OFDM visible light communication transmitter based on LED array

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In this letter, we present a scheme generating OFDM signals in optical domain instead of electrical domain by transmitting subcarrier signals with multiple LEDs. According to the simulation, this scheme can effectively eliminate signal degradation caused by the high peak-to-average power ratio of OFDM signals in traditional transmitter. Computational complexity in digital part of the transmitter can be reduced by using look-up table. Receiver will stay unchanged.

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While visible light communication (VLC) is drawing more and more attention, orthogonal frequency division multiplexing (OFDM) has been applied in VLC systems widely[1−7]. It is well known that OFDM is characterized by a large peak-to-average power ratio (PAPR). When the OFDM signal goes through nonlinear devices, system performance can deteriorate significantly. In VLC the main source of nonlinearity is the light emitting diode (LED). The impact of the LED focuses mainly on two aspects: amplitude distortion and clipping of the peaks[8].

A predistorter can be used to compensate LED's nonlinear transmission characteristic and condition the signal prior to the LED modulation[9]. Clipping on OFDM has been widely studied before[10,11]. Generally, according to the Bussgang theorem and the central limit theorem (CLT), clipping noise can be modeled as attenuation of the data-carrying subcarriers at the receiver and addition of zero-mean complex valued Gaussian noise. This puts a limitation on system performance. Solutions such as power back-off and PAPR reduction techniques (clipping, filtering, constrained coding, and selective mapping) have been proposed[12]. However, power back-off may result in a power efficiency penalty and can reduce signal coverage. When using PAPR reduction techniques, the system becomes more complex and/or its bandwidth efficiency becomes lower[13]. These methods are all realized in electrical domain.

A novel method to reduce signal clipping distortion in VLC-OFDM systems is proposed in optical domain. In the transmitter of DC-biased OFDM (DCO-OFDM) systems, OFDM signals are usually generated by inverse fast Fourier transform (IFFT) in FPGA/DSP devices, after going through digital-to-analog converters (DACs) and power amplifiers, they are loaded on the LEDs. In the new scheme, we use multiple LEDs and transmit a sinusoidal subcarrier by one LED which can also be implemented in FPGA/DSP devices. In view of the incoherence of the light emitted by LED, superposition of optical power of the LEDs generates the OFDM signal in optical domain and the superimposed optical power is received by photo diode (PD) at the receiver. The subcarrier signal can be restricted in the linear range of LED. Thus the influence of OFDM signals' PAPR on transmitter can be eliminated. Receivers of the two systems are the same. Besides, by using look-up table computational complexity of the digital part of the transmitter can be decreased while bandwidth efficiency remains unchanged.

In optical OFDM, serial data bits are divided into parallel, and after being mapped into quadrature amplitude modulation (QAM) symbols, they are modulated on a number of orthogonal subcarriers. Usually IFFT is used to generate the time domain sampled waveform of an OFDM symbol in transmitter. In VLC Hermitian symmetry is applied to the input of the IFFT operation so that a real OFDM signal is generated in consideration of intensity modulation. Generally, the baseband sampled signal at the output of IFFT can be described as

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

$2N$ is the size of IFFT. $X(k)$ is a QAM symbol and is commonly complex. It is constrained by Hermitian symmetry:

$$X(k) = X^*(2N-k), \quad k = 1, 2, \cdots, N-1, \tag{2}$$

where $X(0)$=0, $X(N)$=0. And Eq. (1) can be simplified as

$$x(n) = \frac{2}{\sqrt{2N}} \sum_{k=1}^{N-1} |X(k)| \cos\left\{ 2\pi k \frac{n}{2N} + \arg\left[X\left(k\right) \right] \right\}$$
$$n = 0, 1, \cdots, 2N-1. \tag{3}$$

It is shown that $x(n)$ is real but bipolar. The sampled OFDM signal goes through a DAC and then the analog OFDM signal is used to change the injection current of the LED to modulate LED's optical intensity. The LED is biased using dc-current to ensure the modulating signal is non-negative.

