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DFT-spread combined with clipping method to reduce the *PAPR* in VLC-OFDM system

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Orthogonal frequency division multiplexing (OFDM) is an attractive technique to realize high data rate in light emitting diodes (LEDs)-based visible light communication (VLC). However, high peak-to-average power ratio (*PAPR*) of OFDM makes VLC-OFDM very sensitive to the nonlinearity of LEDs. In this paper, the discrete Fourier transform-spread (DFT-spread) combined with clipping method is proposed to reduce the *PAPR* of OFDM signal in VLC system. Combining simulation with experiment, a performance comparison is made among conventional OFDM, DFT-spread-OFDM, and clipped DFT-spread-OFDM with different clipping ratios (*CRs*) in a single LED-based VLC system. The experimental results show that the proposed clipped DFT-spread-OFDM method can effectively improve the system performance compared with the other two methods. At the optimum signal peak-to-peak (*PTP*) value, by using the clipped DFT-spread-OFDM scheme with *CR* at 8 dB, the bit error rate (*BER*) of the system can be reduced from 0.003 7 to 0.000 287.

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With the scarcity of wireless spectral resource, visible light communication (VLC) has attracted lots of attention due to the unlimited band licensing[1]. VLC can realize illumination and communication simultaneously, and it has more security, confidentiality and environmental friendliness than the conventional radio frequency (RF) communication[2,3]. To realize a high-speed transmission, orthogonal frequency division multiplexing (OFDM) technique has been used for VLC in many recent works[4-6]. However, the OFDM in VLC inherits the deficiency of high peak to average power ratio (*PAPR*) from the OFDM in RF communications and is sensitive to the nonlinearity of LEDs[7,8].

At present, to reduce OFDM system *PAPR*, there are two categories of methods including linear and nonlinear ones[9]. For example, selective mapping (SLM)[10], partial transmit sequence (PTS)[11], and discrete Fourier transform precoding (DFT-spread)[12] can be included in linear methods. Other well-known methods, such as clipping and companding technique, can be included in the nonlinear methods. Recently, some methods combining the linear with the nonlinear ones together have been proposed. And they show better performance compared with the one only using one-class method. In Ref.[9], the method combining PTS with clipping has been proposed. In Ref.[13], the method combining SLM with clipping has been proposed. However, the SLM method and PTS method are of relatively high complexity. In comparison, the DFT-spread one is a more simple and effective technique to reduce OFDM *PAPR*[14]. Therefore, the DFT-spread OFDM has already been selected as the uplink modulation scheme for the long-term evolution (LTE)[15].

In this paper, a new method combining DFT-spread with clipping, which is named clipped DFT-spread method, is investigated in a single LED-based VLC-OFDM system. To analyze the performance of the new method, we make a comparison among different schemes. Through simulation and experiment, it can be concluded that the *PAPR* performance and bit error rate (*BER*) performance of the clipped DFT-spread-OFDM are both the best. It verifies that the proposed method can effectively improve the system performance compared with the conventional OFDM and DFT-spread-OFDM methods.

The corresponding experimental setup and scene are illustrated in Fig.1. At the transmitter (Tx), an arbitrary-waveform generator (AWG) generates the signal and the signal is amplified by an amplifier (Mini Circuits ZX60-43-S+) to increase the LED modulation depth. Then the amplified signal passes through a bias-Tee (Picosecond 5575A) to superimpose onto the LED bias current to drive the LED module directly. The light source is a commercial low-cost red LED module. At the receiver (Rx), a commercial silicon PIN-type photoelectric detector (PD) (HAMAMATSU, S5971, 1.2 mm diameter, 100 MHz bandwidth) combined with a glass lens is used to receive the light signal and then the light signal

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is transformed into electrical signal. An amplifier (Mini Circuits ZFL-1000GH) is used to boost the electrical signal level up to the operation range of the digital storage oscilloscope (DSO). Finally, the output amplitude is either directly monitored with the oscilloscope or stored for off-line demodulation. In addition, a low-pass filter (LPF) is added into the receiver to remove the noise of high frequency coming from the amplifier.

