Ultra-high-speed single red–green–blue light-emitting diode-based visible light communication system utilizing advanced modulation formats

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We report a 3.75-Gb/s visible light communication (VLC) system thatusessingle-carrier frequency-domain equalization (SC-FDE) based on a single red–green–blue (RGB) light-emitting diode (LED), with the measured bit error rates (BERs) under a pre-forward-error-correction threshold of 3.8×10^{-3}. The fundamental characteristics of an RGB-LED-based VLC system are measured. We also compare SC-FDE with OFDM in terms of peak-to-average power ratio and BER performance, which shows that SC-FDE outperforms the OFDM modulation scheme.

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Visible light communication (VLC) systems based on white light-emitting diodes (LEDs) are recently garnering increasing attention as LEDs and are considered to be a major candidate for future illumination. Two types of white LED devices are used for lighting, i.e., devices that use separate red–green–blue (RGB) emitters and devices that use a blue emitter in combination with a phosphor that emits yellow light. The former type enables easy color rendering by adjusting each color individually, which is very promising for high-speed transmission because of wide bandwidth. The latter type is cost-efficient mainly for its simple technological design, but the bandwidth is limited to several MHz because of the slow relaxation time of the phosphor. The feasibility of uni-directional and bi-directional VLC systems based on both kinds of white LEDs has been widely investigated[1−18]. A data rate of 3.4 Gb/s at a distance of 10 cm has been achieved over an RGB–white LED by discrete multi-tone modulation and avalanche photodiode (APD)[4]. The overall transmission data rate of 875-Mb/s bi-directional transmission has been reported by wavelength division multiplexing (WDM)[5]. Advanced modulation formats are currently widely used in fiber optical communication systems to increase transmission reach and the total system capacity[6−8]. In VLC systems, such formats can play a similar role for high-speed transmission[9−12]. The OFDM signal can be easily equalized in frequency domain, but it suffers from high peak-to-average power ratio (PAPR), frequency offset, and phase-noise sensitivities[11]. The carrier-less amplitude and phase (CAP) modulation format proposed in Ref. [9] can reduce the PAPR; however, the complexity of its time-domain equalization (TDE), such as multi-modulus phase recovery, could be a critical technique limitation.

In this letter, we propose and experimentally demonstrate a novel VLC scheme by using single-carrier frequency-domain equalization (SC-FDE). This scheme has the similar spectral efficiency performance to the aforementioned two methods, i.e., OFDM and CAP[13], but with a reduced calculation complexity compared with the TDE-based CAP. Moreover, SC-FDE can outperform OFDM in terms of PAPR, frequency offset, and phase-noise sensitivities. Quadrature amplitude modulation (QAM) and WDM are also used to increase data rate. The performances of SC-FDE and OFDM are also compared. The aggregate data rates of SC-FDE and OFDM signals at the same experimental condition are 3.75 Gb/s and 2.5 Gb/s, respectively, which show the priority of SC-FDE. The measured bit error rates (BERs) after 1-cm free-space transmission for all wavelength channels are under pre-forward-error-correction (pre-FEC) limit of 3.8×10^{-3}. The results demonstrate that SC-FDE can be a promising candidate for future optical wireless network.

The block diagram of the SC-FDE/OFDMVLC system is presented in Fig. 1. A commercially available RGB-LED (Cree, PLCC) that generates a luminous flux of about 6 lm is used as the transmitter (TX), and an APD (Hamamatsu APD, 0.42-A/W sensitivity at 620 nm and gain=1) is used as the receiver (RX). The wavelength spectra of RGB-LED are shown in Fig. 2, whose center wavelengths are as follows: red, 620 nm; green, 520 nm; blue, 470 nm. The overlap of different wavelengths is limited, resulting in a small crosstalk in this WDM system.

For SC-FDE signals, the binary data would be first mapped into M-ary QAM (M-QAM) format, and then the training sequences (TS) are inserted into the signals. After pre-equalization in the frequency domain and upsampling, circle prefix (CP) is added, and low-pass filters are used to remove the out-of-band radiation. Subsequently, the signals are amplified usingan electrical amplifier (Minicircuits, 25-dB gain), combined with direct current-bias via a bias tee, and applied to the three different color chips. Passing through free-space transmission, lens(50-mm diameter), and optical RGB filter,the signals

