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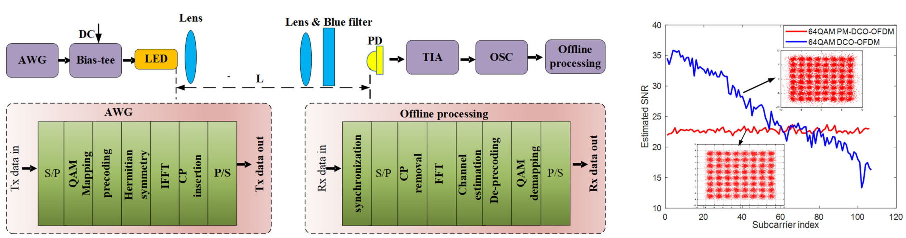

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Investigation of DC-Biased Optical OFDM With Precoding Matrix for Visible Light Communications: Theory, Simulations, and Experiments

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Abstract: Orthogonal frequency-division-multiplexing (OFDM) technology is widely used in visible light communication (VLC) to achieve high data rate transmission. However, the traditional direct-current (DC)-biased optical OFDM (DCO-OFDM) VLC systems suffer from the high peak-to-average power ratio (PAPR) which causes signal clipping distortion, and, thus, performance degradation. Furthermore, severe high-frequency fading due to the limited system bandwidth results in poor bit error rate (BER) performance. Precoding matrix (PM) techniques have been proposed to enhance the performance of VLC OFDM transmission, but a little or no work has been carried out in investigating the theory of PM used in OFDM VLC systems. In this paper, we aim to reveal the theory of PM-DCO-OFDM for a VLC system. To figure out the intrinsic laws of a PM method, we investigate the principles of PAPR reduction, clipping distortion optimization, and signal-to-noise ratio (SNR) distribution equalization. Based on the analysis of PAPR, we theoretically proved the simplicity of PM as a method to reduce the possibility of high PAPR by improving the autocorrelation performance of input symbols. The clipping distortion could be improved due to the reduction of high PAPR. Moreover, the relatively uniform SNR distribution can be achieved by PM through equalizing the clipping and channel noise, which is beneficial to improve the BER performance in high-frequency constrained systems. However, the PM method used in a DCO-OFDM VLC system should consider the transmitting power, modulation format, and transmission distance as a whole to achieve the transmission performance improvement. The simulation results demonstrate the complementary cumulative distribution function of PAPR can be reduced ∼3 dB, while the performance of clipping distortion power and clipping error probability are significantly improved. Furthermore, experiment is carried out with results showing that the PM method can improve the BER performance in the case that VLC OFDM transmission has enough transmitting power, but with the low transmitting power, the PM also can damage the BER performance. The simulation and experiment results are consistent with our theoretical analysis.

Index Terms: Visible light communication, DC-biased optical OFDM, PAPR, SNR distribution, precoding matrix.

1. Introduction

With the rise of social networking, video-on-demand, and cloud based services, the capacity demand of wireless communication increases dramatically [1]. According to [2], more than 50% of this traffic is expected to be offloaded to Wi-Fi, which means most of data consumptions will occur indoors. However, the existing radio frequency (RF) wireless communication is difficult to support the rapid growth of indoor data traffic and multimedia applications with high-bandwidth demand (i.e., HD video, VR) due to its limited bandwidth. The visible light communication (VLC), as a complement to RF systems, has gained increasing attention because of unregulated huge bandwidth (i.e., terahertz band) [3], indicating its potential to provide high-speed indoor transmission.

In the VLC system, the orthogonal frequency division multiplexing (OFDM) with high order multi-level quadrature amplitude modulation (M-QAM) is commonly used to achieve high-rate transmission and eliminate the inter-symbol interference (ISI) [4]–[9]. Different from RF OFDM systems, it is complex to achieve quadrature modulation in intensity-modulation/direct-detection (IM/DD) optical systems, thus the baseband signal must be real before modulating LED. The OFDM signal envelope variations are utilized to modulate the intensity of LED so the bipolar signal must be converted to a positive unipolar signal in VLC systems. Based on the assignment of subcarriers and the bipolar-unipolar conversion scheme, the existing OFDM systems for optical wireless communications (OWC) can be classified into direct current-biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM) respectively [10], [11]. In ACO-OFDM systems, only the odd subcarriers are modulated and only the positive part of the ACO-OFDM signal is transmitted. In DCO-OFDM systems, a DC bias is applied to the real OFDM signal to achieve the bipolar-unipolar conversion. Therefore, the DCO-OFDM achieves higher data rate with the same spectral efficiency due to more available subcarriers.

