

Experimental Demonstration of Optical OFDM with Subcarrier Index Modulation for IM/DD VLC

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Abstract: We for the first time experimentally demonstrate an IM/DD VLC system using optical OFDM with subcarrier index modulation (OFDM-SIM) and digital pre-equalization. Experimental results show that OFDM-SIM achieves greatly improved BER performance than classical OFDM.

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1. Introduction

Visible light communication (VLC) using commercial off-the-shelf white light-emitting diodes (LEDs) has attracted tremendous interest in recent years, due to its advantages such as simultaneous lighting and communication, abundant unregulated spectrum, inherent physical-layer security and no electromagnetic interference emission [1]. However, commercial off-the-shelf white LEDs usually have a very small 3-dB modulation bandwidth, which is typically about a few MHz [2]. Therefore, the actually achievable rate of VLC systems utilizing white LEDs is greatly limited by the small bandwidth, although the spectrum resource can be considered as unlimited. In order to substantially improve the achievable rate of VLC systems, two categories of approaches are generally adopted: one is to extend the effective modulation bandwidth via blue filtering or digital/analog equalization [3,4] and the other is to increase the transmitted bits per unit bandwidth via spectral efficient modulation such as orthogonal frequency division multiplexing (OFDM) using high-order constellations [5] or spectral efficient multiple access such as non-orthogonal multiple access [6].

Recently, OFDM with subcarrier index modulation (OFDM-SIM) has been proposed and widely investigated for next generation broadband wireless communication systems. In OFDM-SIM, information is carried not only by the M -ary constellations as in classical OFDM, but also by the indices of the subcarriers which are activated according to the incoming bit stream [7]. Due to the enhanced performance of OFDM-SIM over classical OFDM, OFDM-SIM has also been applied in VLC systems [8,9]. Nevertheless, only simulation results have been reported and no experimental verification considering a practical IM/DD bandlimited VLC system has ever been conducted. In this paper, we experimentally demonstrate the transmission of optical OFDM-SIM in an IM/DD bandlimited VLC system, where digital pre-equalization (DPE) is performed to achieve a relatively flat system frequency response. It is shown by the experimental results that OFDM-SIM can achieve superior BER performance than classical OFDM. To the best of our knowledge, it is the first experimental demonstration of an optical OFDM-SIM enhanced IM/DD bandlimited VLC system.

2. Principle of IM/DD VLC using optical OFDM-SIM

Fig. 1 shows the principle of an IM/DD VLC system using optical OFDM-SIM. For the transmission of one OFDM-SIM block, the input bits are first split into G groups corresponding to G subblocks through a bit splitter, where each subblock consists of N subcarriers and only K out of these N subcarriers are activated to carry data. In each subblock, two streams of bits are encoded: one stream of bits are used for index selection and the other stream of bits are used to generate M -ary constellations such as M -ary phase shift keying (M -PSK) and M -ary quadrature amplitude modulation (M -QAM). As a result, the total number of bits that can be transmitted by one subblock is calculated by

$$b_{\text{subblock}} = \lfloor \log_2(C(N, K)) \rfloor + K \log_2(M), \quad (1)$$

where $\lfloor \cdot \rfloor$ represents the floor function and $C(N, K)$ denotes the binomial coefficient [7]. Clearly, classical OFDM can be considered as an extreme case of OFDM-SIM with $K = N$. Subsequently, the obtained G subblocks are combined together to generate the OFDM-SIM block. In order to obtain a flat frequency response, DPE is further executed. After performing inverse fast Fourier transform (IFFT) with Hermitian symmetry (HS), digital-to-analog conversion (DAC) and direct-current (DC) bias addition, the resultant signal is used to drive the LED for simultaneous illumination and communication. At the receiver side, the light is captured by a photo-detector (PD) and the transmitted OFDM-SIM block can be recovered after performing analog-to-digital conversion (ADC), fast Fourier transform (FFT) and

frequency-domain equalization (FDE). For the OFDM-SIM block detection, the block is first divided into G subblocks via a block splitter and then each subblock is individually detected. In order to achieve optimal performance, we adopt the maximum likelihood (ML) detector in this experimental demonstration and the details about ML detection can be found in [7]. After subblock detection, the obtained bits of each subblock are combined through a bit combiner so as to generate the output bits.

