-dBm launch power. A BER level of 10^{-3} is chosen as the forward error correction (FEC) threshold. The receiver sensitivity at the FEC threshold is ~−17.1 dBm for the proposed signal, which is ~2-dB better than that of the original signal. As a result, the error vector magnitude (EVM) of the proposed signals is 15.63% for ~−17-dBm received power, while that of the original signal is 21.52%. The corresponding constellation diagrams are provided in the inset of Fig. 3(a). More concentered constellation diagram of the proposed TR-OFDM signal are observed. Such improvement can be attributed to the fact that PAPR-reduced signal alleviates the clipping noise in both electrical amplifier and DAC at the transmitter and mitigates quantification noise at the receiver.

The comparisons of the BER performance for the original and the proposed signal with different launch powers are presented in Fig. 3(b). After 50-km fiber transmission, the receiver sensitivity of both signals at the FEC threshold improves when the launch power increases from 4 dBm to 8 dBm, while degrades when the launch power exceeds 8 dBm. This can be explained by a trade-off between an improved OSNR and enhanced nonlinear effect. The proposed signal always exhibits a better BER performance compared with the original signal for a same launch power. ~2.1, ~2.2, ~2.4, and ~2.6 dB improvements are obtained at the FEC threshold when the launch powers are ~4 dBm, ~6 dBm, ~8 dBm, and ~10 dBm, respectively. Since higher launch power means stronger nonlinear effect and larger degradation of receiver sensitivity, the fact that better improvements obtained by higher launch power can prove the mitigation of the nonlinear effects [7] by using our proposed scheme.

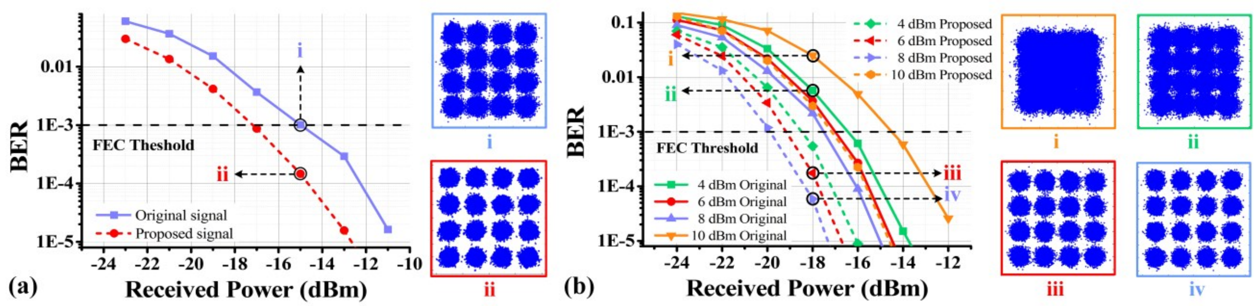

Fig. 3. BER curves of the original OFDM signal and the proposed TR-OFDM signal after 50-km SSMF transmission for (a) a launch power of ~2.5 dBm, (b) launch powers of 4 dBm, 6 dBm, 8 dBm, and 10 dBm.

4. Conclusions

We have proposed and experimentally demonstrated a novel PAPR reduction scheme based on tone reservation by utilizing FGB. A PAPR reduction of 2.8 dB leads to a ~2-dB BER improvement over 50-km fiber transmission for a ~2.5-dBm launch power. The mitigation of nonlinear impairments has also been investigated. The experimental results verify our method as an effective PAPR reduction scheme to improve transmission performance and mitigate nonlinear impairments without sacrificing data rate.

5. Acknowledgments

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