However, DCO-OFDM systems suffer from the high peak-to-average power ratio (PAPR) due to superposition of subcarriers in the process of inverse fast Fourier transformation (IFFT). In VLC systems, the transmitted signal has to be constrained to a limited range due to the nonlinear characteristics of the LED [12]. High PAPR of OFDM signal leads to a large dynamic power excursion that harm the energy efficiency at both the transmitter and receiver sides. OFDM signal with high PAPR is clipped by the LED transmitter causing serious clipping distortion. Researchers have proposed many methods to reduce the PAPR, including clipping with filtering [13], selected mapping (SLM) [14]–[16], partial transmit sequences (PTS) [17], discrete Fourier transform (DFT)-Spread [18] and signal companding [19], [20]. Most of these methods bring certain correlations between subcarrier symbols of the OFDM block and could be classified into deterministic and probabilistic approach. The clipping is a typical deterministic approach, which can cause serious in-band distortion by limiting the overshooting signal amplitude to a predefined level. SLM, PTS, signal companding and DFT-Spread are probabilistic approaches, which reduce the probability of high PAPR. SLM and PTS require the use of side information, which reduces the bandwidth efficiency of the system. Signal companding is a nonlinear transformation that tends to destroy the orthogonality among OFDM subcarriers. DFT-Spread can be treated as a kind of precoding method which adopts M-point DFT before the IFFT to counteract the high PAPR. Furthermore, this precoding method can improve the bit error rate (BER) performance significantly in optical OFDM systems without requiring complicated processing and optimization for each transmitted OFDM block [21].

Recently, another pattern of precoding technique has been used in optical OFDM transmission to improve the PAPR and BER performance [22], [23]. This pattern uses a sequence to build an ordinary matrix and then multiply with the input data for precoding. We name this method as precoding matrix. The precoding matrix has been used in OFDM VLC systems to enhance the transmission performance [23]. In [23], a precoding matrix based on constant amplitude zero auto correlation (CAZAC) sequence is used in OFDM VLC system to improve the PAPR and BER performance. However, to the best of our knowledge, the explicit theoretical analysis of precoding matrix used in VLC systems is still insufficient. it is necessary to find out that: 1) why the precoding matrix can improve the transmission performance of VLC systems; 2) considering the practical communication environment (e.g., dimming/brightness control, influence of surroundings), whether precoding matrix can be used in all cases of VLC scenario; 3) what kind of precoding method (i.e., DFT-Spread and precoding matrix) is the best to be used in VLC systems.

In this paper, we aim to reveal the theory of precoding matrix-DCO-OFDM (PM-DCO-OFDM) for VLC system. We investigate the origin of high PAPR in traditional DCO-OFDM systems and theoretically demonstrate that the relationship between PAPR and the autocorrelation of input symbols carried on orthogonal subcarriers. The higher the relevance of input symbols, the more likely the DCO-OFDM systems get a high PAPR. Precoding matrix is a simple way to improve the correlation performance by rebuilding the input symbols [24]. The theoretical analysis shows that the correlation performance of input symbol vector can be significantly improved by the precoding matrix with zero autocorrelation.

We further theoretically analyze the performance of clipping distortion and SNR distribution in the PM-DCO-OFDM VLC system. In PM-DCO-OFDM, each input symbol vector is multiplied by the precoding matrix before inverse fast Fourier transformation (IFFT). After precoding operation, the clipping distortion could be improved due to the reduction of high PAPR. Moreover, based on the analysis of signal to noise ratio (SNR) distribution, a spectrum with relatively uniform SNR is obtained as a result of clipping and channel noise equalization, which can reduce the high frequency fading effect, especially the bandwidth-constrained VLC systems.

In VLC OFDM transmission, precoding matrix can transfer part SNR of low frequency subcarriers to the high frequency subcarriers which is beneficial to improve the BER performance. However, in the practical VLC with the consideration of dimming/brightness control, the precoding matrix also has its limitation. Transmitting power, modulation format and transmission distance are the three key factors that affect the performance of precoding matrix in OFDM VLC systems. Experimental works taken into account the three key factors are carried out. With enough transmitting power, the BER performance can be improved significantly in all cases of PM-DCO-OFDM VLC transmission. But with the low transmitting power, the precoding matrix may degrade the BER performance, especially with the high order modulation and long transmission distance. In order to figure out the effect of different kinds of precoding method in OFDM VLC system, we also conduct the experiments to compare the precoding matrix with DFT-Spread in the aspects of BER performance and complexity. The experiment results demonstrate that the two method can provide the much of the same BER performance improvement and complexity.

The rest of the paper is organized as follows: in Section 2, the system model of PM-DCO-OFDM VLC is introduced; in Section 3, PAPR reduction through precoding matrix is theoretically analyzed; in Section 4 and 5, the performance of clipping distortion and SNR distribution in PM-DCO-OFDM VLC system is theoretically analyzed; in Section 6, the limitation of precoding matrix used in VLC systems is discussed; in Section 7 and 8 the simulation results, experimental results and discussions are presented respectively; in Section 9, conclusions are given.