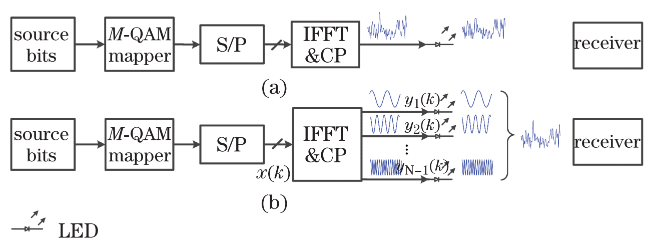

Fig. 1. (a) System model of DCO-OFDM. (b) System model of the new scheme.

Usually, to avoid clipping, the bias point and power back-off should be adjusted deliberately. Different QAM modulation orders should also be considered.

The system model of the proposed scheme is shown in Fig. 1. Implementation of other parts of the system is much the same as the DCO-OFDM system except for generation of OFDM signals. DACs and bias-T modules are not drew in the figure for simplicity.

Define $y(n, k)$ as

$$y(n,k) = \frac{2}{\sqrt{2N}}\left|X\left(k\right)\right|\cos\left\{2\pi k\frac{n}{2N} + \arg\left[X\left(k\right)\right]\right\}$$
$$n = 0, 1, \cdots, 2N-1; \quad k = 1, 2, \cdots, N-1. \quad (4)$$

Then relation between $x(n)$ and $y(n,k)$ can be described as

$$x(n) = \sum_{k=1}^{N-1} y(n,k), \quad n = 0, 1, \cdots, 2N-1. \quad (5)$$

In view of $y(n, k)$ is real, different LEDs can be used to transmit the parallel signals. After the DAC, digital signal $y(n, k)$ is converted into analog signal $y_k(t)$. Then LED 1 transmits $y_1(t)$, LED 2 transmits $y_2(t)$, LED 3 transmits $y_3(t)$, and so on. Suppose all LEDs are identical and transmit signals synchronously. The signals are detected by the same PD at the receiver.

According to previous study[13], if the LEDs are placed close to each other and set to emit light in the same direction, i.e., the same azimuth and elevation, attenuation of the channel paths are very similar. Thus time domain channel impulse response h_k between LED k and the PD is similar with each other. So the signal $g(t)$ at input of the PD can be described as

$$\begin{aligned} g\left(t\right) &= h_1\left(t\right) \otimes y_1\left(t\right) + h_2\left(t\right) \otimes y_2\left(t\right) + \cdots + h_{N-1}\left(t\right) \\ &\quad \otimes y_{N-1}\left(t\right) + w\left(t\right) \\ &= h\left(t\right) \otimes \left[y_1\left(t\right) + y_2\left(t\right) + \cdots y_{N-1}\left(t\right)\right] + w\left(t\right), \end{aligned} \quad (6)$$

where $y_k(t)$ is the signal transmitted by LED k and assume $y_k(t)$ lies in the linear range of LED. $w(t)$ is an additive white Gaussian noise (AWGN) which stands for the sum of thermal noise and shot noise in receiver. Suppose $x(t)$ is the analog signal corresponding to $x(n)$. We can get

$$x\left(t\right) = \sum_{k=1}^{N-1} y_k\left(t\right). \quad (7)$$

If N-1 LEDs are used to send signals, i.e., LED k transmits signal $y_k(t)$. A simplified equation can be derived from Eq. (6)

$$g\left(t\right) = h\left(t\right) \otimes x\left(t\right) + w\left(t\right). \quad (8)$$

The OFDM signal $x(t)$ is generated in optical domain instead of electrical domain as shown in Fig. 1(b). The signal at the input of PD remains the same compared with DCO-OFDM systems so the receiver doesn't have to make a change. LEDs transmit sinusoidal carrier signals with different initial amplitude and phase separately. Signals can be constrained in the linear range of LED effectively. Impact of the high PAPR on the LED or even the power amplifier (PA) disappears. So the new scheme can eliminate the system degradation caused by large PAPR of OFDM signals at the transmitter.