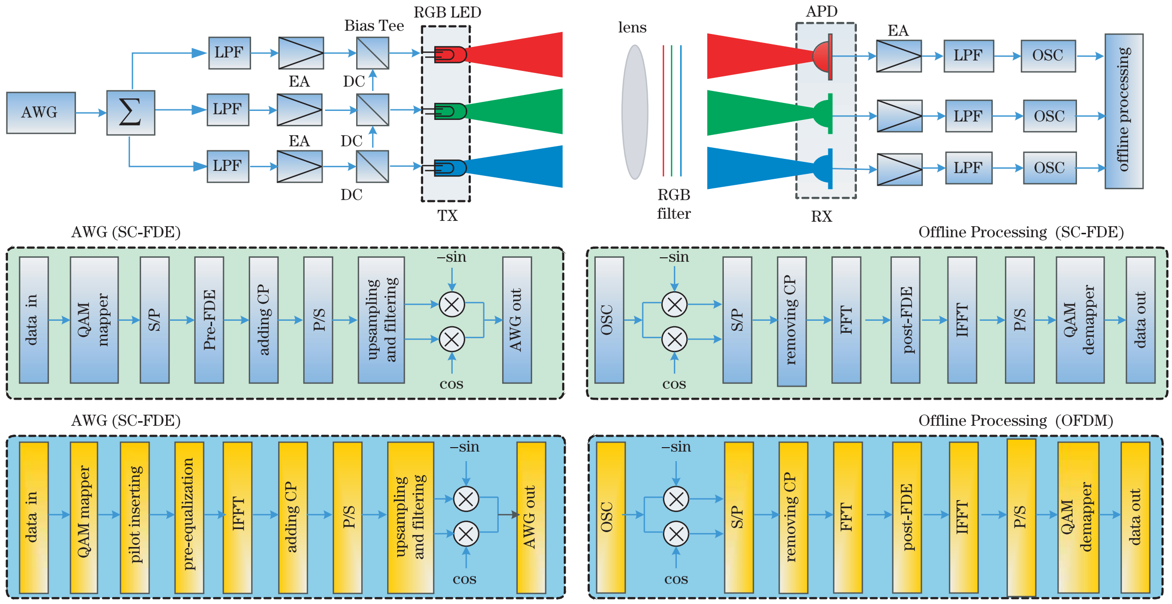

Fig. 1. Block diagrams of the proposed SC/OFDMVLC system (AWG: arbitrary waveform generator, EA: electrical amplifier, LPF: low-pass filter, OSC: real-time oscilloscope, DC: direct current).

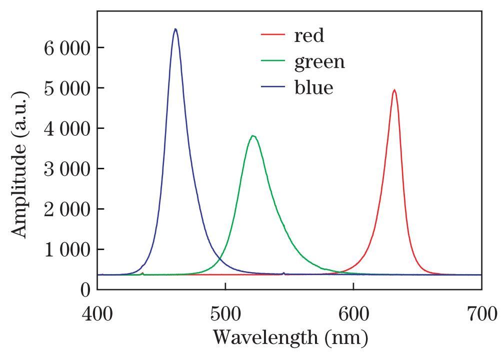

Fig. 2. Wavelength spectra of RGB-LED chip.

are recorded by a commercial high-speed digital oscilloscope (OSC) and sent for demodulation. The demodulation is performed with off-line Matlab® DSP programs.

For OFDM demodulation, after down-converted to baseband and removing CP, the time-domain OFDM signals are transformed into frequency-domain signals by discrete Fourier transform (DFT) with a fast Fourier transform (FFT) size of 128 to implement frequency-domain equalization. For SC-FDE demodulation, the SC-FDE signals are first down-converted to baseband and filtered by a square filter. Secondly, the demodulation process of OFDM is resembled, and the frequency-domain equalization is implemented after removing CP and executing DFT with an FFT size of 128. The frequency-domain SC-FDE signals are transformed into time-domain signals again by inverse DFT. The OFDM and SC-FDE schemes have many similarities in block diagram, as shown in Fig. 1. For instance, both OFDM and SC-FDE schemes require CP to overcome inter-symbol interference issue and DFT for frequency-domain equalization. The only one dissimilarity between the OFDM and SC-FDE schemes is that the inverse fast Fourier transform (IFFT) block is moved from the TX to the RX, as shown in Fig. 1.

In this experiment, SC-FDE/OFDM signals are generated by an arbitrary waveform generator (AWG). Upsampling by a factor 16 is used, and the sample rate of AWG is 2.5 GS/s. At the RX, the electrical signals are recorded by a digital real-time OSC with 5-GS/s sampling rate. The parameters of the OFDM signal include IFFT with a size of 128, a TS of 4%, and M-QAM format. These parameters are similar to those of the SC-FDE signal.In addition, the SC-FDE signal is shaped by a square filter with a bandwidth of 156.25 MHz, which is consistent with that of OFDM.

