Research Article

Experimental Investigation of Zadoff-Chu Matrix Precoding for Visible Light Communication System with OFDM Modulation

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Light-emitting diode- (LED-) based visible light communication (VLC) has become a potential candidate for next generation high-speed indoor wireless communication. Due to the limited modulation bandwidth of the LED, orthogonal frequency division multiplexing (OFDM) modulation is particularly preferred in the VLC system to overcome the ISI, which suffers from the high peak-to-average power ratio (PAPR) and leads to severe performance loss. In this paper, we propose and experimentally demonstrate a novel Zadoff-Chu matrix (ZCM) precoding scheme, which can not only reduce the PAPR, but also provide uniform signal-to-noise ratio (SNR) profile. The theoretical analysis and simulation show that the proposed scheme achieves better PAPR performance compared with the traditional precoding schemes. The experimental demonstration further validates the bit error rate (BER) performance improvement, where the measured BERs are all below the 7% pre-forward error correction (pre-FEC) limit of 3.8×10^{-3} when the transmitted data rate is 50 Mb/s.

1. Introduction

Visible light communication (VLC) has recently emerged as a compelling wireless communication technology beyond traditional radio frequency (RF) communications. Utilizing light-emitting diodes (LEDs), VLC can support illumination and communication simultaneously and offers the benefits of cost effectiveness, high security, low power consumption, and immunity to electromagnetic interference [1, 2].

Since the modulation bandwidth of the LED is very limited, signals modulated at high frequencies suffer from severe attenuation, resulting in serious intersymbol interference (ISI) for high-speed transmissions [3]. Orthogonal frequency division multiplexing (OFDM) has been proved particularly suitable for the VLC system, where the channel is decomposed into multiple frequency-flat channels, and the ISI can be eliminated [4, 5]. However, one major drawback of the OFDM signals is the high peak-to-average power ratio (PAPR), which leads to a severe performance loss because of the nonlinear distortion caused by a LED emitter [6]. Moreover, since intensity modulation with direct detection (IM/DD) is adopted, a direct current (DC) is required to

make sure that the transmitted signals are real and positive in the VLC system. Then high signal peak value implies a need for a large DC bias that causes serious degradation of system power efficiency [7]. Hence it is even more urgent to reduce PAPR in the OFDM based VLC system.

In order to reduce the high PAPR, several schemes have been proposed in the VLC system. In [8], a pilot-assisted PAPR reduction technique is used at the cost of the data rate loss, whose PAPR reduction performance can be determined by the number of pilot sequences. The iterative clipping and exponential nonlinear companding methods are other ways to reduce PAPR in VLC systems [9, 10]. However, both methods mentioned above can result in the bit error rate (BER) performance degradation. The active constellation extension [11], the tone reservation [12], and the tone injection [7] schemes are also presented to reduce PAPR in VLC systems. However, the computational complexity of these methods is extremely high.

Moreover, precoding is considered an efficient way to reduce the PAPR, by which the frequency diversity can be provided as well [13]. Since only simple linear computation is required, great promise in OFDM based VLC system has

been shown. In [14, 15], the Walsh-Hadamard matrix and the discrete Fourier transform (DFT) operation have been used as precoding matrices to decrease the PAPR of the OFDM signals. Both results confirm that the PAPR can be reduced significantly. In [16], an orthogonal circulant matrix transform (OCT) based precoding scheme is proposed, which achieves a relatively flat signal-to-noise ratio (SNR) profile over the signal bandwidth and alleviates significant BER degradation at high frequency carriers.

In this paper, we propose and experimentally demonstrate a novel Zadoff-Chu matrix (ZCM) precoding scheme for OFDM VLC system. Benefitting from the ideal periodic autocorrelation and constant magnitude, ZCM gains the advantage of the low PAPR while retaining the feature of the uniform SNR profile at the same time. Theoretical simulation results show that the PAPR of the ZCM precoding scheme is much lower than the existing Walsh-Hadamard matrix and the OCT precoding schemes. Finally, an experimental demonstration is set up to verify the effectiveness of the proposed precoding scheme. Experimental results indicate that the ZCM precoding scheme achieves the best BER performance, where the measured BERs are all below the 7% pre-forward error correction (pre-FEC) limit of 3.8×10^{-3} with 50Mb/s transmission data rate and 1-meter transmission distance.

2. Principle

2.1. OFDM VLC System Based on the ZCM Precoding. The principle of the OFDM VLC system based on the ZCM precoding is presented in Figure 1. At the transmitter (TX), a stream of random binary input data is firstly mapped into complex signals according to the certain quadrature amplitude modulation (QAM) format. After serial-parallel (S/P) conversion, parallel data streams are transmitted, each of which corresponds to a frequency-flat subchannel in the OFDM system. Then the ZCM precoding is implemented before OFDM modulation. The OFDM modulation is realized by inverse fast Fourier transform (IFFT), and cyclic prefix (CP) is attached to each OFDM symbol to overcome the ISI. The preamble is inserted for synchronization and channel estimation at the receiver. Since only real and positive signals can be transmitted in the VLC system, the upsampling and upconverting operations are applied, where real-value signals are obtained by the complex-to-real-value conversion [17]. Finally, positive signals can be achieved by simply adding the DC offset. At the receiver (RX), frame synchronization, channel estimation and channel equalization are carried out to eliminate the effect of the channel with the help of the preamble. The remaining processing is the inverse process of the signal modulation at the transmitter.