2. PM-DCO-OFDM VLC System Model

PM-DCO-OFDM VLC system is shown in Fig. 1. A sentence with length $L = (N-1)^2$ is used to construct a $(N-1) \times (N-1)$ precoding matrix P, which is defined as:

$$P = \frac{1}{\sqrt{N-1}} \begin{bmatrix} p_{1,1} & \cdots & p_{1,N-1} \\ \vdots & \ddots & \vdots \\ p_{N-1,1} & \cdots & p_{N-1,N-1} \end{bmatrix} \quad (1)$$

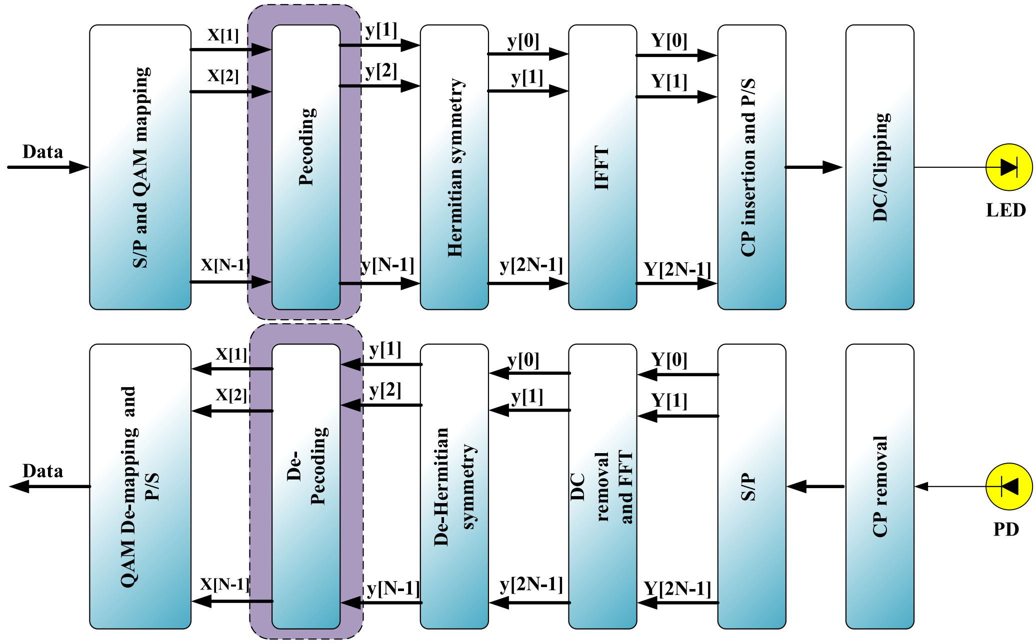


Fig. 1. Block diagram of PM-DCO-OFDM VLC system.

The input column vector, $\mathbf{X} = [X(1), X(2),\ldots X(N-1)]$, is multiplied by the precoding matrix P to get a new column vector, $\mathbf{y}$, which can be written as:

$$y = PX = [y_1, \ldots, y_{N-1}]^T \tag{2}$$

Where,

$$y_i = \frac{1}{\sqrt{N} - 1} \sum_{m=1}^{N-1} P_{i}, m X_m \quad i = 1 \ldots N-1 \tag{3}$$

As a result, the new column vector $\mathbf{y}$ is sent to the block of IFFT.

3. PAPR Reducing Through Precoding Matrix

In IM/DD VLC systems, the output vector of IFFT must be real-valued, so the input vector is sent to the Hermitian symmetry block. The Hermitian symmetry block transforms the vector into a new vector of length 2N with

$$\mathbf{y} = [\mathbf{y}_0, \ldots \mathbf{y}_\mathbf{k}, \ldots \mathbf{y}_\mathbf{N}, \ldots \mathbf{y}_{\mathbf{2N-k}}, \ldots \mathbf{y}_{\mathbf{2N-1}}]^T \tag{4}$$

and

$$\mathbf{y}_{\mathbf{2N-k}} = \mathbf{y}_\mathbf{k}^*, \ k = 1 \ldots N-1 \tag{5}$$

where $*$ denotes the complex conjugation. The symmetry vector is sent to the IFFT block and the transmitted OFDM signal can be written as:

$$\mathbf{Y}(\mathbf{n}) = \frac{1}{\sqrt{2N}} \sum_{\mathbf{i}=\mathbf{0}}^{\mathbf{2N-1}} \mathbf{y}_\mathbf{i} \mathbf{e}^{j2\pi \mathbf{i} \frac{\mathbf{n}}{\mathbf{2N}}} \tag{6}$$

Combining (5), (6) can be written as:

$$Y(n) = \frac{1}{\sqrt{2N}}\left(y_0 + \sum_{i=1}^{N-1} y_i e^{j2\pi i \frac{n}{2N}} + y_N e^{jn\pi} + \sum_{i=1}^{N-1} y_i^* e^{j2\pi(2N-i)\frac{n}{2N}}\right) \tag{7}$$

which can be simplified as:

$$Y(n) = \frac{1}{\sqrt{2N}}\left[y_0 + 2Re\sum_{i=1}^{N-1} y_i e^{j2\pi i \frac{n}{2N}} + y_N e^{jn\pi}\right] \tag{8}$$

From (8), y_0 and y_N are set to zero to make ***Y(n)*** with no residual complex parts. The transmitted signal ***Y(n)*** can be written as:

$$Y(n) = \frac{1}{\sqrt{2N}}\left(2Re\sum_{i=1}^{N-1} y_i e^{j2\pi i \frac{n}{2N}}\right) \tag{9}$$