Aside from the limited modulation bandwidth of LED, another drawback of LED is its small modulation index caused by its significant nonlinearity[14]. The current–voltage characteristic is shown in Fig. 3. In this figure, C point represents the bias point, and the current at this point can be noted as I_C. A and B points represent the highest current and the lowest current during the quasi-linear working area, respectively. Thus, the modulation index m can be expressed as

$$m = \frac{\delta}{I_C}. \tag{1}$$

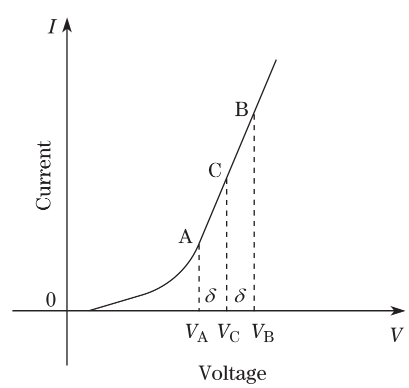

Fig. 3. Current–voltage characteristic of LED.

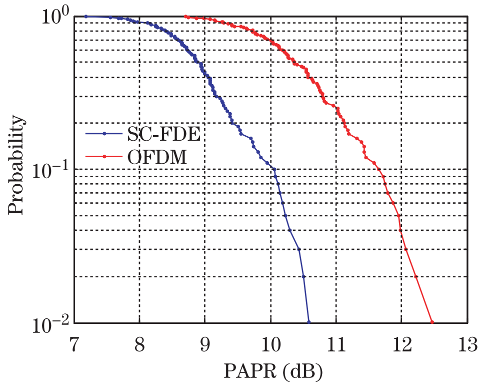

Fig. 4. PAPR performance comparison of SC-FDE and OFDM.

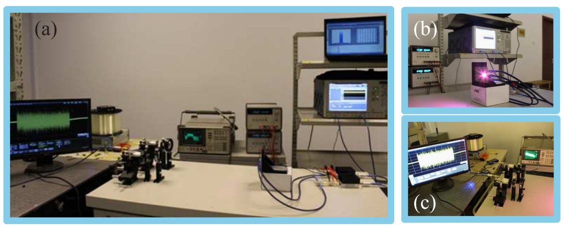

Fig. 5. Experimental setup for (a) the proposed VLC system, (b) TX, and (c) RX.

As the modulation index of LED is small, the dynamic range of the transmitted signals can also be limited. Therefore, the high PAPR of the signal can severely affect the performance in our experiment. Figure 4 shows the complementary cumulative distribution function curves of the PAPR of the OFDM and SC-FDE signals. The FFT sizes of these two schemes are both 128. The PAPR of the OFDM is approximately 2 dB better than that of the SC-FDE signals. Hence, SC-FDE is more suitable for LED-based VLC system at this point.

The experimental setup for the proposed SC-FDE/OFDMVLC system based on RGB-LED is shown in Fig. 5. In this experiment, Tektronix AWG7122C is used to generate SC/OFDM signals. Data are recorded by a commercial high-speed digital OSC (Lecroy) with a maximum sampling rate of 20 GSa/s. The signal peak-to-peak voltages are 0.5 Vpp.

The frequency responses of the three individual LED chips are shown in Fig. 6. The 10-dB bandwidth is approximately 25 MHz. Another comparison of OFDM and SC-FDE is conducted in the same experimental condition. All parameters are the same, including the peak-to-peak voltages, amplifier factors, the bandwidths of low pass-filter, and the bias voltages of the three LED chips. The transmission distance is approximately 1 cm, and no pre-equalization is adopted in both schemes. The power and bit loading method is also not implemented in this experiment. The measured spectra of red-LED chip thatuse SC-FDE and OFDM are depicted in Fig. 7, which illustrates that the power of high frequency is small.

We then measure BER performance with different modulation formats. The modulation orders range from 6 to 9 for SC-FDE and from 5 to 9 for OFDM. The experimental results are shown in Figs. 8(a)–(c). The maximum modulation orders of SC-FDE in red, green,

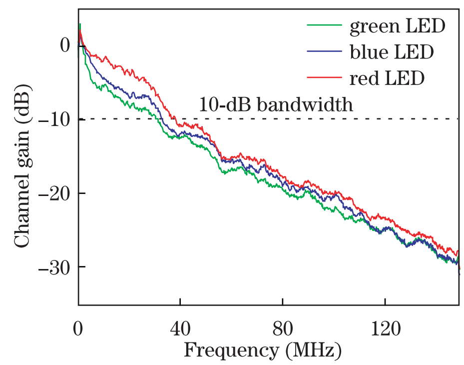

Fig. 6. (Color online) Measured frequency response of the three individual LED chips.