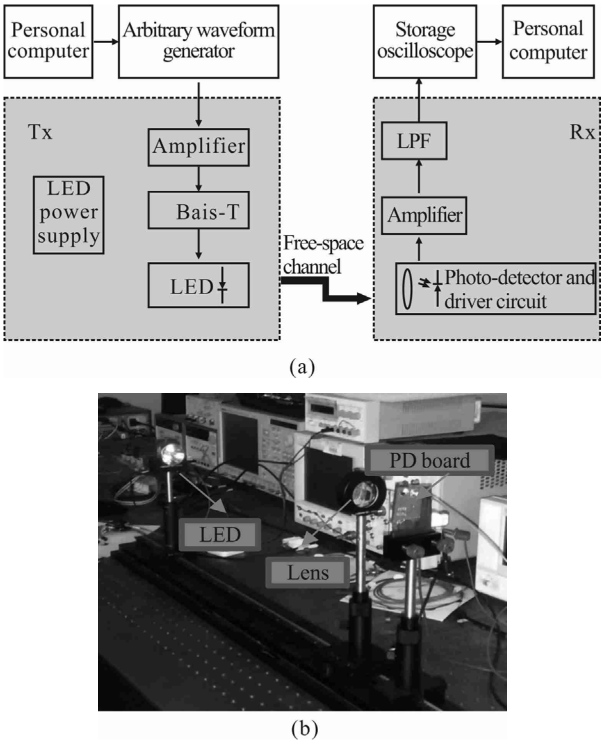


Fig.1 (a) Experimental setup and (b) experimental scene

The amplitude of the normalized electro-optical-electrical (EOE) channel frequency response is shown in Fig.2, which is measured by varying the frequency of a small-signal sine wave provided by the AWG, and an off-line processing is conducted after being stored by the oscilloscope.

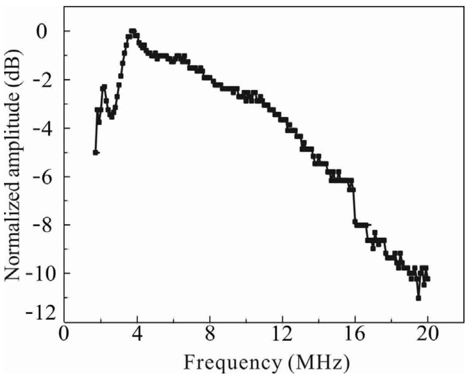


Fig.2 EOE channel response of the data-transmission link in Fig.1

Different from conventional OFDM, in the clipped DFT-spread-OFDM, a DFT-spread operation is added before IFFT in the OFDM transmitter and a clipping operation is added after the IFFT. The principle of clipping can be found in Ref.[8] and the principle of DFT-spread can be found in Ref.[12].

The principle diagram of the proposed clipped DFT-spread-OFDM scheme can be seen in Fig.3. In the transmitter off-line processing (TX DSP), a pseudo-random binary sequence (PRBS) is firstly generated and fed into the following mapper to realize quadrature phase shift keying (QPSK) modulation. Meanwhile, the generated binary data is stored for the *BER* analysis. Then, an FFT module is used to realize the DFT-precoding of the QPSK symbols. After that, because the imaginary signal can't be transmitted in the single LED-based VLC system, the DFT-precoded data should be reconstructed to satisfy Hermitian symmetry for generating direct detection OFDM signal. Subsequently, the DFT-spread-OFDM signal can be generated after IFFT operation. In general, compared with conventional OFDM, the *PAPR* performance of the DFT-spread-OFDM has been improved. To further improve the *PAPR* performance, clipping operation will be adopted after IFFT. At last, the clipped DFT-spread-OFDM signal can be achieved. In addition, at the end of the transmitter off-line processing, similar to the conventional OFDM, the cyclic prefix (CP) addition is adopted before the signal transmission. In our experiment, an extra training sequence (TS) is added to be header of the clipped DFT-spread-OFDM signal for realizing timing synchronization, channel estimation and equalization in the receiver off-line processing. Hence, corresponding to the transmitter off-line processing, the receiver off-line processing can be divided into seven stages as shown in Fig.3.