Then the PAPR of the transmitted OFDM signal is:

$$PAPR = \frac{max|Y(n)|^2}{E\left\{|Y(n)|^2\right\}} \tag{10}$$

where E [·] donates expectation operation. From (9), the $|Y(n)|^2$ can be expressed as:

$$|Y(n)|^2 = \frac{2}{N}\left\{Re\sum_{i=1}^{N-1} y_i e^{j2\pi i \frac{n}{2N}}\right\}^2 \leq \frac{2}{N}\left|\sum_{i=1}^{N-1} y_i e^{j2\pi i \frac{n}{2N}}\right|^2 \tag{11}$$

and the $E(|Y(n)|^2)$ is written as:

$$E\left\{|Y(n)|^2\right\} = \frac{\sum_{n=0}^{2N-1}|Y(n)|^2}{4N^2} = \frac{\sum_{n=1}^{N-1}|Y(n)|^2}{2N^2} \tag{12}$$

The PAPR of the OFDM signal can be upper bounded as:

$$PAPR \leq 4N^* \frac{\left|\sum_{i=1}^{N-1} y_i e^{j2\pi i \frac{n}{2N}}\right|^2}{\sum_{n=1}^{N-1}|Y(n)|^2} \tag{13}$$

the maximum PAPR is then obtained as:

$$PAPR_{max}(n) = \frac{4N}{\sum_{n=1}^{N-1}|Y(n)|^2} * \max\left(\left|\sum_{i=1}^{N-1} y_i e^{j2\pi i \frac{n}{2N}}\right|^2\right) \tag{14}$$

From (14), we can define a function p(n) as:

$$p(n) = \left|\sum_{i=1}^{N-1} y_i e^{j2\pi i \frac{n}{2N}}\right|^2 \tag{15}$$

p(n) can be upper bounded as follows:

$$p(n) = \left(\sum_{i=1}^{N-1}|y_i|^2 + 2Re\sum_{k=1}^{N-2}\sum_{i=1}^{N-k-1} y_i y_{i+k}^* e^{-j\pi k \frac{n}{N}}\right) \tag{16}$$

The maximum p(n) can be written as:

$$p(n)_{max} = \left(\sum_{i=1}^{N-1}|y_i|^2 + 2\sum_{k=1}^{N-2}\rho(k)\right) \tag{17}$$

where, the $\rho(k)$ is defined as:

$$\rho(\mathbf{k}) = \sum_{i=1}^{N-k-1} \left| y_i * \mathbf{y}_{i+k}^* \right| \tag{18}$$

representing the k-th correlation metric of input signals. Combining (12), (15) and (16), the maximum value of PAPR is then obtained:

$$PAPR_{max}(n) = \frac{4N}{\sum_{n=1}^{N-1} |\mathbf{Y}(\mathbf{n})|^2} * \left(\frac{2}{\mathbf{N}} \left(\sum_{i=1}^{N-1} |\mathbf{y}_i|^2 + 2\mathbf{max} \left(\sum_{k=1}^{N-2} \rho(\mathbf{k}) \right) \right) \right) \tag{19}$$

From (19), the maximum value of PAPR is related to $\rho(k)$. The original input signal is random distributed and thus has poor autocorrelation, which results in the high PAPR in most of OFDM signals. Combining (3) and (18), the $\rho(k)$ can be written as follows:

$$\rho(\mathbf{k}) = \frac{1}{N-1} \sum_{i=1}^{N-k-1} \left| \sum_{m=1}^{N-1} \sum_{h=1}^{N-1} \mathbf{P}_{i,m} \mathbf{X}_m \mathbf{P}_{i+k,h}^* \mathbf{X}_h^* \right| \tag{20}$$

Equation (20) can be simplified as:

$$\rho(\mathbf{k}) = \frac{1}{N-1} \sum_{i=1}^{N-k-1} \left| \sum_{m=1}^{N-1} \mathbf{P}_{i,m} \mathbf{P}_{i+k,m}^* |\mathbf{X}_m|^2 + \sum_{m \neq h}^{N-1} \sum_{h=1}^{N-1} \mathbf{P}_{i,m} \mathbf{X}_m \mathbf{P}_{i+k,h}^* \mathbf{X}_h^* \right| \tag{21}$$

Normalizing power of the input signals, equation (21) can be written as:

$$\rho(\mathbf{k}) = \frac{1}{N-1} \sum_{i=1}^{N-k-1} \left| \sum_{m=1}^{N-1} \mathbf{P}_{i,m} \mathbf{P}_{i+k,m}^* + \sum_{m \neq h}^{N-1} \sum_{h=1}^{N-1} \mathbf{P}_{i,m} \mathbf{P}_{i+k,h}^* \right| \tag{22}$$

And maximum $\rho(k)$ can be written as:

$$\rho(\mathbf{k})_{max} = max \left(\frac{1}{N-1} \sum_{i=1}^{N-k-1} \left| \sum_{m=1}^{N-1} \mathbf{P}_{i,m} \mathbf{P}_{i+k,m}^* + \sum_{m \neq h}^{N-1} \sum_{h=1}^{N-1} \mathbf{P}_{i,m} \mathbf{P}_{i+k,h}^* \right| \right) \tag{23}$$