2.2. The ZCM Precoding. The Zadoff-Chu sequences are the special case of the generalized Chirp-Like poly phase sequences having both ideal periodic autocorrelation property and very low cross-correlation characteristics. Different from the precoding matrix in OCT scheme, we use a much longer Zadoff-Chu sequence to form a ZCM rather than cyclically shifting the Zadoff-Chu sequence to obtain a circulant matrix.

After QAM mapping and serial-parallel conversion, the mapped signals are precoded with a ZCM. The proposed ZCM is generated according to the following two steps.

Step 1. A Zadoff-Chu sequence $\mathbf{Z}$ of length L is generated, where each element is defined by [18]

$$z(k) = \begin{cases} e^{(j2\pi r/L)(k^2/2+qk)}, & \text{for } L \text{ Even} \\ e^{(j2\pi r/L)(k(k+1)/2+qk)}, & \text{for } L \text{ Odd} \end{cases} \quad (1)$$

where $k = 0, 1, 2, \dots, L-1$, q is any integer, r is any integer relatively prime to L , and $j = \sqrt{-1}$.

Step 2. The ZCM $\mathbf{A}$ is formed by reshaping the Zadoff-Chu sequence, which is denoted as follows:

$$\mathbf{A} = \frac{1}{\sqrt{N}} \begin{bmatrix} a(0,0) & a(0,1) & \cdots & a(0,N-1) \\ a(1,0) & a(1,1) & & a(1,N-1) \\ \vdots & \vdots & \ddots & \vdots \\ a(N-1,0) & a(N-1,1) & \cdots & a(N-1,N-1) \end{bmatrix} \quad (2)$$

In (2), the relationship between $a(m,l)$ and $z(k)$ is $a(m,l) = z(m \times N + l)$, $L = N \times N$, and N is the subcarrier number. To keep the transmitted power constant, the normalization factor $1/\sqrt{N}$ is multiplied by the matrix. Obviously, based on the properties of the Zadoff-Chu sequence, the ZCM satisfies $\mathbf{A}\mathbf{A}^H = \mathbf{I}$, where $(\cdot)^H$ denotes Hermitian transpose and $\mathbf{I}$ is the identity matrix. Then the original transmitted signals can be easily recovered by multiplying the received signals after data subcarrier extraction by $\mathbf{A}^H$.

Let $\mathbf{X} = [x_0 \ x_2 \ \cdots \ x_{N-1}]$ be the vector of the QAM mapped signals allocated to N subcarriers. The vector of precoding signals $\mathbf{Y} = [y_0 \ y_1 \ \cdots \ y_{N-1}]$ can be expressed as

$$\mathbf{Y} = \mathbf{A} \cdot \mathbf{X} \quad (3)$$

After N -point IFFT operation, the OFDM signals are obtained by

$$w_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} y_k e^{j(2\pi kn/N)}, \quad n = 0, 1, \dots, N-1 \quad (4)$$

Then, according to [6], the PAPR of the OFDM signals can be denoted as

$$PAPR = \frac{\max |w_n|^2}{E\{|w_n|^2\}} \quad (5)$$

where $E(\cdot)$ denotes the expectation operation.

The statistics for the PAPR of an OFDM signal can be given in terms of its complementary cumulative distribution function (CCDF). The CCDF for an OFDM signal is defined by $P(PAPR > PAPR_0)$, where $PAPR_0$ is the given threshold. The

FIGURE 1: Block diagram of OFDM VLC system with ZCM precoding.

TABLE 1: System parameters.

Parameters	Values
Bandwidth	0 – 12.5 MHz
Up-converted frequency	6.25 MHz
Modulation type	16QAM
Subcarrier number	256
Up-sampling rate	4
Transmission distance	1 m

CCDF of the PAPR indicates the probability that the PAPR of a symbol block exceeds a given threshold.

Figure 2 illustrates the computer simulation results of CCDF curves based on different precoding schemes and modulation orders, where the proposed ZCM is compared with the Walsh-Hadamard matrix, the DFT operation, and the OCT. As shown, the PAPR of the ZCM precoding scheme is similar to the DFT precoding scheme, while being much lower than the PAPR of the Walsh-Hadamard matrix precoding scheme. The OCT precoding scheme is useless in PAPR reduction, where the PAPR is almost the same as the traditional OFDM scheme without precoding. In addition, the PAPRs of the ZCM, DFT, and the Walsh-Hadamard matrix precoding schemes would be increased when the modulation orders are increased. Meanwhile the PAPRs of the OCT precoding scheme and the traditional OFDM without precoding are kept fixed with the modulation orders varying.

