Combining discrete cosine transform with clipping for PAPR reduction in intensity-modulated OFDM systems*

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In this paper, the peak-to-average power ratio (PAPR) of orthogonal frequency division multiplexing (OFDM) signal is reduced by combining the discrete cosine transform (DCT) with clipping in optical intensity-modulated direct-detection (IM/DD) OFDM systems. First, the data are transformed into new modified data by DCT. Second, the proposed scheme utilizes the clipping technique to further reduce the PAPR of OFDM signal. We experimentally demonstrate that the optical OFDM transmission system with this proposed scheme can achieve significant performance improvement in terms of PAPR and bit error rate (BER) compared with the original optical OFDM systems.

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Orthogonal frequency division multiplexing (OFDM) has been widely used in optical communication systems, such as wireless optical systems, coherent optical OFDM (CO-OFDM) systems and intensity-modulated direct-detection (IM/DD) OFDM systems[1-3]. However, the IM/DD systems are simpler and can be easily implemented. The wireless optical communication systems also employ IM/DD techniques. In this paper, we mainly consider the IM/DD scheme.

The high peak-to-average power ratio (PAPR) of OFDM signal is the main problem in the IM/DD OFDM system. When OFDM signals propagate over an optical fiber channel, the high PAPR of the OFDM signal can result in distortions caused by nonlinear devices, such as analog to digital (A/D) converter, external modulator and transmission fiber. To reduce the PAPR of the optical OFDM signal, many methods have been proposed for optical OFDM systems[4-7].

The precoded optical OFDM system can benefit from the frequency diversity of the optical channel. The PAPR and bit error rate (BER) are both decreased. So some precoding techniques have been proposed for the application in optical IM/DD OFDM systems[8-10]. For an IM/DD optical OFDM system, the OFDM signal is a real value. The PAPR performance of these precoding techniques for real OFDM signals is different from that of complex-valued OFDM signals in wireless communication systems. The discrete cosine transform (DCT)-precoding technique has been researched in wireless OFDM communications for PAPR reduction of OFDM signals[11,12]. Wang et al[13] researched a grouped DCT-precoding scheme to reduce the PAPR in IM/DD optical OFDM systems by computer simulation method. The signal clipping technique is also an effective PAPR reduction scheme for OFDM signals.

In this paper, we propose an efficient technique based on joint DCT-precoding and clipping techniques for reducing PAPR. The main idea of the proposed scheme is that firstly the transmitted data are transformed by the DCT precoding matrix before being processed with inverse fast Fourier transform (IFFT) operation, which can reduce the PAPR of OFDM signals. Then, the clipping is applied to further reduce the PAPR of the OFDM signal after the IFFT operation. We show the first experimental demonstration of the optical OFDM system based on the proposed PAPR reduction scheme, in which 256 OFDM subcarriers with sampling rate of 2.5×10^9 s^{-1} are successfully processed and recovered after 100 km transmission through standard single mode fiber (SSMF) link. The experimental results can verify the feasibility and effectiveness of the proposed signal processing scheme.

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Let us consider an IM/DD optical OFDM system with N subcarriers. The information bit stream is firstly encoded in quadratic-amplitude modulation or phase-shift keying (PSK) symbols. According to the property of IFFT, the real-valued time signal $x(n)$ corresponds to a Hermitian-symmetric frequency-domain signal $X(k)$, which is expressed as

$$X(k)=X^{*}(N-k),\ 0\le k\le N-1, \tag{1}$$

where * denotes the complex conjugate. The data signal $X(k)$ is modulated by the N-point IFFT. The modulated signal, which is the output of the IFFT, is written as

$$x(n)=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}X(k)\exp\left(\frac{\mathrm{j}2\pi kn}{N}\right). \tag{2}$$

The PAPR is defined as the ratio of the maximum peak power to the average power of the transmitted OFDM signal. The PAPR of the OFDM signal $x(n)$ is defined as

$$PAPR=\frac{\max\limits_{0\le n\le N-1}\left[\left|x(n)\right|^{2}\right]}{E\left\{\left|x(n)\right|^{2}\right\}}, \tag{3}$$

where $E\{\cdot\}$ denotes the expectation operation. The PAPR of OFDM signal is expressed in decibels as

$$PAPR=10\log_{10}PAPR. \tag{4}$$

A better method for characterizing the PAPR is to use the complementary cumulative distribution function (CCDF) of the PAPR (namely, P_{c}), which is expressed as

$$P_{\mathrm{c}}=\Pr\left\{PAPR>\zeta_{\mathrm{p}}\right\}. \tag{5}$$

Namely, P_{c} is the probability that the PAPR exceeds a particular value ζ_{p}.