If the precoding matrix meets the relation that:

$$\sum_{m=1}^{N-1} \mathbf{P}_{i,m} \mathbf{P}_{i+k,m}^* = 0, k \neq 0 \tag{24}$$

the maximum $\rho(k)$ can be reduced as:

$$\rho(\mathbf{k})_{max} = max \left(\frac{1}{N-1} \sum_{i=1}^{N-k-1} \left| \sum_{m \neq h}^{N-1} \sum_{h=1}^{N-1} \mathbf{P}_{i,m} \mathbf{P}_{i+k,h}^* \right| \right) \tag{25}$$

From (25), the maximum value of PAPR can be reduced with the reduction of maximum $\rho(k)$. However, only the sequence with zero k-th autocorrelation can be used as precoding matrix to reduce the possibility of high PAPR.

4. Clipping Distortion in PM-DCO-OFDM VLC System

Due to the nonlinear characteristics of LED, the transmitted signal has to be constrained in the linear regime. The minimum and maximum value of the forward voltage for LED is defined as the V_{min} and V_{max}, respectively. The resulting output signal $S(n)$ is [25]:

$$S(n) = Y(n) + V_{DC} \tag{26}$$

The signal after clipping C(n) can be written as:

$$C(n) = \begin{cases} V_{max} & S(n) > V_{max} \\ S(n) & V_{min} < S(n) < V_{max} \\ V_{min} & S(n) < V_{min} \end{cases} \quad (27)$$

The clipping distortion power is

$$\delta^2 = \frac{1}{2N}\sum_{n=0}^{2N-1}(\delta(n))^2 = \frac{1}{2N}\sum_{n=0}^{2N-1}(Y(n) + V_{DC} - C(n))^2 \quad (28)$$

When the number of subcarrier is large ($N > 10$), the ensemble average of S(n) can be accurately modeled as a Gaussian random process (central limit theorem) with V_{DC} mean [29]. The probability density function (PDF) is given by:

$$P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left(-\frac{(x - V_{DC})^2}{2\sigma^2}\right), \min S(n) < x < \max S(n) \quad (29)$$

where, variance σ^2 equals to the total power of the electrical OFDM signal. The clipping error probability is

$$P_c(x > V_{max}\ or\ x < V_{min}) = \int_{V_{max}}^{maxS(n)} P(x)\,dx + \int_{minS(n)}^{V_{min}} P(x)\,dx \quad (30)$$

The overshooting signal distorts due to clipping, which can severely degrade the OFDM VLC system. From (28) and (30), we can observe that reducing the peak power of transmitted OFDM signal is an approach to mitigate the clipping noise. From the theoretical analysis of PAPR, the maximum value of |Y(n)| is related to the correlation performance of the input signals which can be improved by precoding leading to further suppression of the clipping distortion in PM-DCO-OFDM VLC system.

5. SNR of Subcarriers in PM-DCO-OFDM VLC System

The signal transmission can be depicted by:

$$\begin{cases} T(n) = H(n) * C(n) + \varphi(n) \\ C(n) = Y(n) + V_{DC} + \delta(n) \end{cases} \quad (31)$$

where H(i) denotes the channel transfer matrix, $\varphi(n)$ and $\delta(n)$ is the channel noise and clipping noise respectively. In the receiving end, the signals can be depicted by:

$$R(n) = H(n)^{-1} * T(n) - V_{DC} \quad (32)$$

In the practical VLC, the optical path difference due to the reflection leads to the multipath effects. The multipath effects can induce inter-symbol interference (ISI) which limits the achievable data rate. However, this effect was not included in the OFDM transmission model due several reasons. First, in OFDM transmission, the high rate of series signals are mapped to parallel signals of low rate, which can help reduce the impact of multi-path delay. Second, cyclic prefix (CP) is inserted in the OFDM signals to mitigate the multipath effect. [32]. If the CP duration is longer than the maximum multipath delay, the multipath effects will be mitigated in the process of receiving. Therefore, even when the multipath components exists, OFDM inherently combat multipath induced ISI with a proper CP length [33]. In addition, the subcarriers are orthogonal, so H(n) can be expressed by diag(h_1, $h_2 \cdots h_{N-1}$) for the channel gain of each subcarrier. After de-precoding, the receiving signal of i-th subcarrier can be written as:

$$U(i) = \left(\sum_{k=1}^{N-1} P^{-1}(i,k) * y(k) + \sum_{k=1}^{N-1} P^{-1}(i,k) * \delta(n)_k + \sum_{k=1}^{N-1} P^{-1}(i,k) * h_k^{-1} * \varphi(n)_k\right)$$
$$= X(i) + \left(\sum_{k=1}^{N-1} P^{-1}(i,k) * \delta(n)_k + \sum_{k=1}^{N-1} P^{-1}(i,k) * h_k^{-1} * \varphi(n)_k\right) \tag{33}$$