3. Experimental Results

The experimental setup is shown in Figure 3. In the experiments, an arbitrary function generator (AFG: Tektronix AFG3252C) is used to generate transmitted signals and DC supplied by AFG is offset to ensure that the transmitted signals are positive at the transmitter. Then, the mixed signals are transmitted through the LED in the form of the optical power. At the receiver, optical signals entering the PD are converted into electrical signals. Afterwards, the signals are recorded by a high-speed digital oscilloscope (OSC: Tektronix MSO4104) and then sent for offline processing. We use a commercially available LED (Cree XLamp XP-E) radiating red light as the transmitter, whose center wavelength is 620 nm and maximum power is 1W. Because the LED is a point light source, a reflection cup with 60° is used to concentrate the light. We use a PD module (Hamamatsu C12702-11, 0.42A/W responsivity at 620 nm) with 1 mm² active area and about 100

FIGURE 2: CCDF of PAPRs for the different precoding schemes.

MHz bandwidth as the receiver. The system parameters of our experiments are listed in Table 1. According to the parameter configuration, data is transmitted at the rate of 50Mb/s over 1-meter transmission distance in the experimental demonstration.

The nonlinearity of the LED results from the nonideal transform function. The nonlinear relationship between driving voltage and forward current causes two kinds of signal distortion. One is the nonlinear mapping in electrical-to-optical conversion within the dynamic range; the other is the hard clipping of signals when the voltage is beyond the maximum permissible voltage [19]. In Figure 4, the U-I curve of the LED used in the experiments is given. According to the figure, we find that the U-I curve becomes nonlinear when the voltage is below 1.9 V or above 2.2V.

As mentioned above, the high PAPR would result in the BER performance loss because of the nonlinearity of the LED. Therefore, BERs are measured under the condition of the different DC offsets, as shown in Figure 5. In the experiments, the DC offsets are set as 1.8V, 2.0V, and 2.3V respectively, corresponding to the different working states of the LED. Note that the transmitted power is always kept

FIGURE 3: Experimental setup of the OFDM VLC system with ZCM precoding.

FIGURE 4: U-I curve of the LED.

FIGURE 5: BER versus DC offset.

constant when using the different DC offsets and different precoding schemes. According to the U-I curve in Figure 4, the LED works in the nonlinear region most of the time when the DC offset is 1.8V or 2.3V and in the linear region more often when the DC offset is set to 2.0V. As a result, experimental results showed that the BER performance can be improved when the DC offset is equal to 2.0V, no matter which precoding schemes are applied to the system. Compared with the different precoding schemes, it can be seen that the ZCM precoding scheme always gains the best BER performance. When the DC offset is 1.8V or 2.3V, the ZCM precoding scheme performs better than the OCT and Walsh-Hadamard matrix precoding schemes because of its lower PAPR. In addition, although the PAPR of the ZCM

precoding scheme is almost the same as the DFT precoding scheme, it still gains the better BER performance profiting from its uniform SNR profile. When the DC offset is set to 2.0V, the BERs of all the schemes become closer. This is because the impact of the high PAPR would be reduced when the LED works in the linear region more often. Similarly, the BERs of the ZCM and the OCT are lower than other schemes considering their flatter SNR profiles in this case.

Furthermore, we study the BER performance of the different schemes with the varieties of the transmitted electrical power (DC is not included). The experimental results are depicted in Figure 6, plotted with the transmitted electrical

FIGURE 6: BER versus transmitted electrical power.

power on the horizontal axis and the BER on the vertical axis. The DC offset is set equal to 2.3V in the experiments so that the LED may work in the nonlinear region most of the time. At the beginning, the BER performance of the different schemes is all improved when increasing the transmitted electrical power. The result is straightforward because the SNRs are increased with the higher transmitted power, which leads to better BER performance. However, when the transmitted electrical power grows to 0.8dB, the BERs increase again. It means that the nonlinearity of the LED would be the dominant factor when the transmitted electrical power grows to a certain degree. There is a tradeoff between the SNR and the nonlinearity. Compared with other precoding schemes, the proposed ZCM precoding scheme always gains the best performance for its lower PAPR and the flatter SNR profile under the condition of different transmitted electrical power, as shown in Figure 6.

4. Conclusion

In this paper, we propose and experimentally demonstrate a novel ZCM precoding based OFDM VLC system. Firstly, through the theoretical analysis and the computer simulation, we reach the conclusion that the ZCM precoding scheme achieves the same PAPR performance as the DFT precoding scheme, but much better than the traditional Walsh-Hadamard matrix and the OCT precoding schemes. Then, the BER performance of the precoding based OFDM VLC system is evaluated by the experiments, where the 50Mb/s data rate transmissions are demonstrated under the 7% pre-FEC threshold of 3.8×10^{-3} over 1-meter transmission distance. By varying the DC offsets, experimental results confirm that the BERs would increase when the LED works in

the nonlinear region. Furthermore, the tradeoff between the SNR and the nonlinearity is studied. On one hand, the BER performance would be improved for higher SNR with the transmitted electrical power increasing; on the other hand, too higher transmitted electrical power would result in BER performance decrease because of more serious nonlinearity. Experimental results also show that the proposed ZCM precoding scheme always owns the best BER performance for its lower PAPR and the flatter SNR profile, compared with the existing precoding schemes.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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