Amplitude clipping is considered as the simplest technique which can be used for PAPR reduction in an OFDM system. The amplitudes of the time-domain signal samples are limited by the threshold A. When the phase is unchanged, the clipped time sample is expressed as

$$x(n)=\begin{cases}x(n), & \text{if}\left|x(n)\right|\le A\\ A\ , & \text{if}\left|x(n)\right|\ge A\end{cases}. \tag{6}$$

Thus, the magnitude of the clipped signal does not exceed A, and the phase of the signal is preserved. The clipping ratio is defined as

$$CR=\frac{A}{\sqrt{P_{\mathrm{in}}}}, \tag{7}$$

where CR is the clipping ratio, and P_{in} is the average power of the transmitted signal.

DCT is a real transform in which the data are multiplied by a cosine function. The $M\times M$ DCT matrix $\boldsymbol{C}$ is given as

$$C_{ij}=\begin{bmatrix}\dfrac{1}{\sqrt{M}}, & i=0,\quad 0\le j\le M-1\\ \sqrt{(2/M)}\cos\left[\dfrac{(2j+1)i\pi}{2M}\right], & 1\le i\le M-1,\quad 0\le j\le M-1\end{bmatrix}, \tag{8}$$

where i and j represent the row and column entries, respectively. The application of this DCT matrix converts the time-domain signal into the new transform-domain signal.

The main idea of the proposed scheme is to use the combination of two appropriate methods. One is the DCT matrix transform technique, and the other is the clipping technique. On the transmitter end, the baseband modulated data stream is firstly transformed by the DCT matrix. Then, the transformed data are processed by the IFFT unit. A clipping technique is adopted after the IFFT to further reduce the PAPR of the signal. The proposed scheme is applied to an IM/DD optical OFDM system. The block diagram of the optical IM/DD OFDM system is shown in Fig.1.

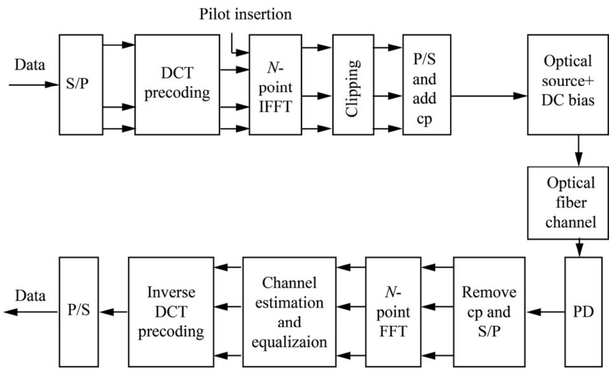


Fig.1 IM/DD optical OFDM system with the proposed scheme

The key signal processing steps of the proposed system are described below. (I) The transmitted data signal $\boldsymbol{X}$ with 256 subcarriers is formed according to the IEEE802.16-2004 standard[14], which is shown in Fig.2. (II) The transmitted data sequence $\boldsymbol{X}$ is transformed by DCT precoding matrix $\boldsymbol{C}$, i.e., $\boldsymbol{Y}=\boldsymbol{CX}$. (III) $\boldsymbol{y}$=IFFT($\boldsymbol{Y}$), where $\boldsymbol{y}=[y(1)\ y(2)\ \cdots\ y(N)]^{\mathrm{T}}$. (IV) A clipping technique is then applied to $\boldsymbol{y}$, i.e., $\boldsymbol{y}_{\mathrm{c}}=clipping\{\boldsymbol{y}\}$. (V) The OFDM signal $\boldsymbol{y}_{\mathrm{c}}$ is modulated by Mach-Zehnder modulator (MZM). (VI) At the receiver end, a fast Fourier transform (FFT) is applied to the received discrete sample signal vector $\hat{\boldsymbol{r}}$, i.e., $\hat{\boldsymbol{Y}}=\mathrm{FFT}(\hat{\boldsymbol{r}})$, where $\hat{\boldsymbol{r}}=\left[\hat{r}(1)\quad \hat{r}(2)\quad \cdots\quad \hat{r}(N)\right]^{\mathrm{T}}$. (VII) Channel estimation and equalization are applied. Then, the pilot symbols are extracted, and the Hermitian-symmetric data are removed. Therefore, a new estimated data sequence $\hat{\boldsymbol{U}}$ is obtained. (VIII) Do inverse DCT transform to obtain the signal $\hat{\boldsymbol{U}}$, i.e., $\hat{\boldsymbol{X}}=\boldsymbol{C}^{\mathrm{T}}\hat{\boldsymbol{U}}$. Then the demodulated signal $\hat{\boldsymbol{X}}$ is demaped to bit stream.