$\varphi(n)$ and $\delta(n)$ denotes $(N-1) \times 1$ channel noise vector and clipping noise vector respectively. SNR in optical OFDM systems can be defined as follows:

$$SNR = \frac{\sigma^2}{\delta^2 + \varphi^2} \tag{34}$$

Where the σ^2 is signal power, δ^2 is the clipping distortion power, φ^2 is the channel noise power. The SNR of i-th subcarrier can be expressed as:

$$SNR(i) = \frac{|X(i)|^2}{\left|\sum_{k=1}^{N-1} P^{-1}(i,k) * \delta(n)_k\right|^2 + \left|\sum_{k=1}^{N-1} P^{-1}(i,k) * h_k^{-1} * \varphi(n)_k\right|^2} \tag{35}$$

where the received clipping noise of i-th subcarrier is:

$$\delta_i^2 = \left|\sum_{k=1}^{N-1} P^{-1}(i,k) * \delta(n)_k\right|^2 \tag{36}$$

and the received channel noise of i-th subcarrier is:

$$\varphi_i^2 = \left|\sum_{k=1}^{N-1} P^{-1}(i,k) * h_k^{-1} * \varphi(n)_k\right|^2 \tag{37}$$

Combining equation (24), the precoding matrix P has:

$$P^*P = \frac{1}{N-1} diag\left[\sum_{j=1}^{N-1} |p(1,j)|^2, \ldots \sum_{j=1}^{N-1} |p(N-1,j)|^2\right] \tag{38}$$

Considering all the elements in the matrix has the same modulus and then normalizing all the elements, i.e., $|p(i,j)| = 1$. The equation (38) can be written as:

$$P^*P = P^{-1}P = I \tag{39}$$

Therefore, the equation (36) can be simplified as:

$$\delta_i^2 = \frac{1}{N-1} \sum_{k=1}^{N-1} p(i,k)^* * \delta(n)_k * \sum_{k=1}^{N-1} p(i,k) * \delta(n)_k^* \approx \frac{1}{N-1} \sum_{k=1}^{N-1} \left|\delta(n)_k\right|^2 \tag{40}$$

And the equation (37) can be simplified as:

$$\varphi_i^2 = \frac{1}{N-1} \sum_{k=1}^{N-1} p(i,k)^* * h_k^{-1} * \varphi(n)_k * \sum_{k=1}^{N-1} p(i,k) * h_k^{-1} * \varphi(n)_k^* \approx \frac{1}{N-1} \sum_{k=1}^{N-1} \left|\frac{\varphi(n)_k}{h_k}\right|^2 \tag{41}$$

In the process of de-precoding, the received signals are multiplied by the inverse precoding matrix. The channel noise and clipping noise are also multiplied by the inverse precoding matrix as shown in equation (33). From the equation (36) and (40), we can see the matrix operation is a way to average the total clipping noise power for each subcarrier. Therefore, the clipping noise power is equalized by precoding in each subcarrier. Similarly, the channel noise of each subcarrier is also equalized by precoding as shown in the equation (41). It is worth stressing that the precoding matrix with zero autocorrelation is the premise of equalization of channel noise and clipping noise. Combining equation (35), (40) and (41), signal power of each subcarrier is generally normalized in practical application, which means $|\boldsymbol{X}(\boldsymbol{i})|^2$ is a constant, so the noise equalization results in a uniform distribution of SNR among each subcarrier.

6. Discussion of Precoding Matrix Method Used in VLC System

Precoding matrix can reduce the clipping distortion which is beneficial to improve the BER performance. In addition, the uniform distribution of SNR among the subcarriers also can affect the BER performance. In the case of no precoding, the SNR of i-th subcarrier is the ratio of signal power to the noise power including clipping noise power and channel noise power which can be defined as:

$$\boldsymbol{SNR}(\boldsymbol{i}) = \frac{|\boldsymbol{X}(\boldsymbol{i})|^2}{\delta_i^2 + \boldsymbol{h}_i^{-1}\varphi_i^2} \tag{42}$$

In the case of precoding, from the equation (35), (40) and (41), the SNR of i-th subcarrier is:

$$\boldsymbol{SNR}(\boldsymbol{i}) = \frac{|\boldsymbol{X}(\boldsymbol{i})|^2}{\frac{1}{N-1}\sum_{i=1}^{N-1}\delta_i^2 + \frac{1}{N-1}\sum_{i=1}^{N-1}\boldsymbol{h}_i^{-1}\varphi_i^2} \tag{43}$$

If $\delta_i^2 + \boldsymbol{h}_i^{-1}\varphi_i^2 < \frac{1}{N-1}\sum_{i=1}^{N-1}\delta_i^2 + \frac{1}{N-1}\sum_{i=1}^{N-1}\boldsymbol{h}_i^{-1}\varphi_i^2$, the SNR of i-th subcarrier will be pulled down by precoding matrix and thus the BER performance of this subcarrier will be degraded. If $\delta_i^2 + \boldsymbol{h}_i^{-1}\varphi_i^2 > \frac{1}{N-1}\sum_{i=1}^{N-1}\delta_i^2 + \frac{1}{N-1}\sum_{i=1}^{N-1}\boldsymbol{h}_i^{-1}\varphi_i^2$, the SNR of i-th subcarrier will be increased by precoding matrix and thus BER performance of this subcarrier will be improved. Using the precoding matrix, the subcarriers with low SNR will get extra SNR, but the subcarriers with high SNR will lose part of SNR. Therefore, precoding matrix is a trade-off method which improves the BER performance of subcarriers with low SNR but increases the error probability of subcarriers with high SNR. The uniform distribution of SNR can be seen as transferring part SNR of subcarriers with high SNR to the subcarriers with low SNR, as a result, each subcarrier obtains an average SNR. If the average SNR is sufficient for the M-QAM decoding, the total BER performance will be improved by precoding matrix. Otherwise, the total BER performance will be degraded by precoding matrix.