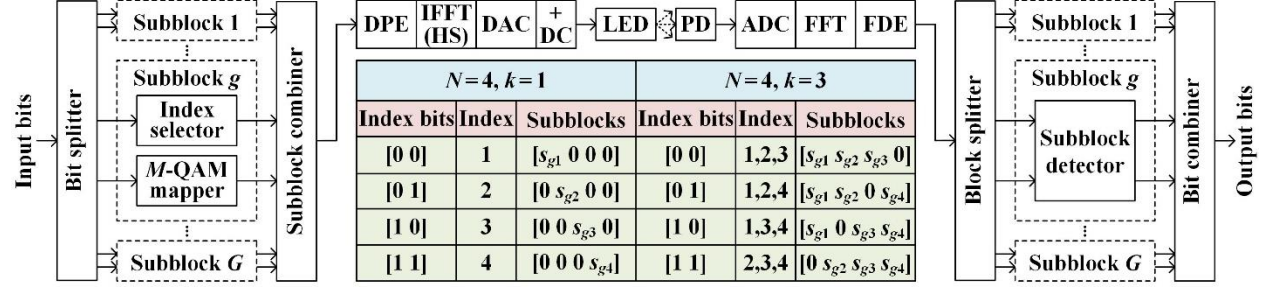


Fig. 1. Principle of IM/DD VLC using optical OFDM-SIM.

In this work, we set the length of the subblock as $N=4$ and the number of activated subcarriers in each subblock as $K=1, 3$. The mapping tables for $N=4, K=1$ and $N=4, K=3$ are shown in Fig. 1, where s_{gi} denotes the transmitted M -ary constellations for the i -th subcarrier in the g -th subblock. For $N=4$ and $K=1$, we have $b_{subblock} = 2 + \log_2(M)$. To achieve $b_{subblock} = 4$ bits for both OFDM-SIM and classical OFDM, we adopt 4-QAM and BPSK for OFDM-SIM and classical OFDM, respectively. For $N=4$ and $K=3$, we have $b_{subblock} = 2 + 3\log_2(M)$ and $b_{subblock} = 8$ bits can be achieved when both OFDM-SIM and classical OFDM adopt 4-QAM.

3. Experimental setup and results

Fig. 2 illustrates the experimental setup of the IM/DD VLC system. The transmitted OFDM-SIM signal is generated offline by MATLAB and uploaded to an arbitrary waveform generator (AWG, Tabor WW2074) with a sampling rate of 100 MSa/s. The output signal is then combined with a 250-mA DC bias current to obtain a unipolar signal and the resultant signal is subsequently used to drive a white LED (Luxeon SR-12 Rebel Star/O). After 100-cm free-space transmission, the light passes through a blue filter (BF) which is further captured by an avalanche photodiode (APD, Hamamatsu S8664-50K). The detected electrical signal is recorded by a mixed domain oscilloscope (MDO, Tektronix MDO3104) with a sampling rate of 1 GSa/s and further processed offline by MATLAB. For performance comparison, we also transmit the classical OFDM signal through the same system.

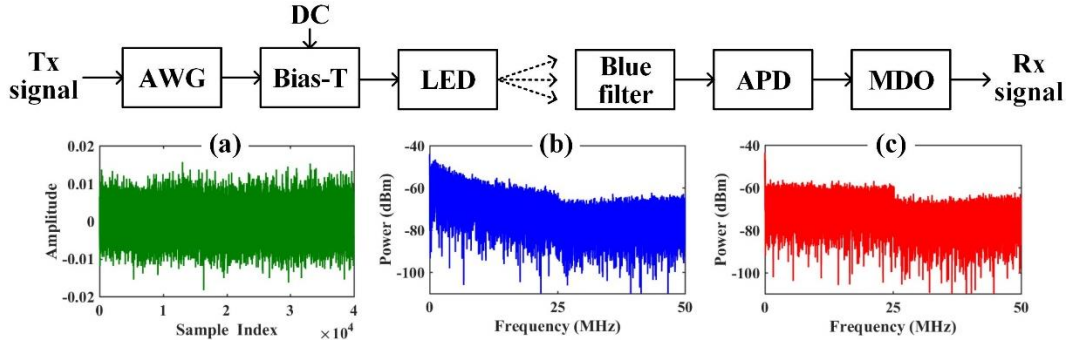


Fig. 2. Experimental setup. Insets: (a) waveform, (b) spectrum without DPE and (c) spectrum with DPE.

The IFFT/FFT size of both OFDM-SIM and classical OFDM is 256 and totally 64 (2^{nd} to 65^{th}) are utilized to carry valid data. Thus, the bandwidth of the OFDM-SIM/classical OFDM signal is 25 MHz. As a result, the achievable bit rate for both OFDM-SIM with $N=4$ and $K=1$ using 4-QAM and classical OFDM using BPSK is 25 Mbit/s. For both OFDM-SIM with $N=4$ and $K=3$ using 4-QAM and classical OFDM using 4-QAM, the achievable bit rate becomes 50 Mbit/s. For BER measurement, a total of 200 OFDM-SIM/classical OFDM symbols are transmitted through the IM/DD VLC system. The inset (a) in Fig. 2 depicts the waveform of the received OFDM-SIM signal. The insets (b) and (c) illustrates the received electrical spectra without and with DPE, respectively. As we can see, the high frequency components suffer from a large power attenuation when DPE is not performed and the electrical spectrum is greatly flattened after applying DPE. The procedures to perform DPE can be found in [4].