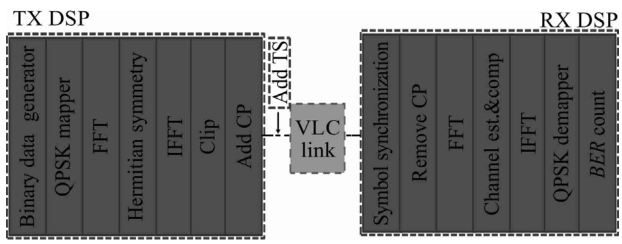
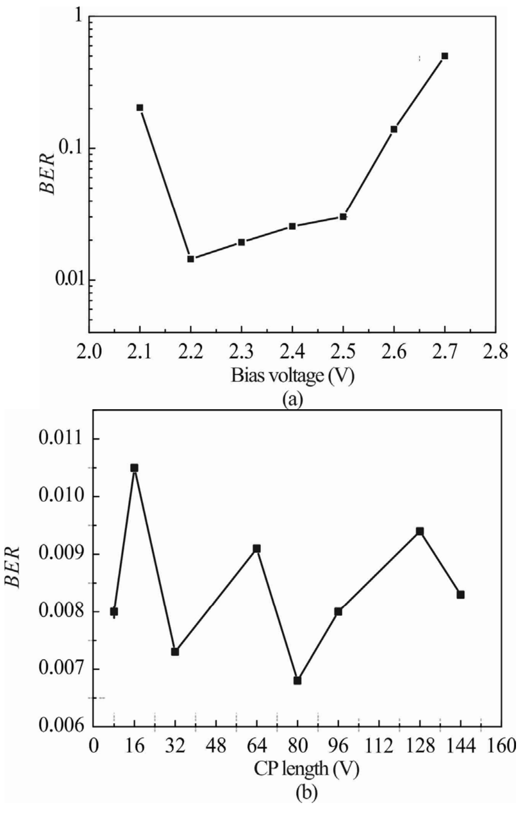


Fig.3 Off-line DSP for clipped DFT-spread-OFDM transceiver

In this paper, the sampling rate of AWG is set at 40 M/s and that of DSO is set at 125 M/s to realize about three times of oversampling. In addition, it should be mentioned that the IFFT length in the transmitter is optimized in our experiment. But no matter how the IFFT length changes, the utilized frequency band of the data-carrying sub-carriers is about 119 MHz. It means that when the IFFT length is N points, the index of the valid data-carrying sub-carriers is from $(N/2)\times 1/20$ to $(N/2)\times 19/20$. Due to the Hermitian symmetry construction, the data from 540 to 1 000 subcarriers is the conjugate symmetry of the data from 26 to 486 subcarriers, and the other subcarriers are null. The raw bit rate of the generated OFDM signal is about 35.9 Mbit/s. On the whole, because the mapping format is QPSK and the utilized frequency bandwidth is always 18 MHz (1—19 MHz), no matter how the IFFT length changes, the raw bit rate of the generated OFDM signal is always about 36 Mbit/s.

In the parameters optimization, only the DFT-spread-OFDM scheme is applied. The peak-to-peak (*PTP*) voltage of the electrical signal from AWG is set at 0.5 V, and the experimental parameters, including bias voltage, the length of CP and the length of IFFT at the transmitter (corresponding to the FFT length at the receiver), are optimized successively. Before the IFFT length at the transmitter is optimized, the length is chosen at 512 points. In addition, the intra-symbol frequency-domain averaging (ISFA) channel estimation[16] is applied in the experiment, and the average length for ISFA is also optimized. From Fig.4(a) and Fig.4(d), it can be seen that the optimal bias voltage is about 2.2 V and the optimal average length for ISFA operation is about 9 points. Then in Fig.4(b), the irregular curve illustrates that the multipath effect of the single LED-based system is not prominent. The CP length has little effect on the *BER*. In Fig.4(c), it shows that the *BER* is reduced with the increase of the IFFT length. The reason is that the large-size IFFT can be used to improve the robustness of ISI produced by the limited modulation bandwidth in the OFDM system[17,18]. Hence, according to the experimental results, in the following experiment, the bias voltage is set at 2.2 V, the average length for ISFA operation is set as 9 points, and the CP length is chosen as 8 points. Meanwhile, considering the calculation complexity and the running efficiency of the off-line processing, the transmitter IFFT length is chosen as 1 024 points.



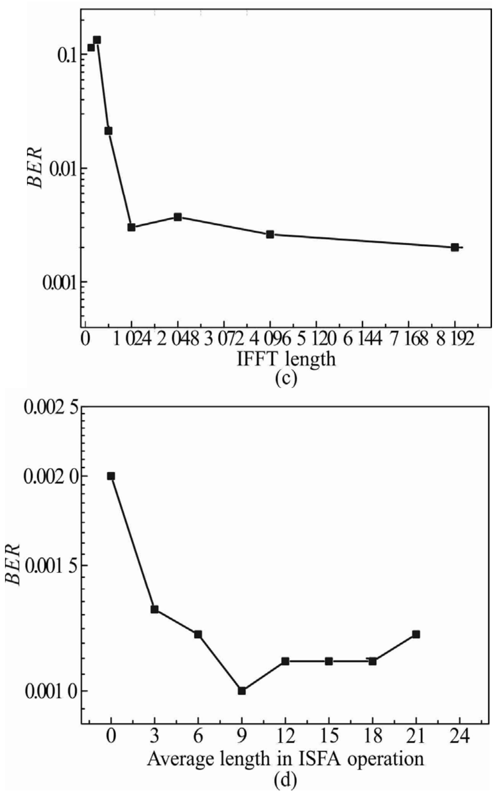


Fig.4 *BER* versus (a) bias voltage, (b) CP length, (c) IFFT length and (d) average length in ISFA operation