In VLC OFDM transmission, the low frequency subcarriers have much higher SNR than the ones of high frequency subcarriers due to the serious fading. Precoding matrix can transfer part SNR of low frequency subcarriers to the high frequency subcarriers which is beneficial to improve the BER performance. However, in the practical VLC, the transmitting power has to meet the requirement of dimming/brightness control, so transmitting power will change in different VLC scenarios. For example, when we do not need LEDs for illumination, the transmitting power will be set to a low level to reduce the brightness. In this situation, the signal power is very small which results in a relatively low SNR for all subcarriers, so the average SNR will be small. When the average SNR is insufficient to support the M-QAM decoding, the precoding matrix will damage the BER performance.

In addition to the transmitting power, transmission distance is also a main factor for the received SNR due to the attenuation of signal power in the transmission. Furthermore, modulation format also can affect the use of precoding matrix in VLC system. To achieve the same BER performance, the higher modulation order need more SNR for decoding. In the VLC of high order modulation, the subcarriers need more SNR to support the SNR equalization which increases the difficulty of using precoding matrix. Therefore, for precoding matrix method used in DCO-OFDM VLC system, we need to consider the transmitting power, transmission distance and modulation format as a whole in order to achieve transmission performance improvement.

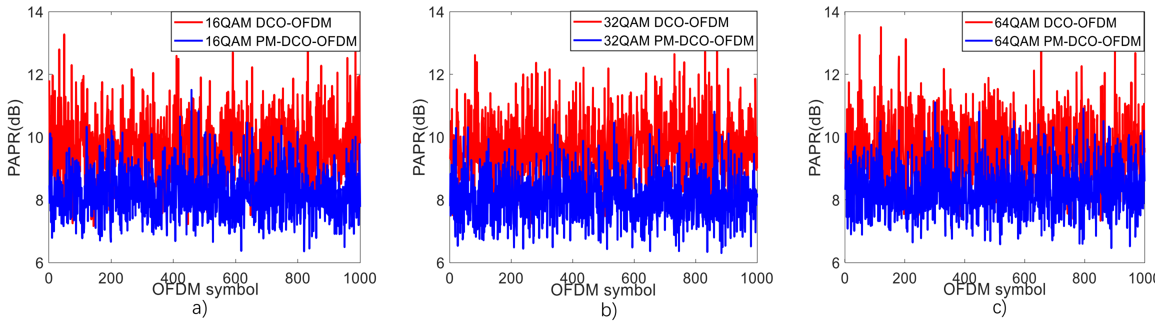


Fig. 2. PAPR of PM-DCO/DCO-OFDM symbols: a) 16 QAM and 128 subcarriers; b) 32 QAM and 128 subcarriers; c) 64 QAM and 128 subcarriers.

7. Simulation Results and Discussions

According to the equation (24), only the precoding matrix with zero autocorrelation could improve the OFDM transmission performance. In order to verify the investigation, we randomly select a sequence with zero autocorrelation. The sequence is defined as:

$$a_k = \begin{cases} exp\left[j2\pi \frac{M}{L}\left(\frac{k(k-1)}{2} + q(k-1)\right)\right], \; k = 1 \ldots L \quad L \quad is\, odd \\ exp\left[j2\pi \frac{M}{L}\left(\frac{(k-1)^2}{2} + q(k-1)\right)\right], \; k = 1, \ldots L \quad L \quad is\, even \end{cases} \tag{44}$$

where, L is the length of sequence, M and L are prime numbers, q is an arbitrary integer. The sequence has excellent autocorrelation property that

$$\sum_{k=1}^{L} a_k \left(a_{k+l}^*\right)_{mod\ L} = \begin{cases} L, & l = 0 \\ 0, & l \neq 0 \end{cases} \tag{45}$$

and $|a_k| = 1$. We rearrange the sequence with length $L = (N-1)^2$ to construct an $(N-1) \times (N-1)$ precoding matrix P. $P_{m,n}$ in the precoding matrix can be written as:

$$P_{m,n} = a_{(m-1)*(N-1)+n} \tag{46}$$

where, $k = (m-1)^* (N-1) + n$. In the simulations, M = 1, N = 128 and q = 0.