Except for elimination of the impact of PAPR, the scheme can also reduce the computational complexity of the digital part of the transmitter by using look-up table. After being mapped into QAM symbol $X(k)$, the sampled sinusoidal signal $y(n, k)$ in each sub-channel will be read from a look-up table. IFFT operation is no longer needed in the new scheme. Implementation principle is as follows. In one OFDM symbol, $2N$ data points should be computed for each sub-channel. If realized in real-time IFFT operation costs both time and hardware resources. Considering a M-QAM symbol $X(k)$, it belongs to a finite set with M elements. The initial amplitude and phase of $y(n, k)$ also belong to a finite set with M elements according to Eq. (4). Therefore $y(n, k)$ can be calculated in advance and stored in an array, i.e., a lookup table. Matched with the input M-QAM symbol $X(k)$, the corresponding sampled sinusoidal signal $y(n, k)$ in each sub-channel can be retrieved efficiently. The lookup table can be organized as Fig. 2.

An example will be used to illustrate how look-up table is used. Suppose N=32, M=16, there will be N-1=31 kinds of sub-carrier frequencies according to Eq. (4). In Eq. (4) symbol k stands for the index of the sub-carriers. As for each sub-carrier frequency, M=16 kinds of initial amplitudes and phases should be considered corresponding to M-QAM constellation. In the case of each kind of initial amplitude and phase, $2N$=64 points need to be calculated in accordance with $2N$-IFFT. As shown in Fig. 1, look-up table operation replace IFFT operation and data can be read from the memory instantly and

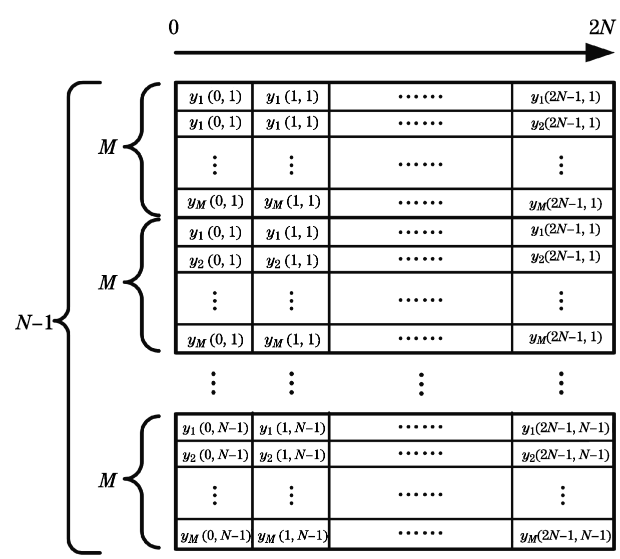

Fig. 2. Example of lookup table.

conveniently. Thus computational complexity in transmitter will be reduced.

For one OFDM symbol, $N-1$ sub-channels are used to transmit sinusoidal carrier signals $y_1(t)$, $y_2(t)$, $\cdots$, $y_{N-1}(t)$. In each sub-channel M types of the initial amplitude and phase should be considered on the basis of M-QAM mapping, which is indicated by index M in $y_M(n, k)$. So the total number of data points which must be calculated and stored is $(N\text{-}1)\times M\times 2N=2M(N^2-N)$. Suppose the value of each data point occupies 8 bits. Memory needed for the lookup table is $16M(N^2-N)$ bits. If N=32, M=16 the memory needed is about 254K bits. And if N=32, M=256 the memory needed is about 4.07M bits. This is obviously acceptable.

The same white LED model in Ref. [14] is used here. Nonlinearity behavior of the high power white LED is adequately compensated by a predistorter[15]. The linear range of the voltage of LED is 1 V (0.25−1.25 V) and only clipping effects are considered. In normal VLC-OFDM system, all $N-1$ LEDs transmit the same OFDM signal while in the new scheme each LED transmits a sinusoidal carrier signal. In the following results, the x-axis represents the average electrical signal power in one OFDM symbol loaded on each LED. The signal power modulating each LED varies from 0 to 30 dBm and an AWGN power of −10 dBm is supposed[13]. The length of IFFT is 64 and the length of cyclic prefix (CP) is 16. $N-1=31$ LEDs are considered in both two systems in simulation. At least 10^6 OFDM symbols are considered for each result. And only DCO-OFDM is considered. A summary of the simulation parameters is presented in Table 1.