Figs. 3(a) and (b) show the measured BER of OFDM-SIM/classical OFDM versus the input peak-to-peak voltage (PPV) of AWG for the bit rates of 25 and 50 Mbit/s, respectively. As can be seen from Fig. 3(a), for both OFDM-SIM with $N=4$ and $K=1$ using 4-QAM and classical OFDM using BPSK, the BER performance can be greatly improved by performing DPE. Furthermore, OFDM-SIM significantly outperforms classical OFDM for the bit rate of 25 Mbit/s without and with DPE. Specifically, for classical OFDM, a PPV of 0.83 V is required to achieve a BER of 10^{-3} after performing DPE. In contrast, for OFDM-SIM, the required PPV to achieve BER = 10^{-3} is about 0.67 V, which indicates a 19.3% reduction of AWG input PPV in comparison to classical OFDM. Therefore, the OFDM-SIM technique has a much higher power efficiency than classical OFDM to achieve the same bit rate of 25 Mbit/s. The insets in Fig. 3(a) depict the corresponding received constellation diagrams.

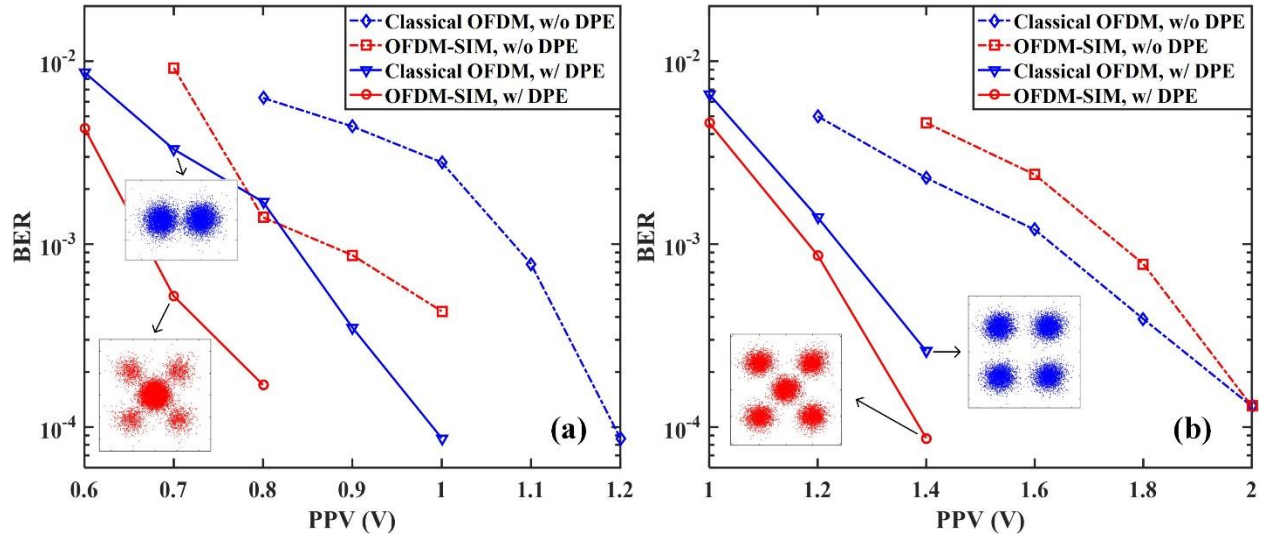


Fig. 3. Measured BER vs. the input PPV of AWG for (a) 25 Mbit/s and (b) 50 Mbit/s.

Fig. 3(b) compares the BER performance of OFDM-SIM with $N=4$ and $K=3$ using 4-QAM and classical OFDM using 4-QAM for the bit rate of 50 Mbit/s without and with DPE. Similarly, the BER performance of both OFDM-SIM and classical OFDM can be substantially enhanced after performing DPE. It is interesting to observe that classical OFDM achieves lower BER than OFDM-SIM for the PPVs below 2 V, when DPE is not performed. However, when DPE is performed, OFDM-SIM outperforms classical OFDM, showing its superior power efficiency. Based on Figs. 3(a) and (b), it can also be found that the performance gain of OFDM-SIM over classical OFDM is very significant for a relatively low bit rate of 25 Mbit/s, and the performance gain becomes less significant if the bit rate is increased to 50 Mbit/s. To achieve a comparable performance gain at high bit rates, more advanced schemes (such as dual-mode OFDM-SIM [9]) can be applied in IM/DD bandlimited VLC systems.

4. Conclusion

In this paper, we have experimentally demonstrated the transmission of optical OFDM-SIM with DPE in an IM/DD bandlimited VLC system. Via index selection of active subcarriers, OFDM-SIM can encode additional information bits in comparison to classical OFDM. In order to achieve a flat system frequency response, DPE is performed at the transmitter side. Experimental results verify that OFDM-SIM can achieve substantially improved BER performance than classical OFDM and hence has the potential for the practical application in IM/DD bandlimited VLC systems.

5. References

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