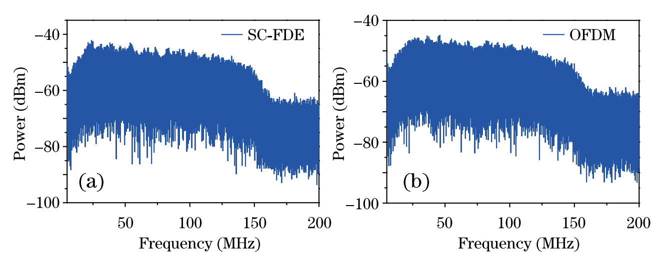

Fig. 7. Measured electrical spectra of red color using (a) SC-FDE and (b) OFDM.

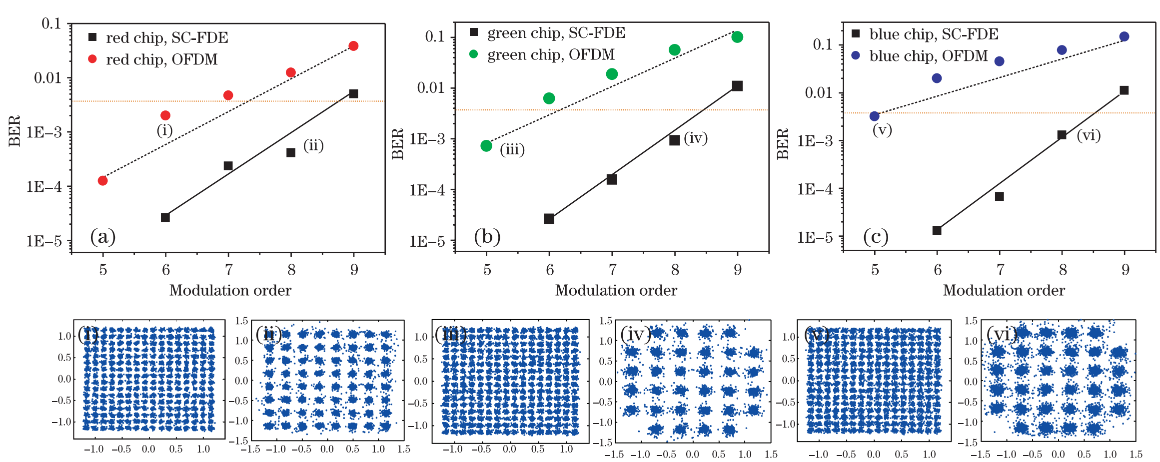

Fig. 8. Measured BER performance versus different modulation orders of SC-FDE and OFDM; (a) red-LED chip, (b) green-LED chip, and (c) blue-LED chip.

and blue chips are 8 (256 QAM), while those of OFDM in red, green, and blue chips are 5 (32 QAM), 5 (32 QAM), and 6 (64 QAM), respectively. Therefore, the achieved data rates of SC-FDE and OFDM are 3.75 Gb/s and 2.5 Gb/s, respectively, with BERs for all wavelength channels under a pre-FEC threshold of 3.8×10^{-3}. The constellations in the individual LED chips of different modulation schemes are also inserted in Fig. 8, which reveal that the SC-FDE outperforms OFDM. The bandwidth of LEDsis approximately 10 MHz, and the 3-dB bandwidth of APD is 100 MHz, which are both smaller than the baud rate of 156.25 MB. The data rate will be further enhanced by exploiting a larger bandwidth APD at the RX.

In conclusion, we report an ultra-high-speed VLC system based on SC-FDE that uses a single commercially available RGB-LED. The performances of SC-FDE and OFDM are compared. Post-equalization, WDM, and high-order modulation format are implemented to mitigate the limited bandwidth of LED both for OFDM and SC-FDE schemes. The aggregate data rates of SC-FDE and OFDM signals are 3.75 Gb/s and 2.5 Gb/s, respectively. Hence, the SC-FDE scheme outperforms the OFDM scheme. BERs of all wavelength channels are under a pre-FEC limit of 3.8×10^{-3}. The capacity of this system can be further improved by a larger bandwidth APD.

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