The result is shown in Fig. 3. At low levels of signal power, no clipping distortion occurs in either systems and the results match closely. Performance of all considered modulation orders enhances as the signal power increases. However, as the signal power increases above a certain point, clipping distortion appears first in normal VLC-OFDM system which is caused by the large PAPR of OFDM symbols. As for the new scheme, significant improvement in BER performance can be observed. The average signal power increases by about 5 dB in Fig. 3(c) which means an increase in overall SNR and a wider coverage.

Table 1. Main Parameters of the Simulation

Parameter	Value
OFDM Configuration Parameters	
IFFT Length	64
Cyclic Prefix	16 samples
Pilot Length	100 symbols
Signal Length	$> 10^6$ symbols
Sampling Frequency	2 MHz
QAM Size	16, 64, 128, 256
System Parameters	
AWGN Power	−10 dBm
Signal Power	0~30 dBm
Number of LED	31
Linear Range of LED	1 V (0.25−1.25 V)

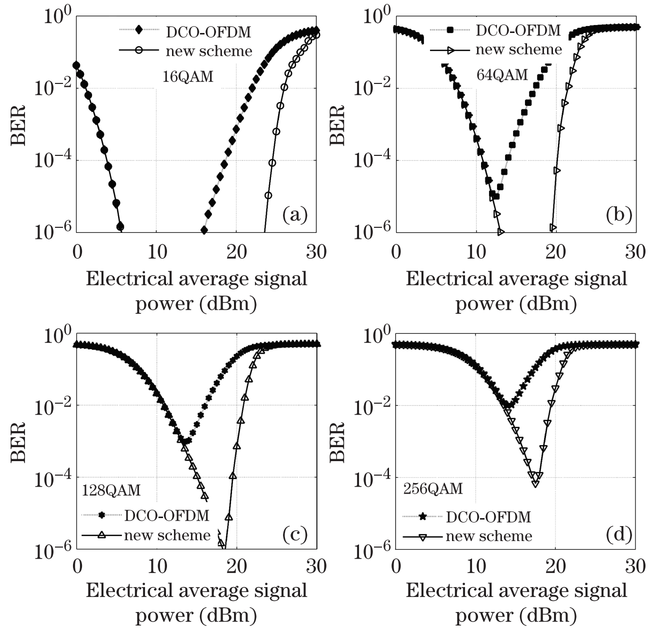

Fig. 3. Performance comparison of a normal VLC-OFDM system and a system using the new scheme with different QAM modulation orders. (a) 16QAM; (b) 64QAM; (c) 128QAM; (d) 256QAM.

This scheme will be of benefit in other ways too. The frequency response characteristic of a commercial blue-chip white LED is low-pass. Its 3-dB bandwidth is about 5 MHz which is a main limitation for high-speed VLC transmission. In the new scheme sub-carriers of different frequency are transmitted separately. Power equalization can be easily applied by adjusting the scaling factor of subcarrier signals in analog domain and available bandwidth can be expanded significantly.

However, if the size of IFFT ($2N$) is too large, a large number of LEDs, power amplifiers, DACs and size of look-up table are needed. Too many LEDs may cause multipath effect and other problems. Several method can be used to make the new scheme more practical, such as smaller LEDs can be adopted. Multiple sub-carriers can be grouped into sub-channel and be transmitted by one LED. Number of LEDs can be reduced. The balance between effectiveness and practicability should be considered when the new scheme is used.

In conclusion, a PAPR mitigation scheme in VLC-OFDM is proposed. After M-QAM mapping, instead of IFFT operation, each subcarrier signal is retrieved from the lookup table and transmitted by one LED. OFDM signals are generated in optical domain through superposition of light intensity. The scheme eliminates the signal clipping caused by large PAPR and reduces the nonlinear distortion effectively. For example in Fig. 3(c), in the case of 128QAM using 31 LEDs, the minimum BER is reduced from 10^{-3} to 10^{-6} when the new scheme is applied. Power efficiency is improved significantly and the signal coverage is increased. The use of lookup table reduces the computation complexity compared to IFFT operation.

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