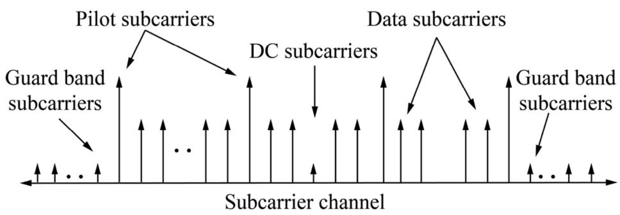
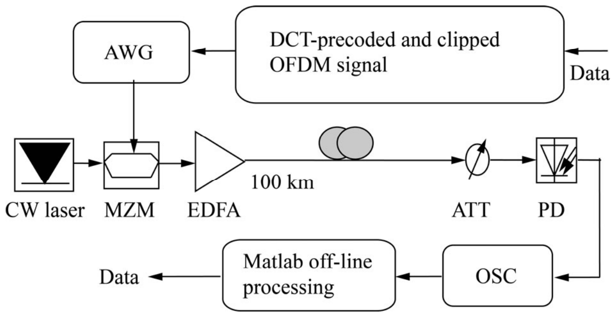


Fig.2 An OFDM symbol frame structure with 256 subcarrier channels

Fig.3 shows the experimental setup of optical OFDM transmission. The test-bed was mainly based on a Tektronix TDS684B oscilloscope, an AQ6317 optical spectrum analyzer, a Sony Tektronix AWG710, an E1748-006 laser and a personal computer. The central wavelength of the continuous wave (CW) generated by a distributed feedback (DFB) laser is 1 565.350 nm.



AWG: arbitrary waveform generator; PD: photodiode; MZM: Mach-Zehnder modulator; EDFA: erbium-doped fiber amplifier; ATT: attenuator; OSC: oscilloscope

Fig.3 Schematic diagram of experimental setup

In the experiment, the OFDM frame based on quadrature phase shift keying (QPSK) in-phase/quadrature (I/Q) modulation scheme has 256 subcarriers, where 192 subcarriers are used for the data symbols, 8 subcarriers are used for the pilot symbols, and 56 subcarriers are used for the guard intervals. The size of the cyclic prefix in every OFDM frame is 32 samples. The frame structure of the OFDM data signals is shown in Fig.2. The digital waveform of the DCT precoding and clipping, which is produced by Matlab program, is then uploaded into the Tektronix AWG operated with sampling rate of 2.5×10^9 s^{-1} to generate a real-time precoded QPSK OFDM signal. An MZM biased at 1.9 V is used to transform the electrical signal to optical signal. The optical OFDM signal is transmitted over an SSMF link with 100 km. The retrieved OFDM signals are sampled by a digital storage oscilloscope. Then the FFT demodulation and BER analysis of the system are realized by an off-line Matlab program.

In the actual IM/DD optical OFDM system, the channel estimation is adopted in the receiver. Therefore, the pilot symbols are inserted into the OFDM symbols frame, and the Hermitian symmetry must be satisfied. Thus the output of the IFFT is real number. Here, the OFDM symbol frame structure shown in Fig.2 is employed. In this case, we evaluate the PAPR of the real-valued QPSK OFDM signal.