In Fig.5, the complementary cumulative distribution function (CCDF) curves of the conventional OFDM, DFT-spread-OFDM and clipped DFT-spread-OFDM systems with different clip ratios (*CRs*) are obtained by simulations, respectively. It can be seen that at the complementary cumulative distribution functional value of 0.001, the DFT-spread-OFDM scheme can achieve 4 dB of *PAPR* reduction compared with the conventional OFDM scheme. Meanwhile, compared with the DFT-spread-OFDM scheme, the clipped DFT-spread-OFDM with *CR* at 9 dB, 8 dB, and 7 dB can further achieve 1 dB, 2 dB, and 3 dB of *PAPR* reduction, respectively. In addition, according to the overall trend of the CCDF curves, it shows that the *PAPR* performance of the DFT-spread-OFDM scheme has been improved significantly compared with the conventional OFDM scheme. Moreover, the *PAPR* performance of the clipped DFT-spread-OFDM scheme becomes more robust than that of the DFT-spread-OFDM scheme.

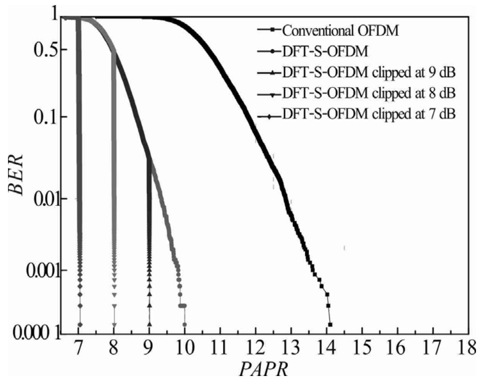


Fig.5 CCDF curves of different system schemes

In the experiment, *BER* performance comparison is made among different systems. As we can see in Fig.6, the *BER* curves are achieved by varying the *PTP* voltage of the output electrical signal from AWG. Each *BER* curve has an optimum *PTP* value. In addition, the optimum *PTP* values of the conventional OFDM and the clipped DFT-spread-OFDM systems are different. It is because of the great *PAPR* difference between conventional OFDM and clipped DFT-spread-OFDM systems. More importantly, in Fig.6, it can be seen that only the clipped DFT-spread-OFDM system can achieve the *BER* below 0.001. In addition, in the clipped DFT-spread-OFDM scheme, at the optimum *PTP* value, the scheme with *CR* of 8 dB can achieve the lowest *BER* of 0.000 287. The reason is that by using the clipping method, it can improve the system *PAPR* performance so as to improve the *BER* performance. However, using the clipping method also can bring the clipping noise into the system and then affect the *BER* performance. When the *CR* is more than a special value, the clipping noise will cause the deterioration of the *BER* performance. In this way, there is an optimum *CR*. According to the experimental results, the optimum *CR* is about 8 dB. The experimental results demonstrate that the proposed clipped DFT-spread-OFDM scheme can improve the system performance compared with the conventional OFDM and DFT-spread-OFDM schemes.

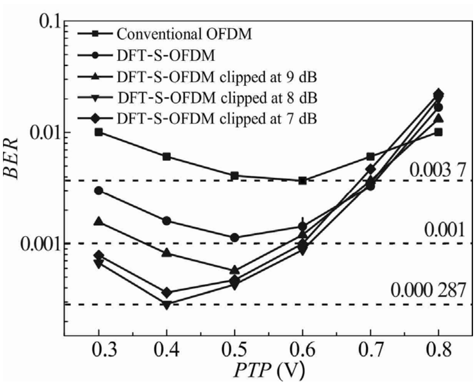


Fig.6 *BER* curves of different system schemes

In this paper, a DFT-spread combined with clipping method is proposed to reduce the OFDM signal *PAPR* in VLC system. In simulations, it is found that compared with the DFT-spread-OFDM and conventional OFDM schemes, the clipped DFT-spread-OFDM scheme can achieve the best *PAPR* performance. In the experiment, it is also demonstrated that the clipped DFT-spread-OFDM scheme with the appropriate *CR* can be used to improve the *BER* performance compared with the DFT-spread-OFDM and conventional OFDM schemes.

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