In order to reduce the PAPR of OFDM signals, a scheme combining DCT-precoding with clipping is proposed. Fig.4 shows the CCDF performance of the proposed scheme for PAPR reduction. The values of CR for the clipping procedure are fixed at 2, 5 and 10, and the PAPRs of OFDM signal at $CCDF=10^{-3}$ are reduced by 7.5 dB, 4.8 dB and 1.9 dB approximately using the proposed scheme, respectively, compared with that using the DCT-precoding scheme. At $CCDF=10^{-3}$, the DCT-precoding scheme can reduce the PAPR of OFDM signal by 1.3 dB approximately compared with that of the original OFDM signal.

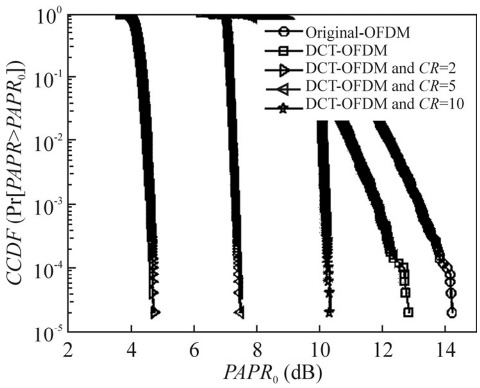


Fig.4 CCDF performance comparison for different PAPR reduction schemes

The BER of the optical OFDM signal with the processing of the DCT-precoding and clipping after 100 km SSMF transmission is measured in an optical OFDM transmission experiment platform. Fig.5 shows the measured BER performance comparison of the OFDM systems with different PAPR reduction techniques. We can see that the receiver sensitivity for the DCT-precoding and clipping scheme with CR=5 at $BER=10^{-3}$ is about 4 dBm better than that of the original OFDM signal and 0.9 dBm better than of the DCT-precoding scheme. From Fig.5, we also clearly see that the DCT-precoding and clipping scheme with CR=2 suffers from a BER floor effect when the receiver optical power is greater than –30 dBm. The BER performance of the DCT-precoding and clipping scheme with CR=2 is the best when the receiver optical power is lower than –32 dBm. The BER performance of the DCT-precoding with CR=5 is better than that of the DCT-precoding scheme with CR=10 when the receiver optical power is lower than –29 dBm.

We observe that the precoding technique takes advantage of the frequency selectivity of the optical channel and improves the BER performance of the proposed system, which is consistent with the previously reported results[16,17].

As clipping is a PAPR reduction technique which is simple in implementation, the introduction of clipping to the DCT-precoding scheme does not increase the complexity of the system. Thus we mainly consider the complexity of the DCT-precoding. In Ref.[18], a fast M-point DCT algorithm was proposed, and the algorithm required $\frac{M}{2}\log_2 M$ multiplications and $\frac{3M}{2}\log_2 M - M + 1$ additions for an M-length sequence. Therefore, the total operations for the proposed DCT-precoding scheme are $M\log_2 M$ multiplications and $2(\frac{3M}{2}\log_2 M - M + 1)$ additions when an M-point DCT in the transmitter and an M-point IDCT in the receiver are used. Thus, the additional computational complexity is required in the proposed DCT-precoding and clipping optical OFDM system.

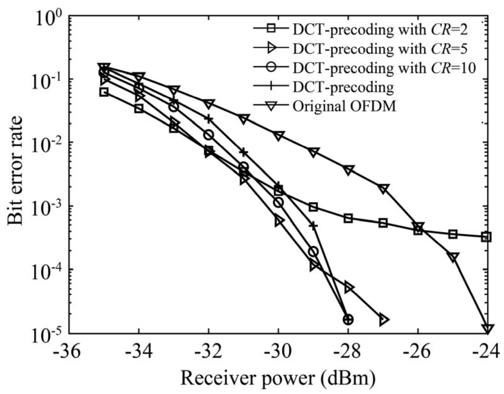


Fig.5 BER performance comparison for different PAPR reduction schemes

The technique combining DCT-precoding with clipping is investigated for IM/DD optical OFDM system. The proposed DCT-precoding and clipping optical OFDM system has low PAPR than the DCT-precoding systems and the conventional systems. The BER of the proposed OFDM system for SSMF channels is evaluated by the experiment platform. The experimental results show that the BER performance of the joint DCT-precoding and clipping optical OFDM system (at CR=5 and 10) is greatly improved compared with the conventional optical OFDM systems.

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