Simulations are carried out to investigate the PAPR of three types of DCO/PM-DCO-OFDM systems with different modulation formats. As shown in Fig. 2, we can observe that the average PAPR of the DCO-OFDM (the red curve) is higher than the one of the PM-DCO-OFDM (representing by the blue curve) in all situations. The average PAPR of 1000 OFDM symbols has been reduced ∼3 dB in PM-DCO-OFDM VLC system and the probability of high PAPR also has been reduced significantly. When the number of subcarriers increases, the problem of high PAPR in DCO-OFDM become more serious. However, the PM-DCO-OFDM system is robust to the PAPR when more subcarriers are adopted to achieve higher frequency efficiency.

In order to investigate the effect of precoding matrix intuitively, we also simulate the complementary cumulative contribution function (CCDF) of PAPR. Without loss of generality, we arbitrarily choose a kind of modulation format and subcarriers as shown in Fig. 3. The CCDF of PAPR in PM-DCO-OFDM VLC system is significantly reduced than the one in DCO-OFDM VLC system. From the Fig. 3. We can see the probability of high PAPR in PM-DCO-OFDM VLC system is suppressed to a certain extent.

According to [26]–[28], the noise power is assumed as additive white Gaussian noise (AWGN) with the power of −10 dBm and the VLC-OFDM signal power varies from 0 dBm to 30 dBm. Therefore, the simulated electrical SNR range is from 10 dB to 40 dB. According to [29], the parameters of OSRAM white LED are shown in the Table 1. According to [30], [31], the optimum DC bias is close to the midpoint of LED work range, so the V_{DC} is set as $0.5(V_{min} + V_{max})$. The overshooting signals

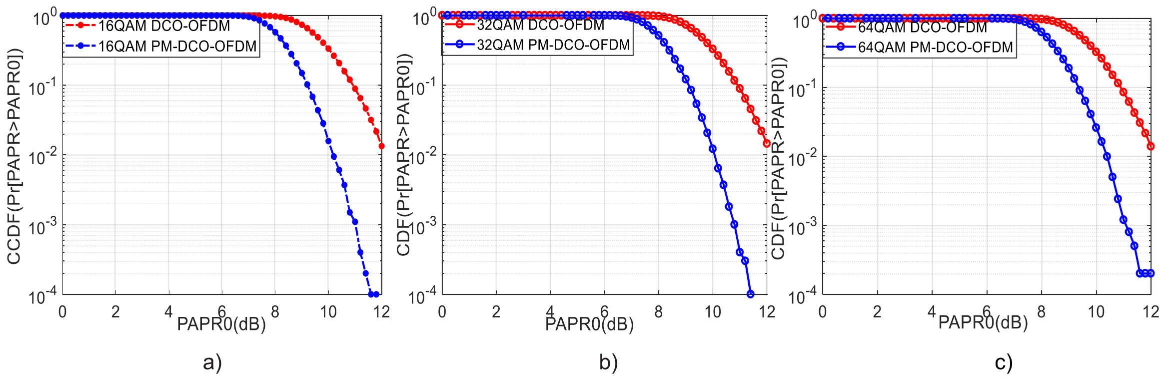


Fig. 3. CCDF of PM-DCO/DCO-OFDM symbols: 16 QAM and 128 subcarriers; b) 32 QAM and 128 subcarriers; c) 64 QAM and 128 subcarriers.

TABLE 1
LED Parameters

Parameter	Value
V_{min}	2.75v
V_{max}	4v
Lambertian order m	1
Transmitter semi-angle (θ)	1/60°
A typical luminous intensity (I_0)	17cd

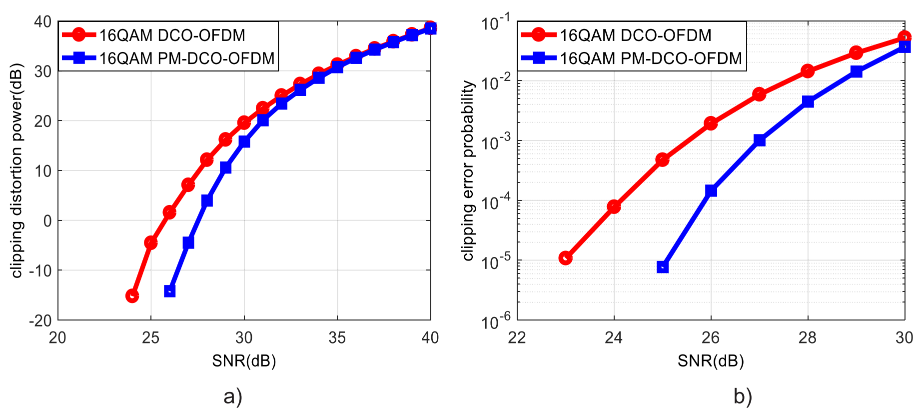


Fig. 4. a) Clipping distortion power of PM-DCO/DCO-OFDM system with 128 subcarriers; b) Clipping error probability of PM-DCO/DCO-OFDM system with 128 subcarriers.

distort in the process of clipping, which is described by clipping distortion power. In the simulation, in order to keep consistent with SNR, the clipping distortion power is expressed by decibels, as shown in Fig. 4. Compared with PM-DCO-OFDM system, the DCO-OFDM system is more likely to have clipping distortion. With the same SNR, the PM-DCO-OFDM system has less clipping distortion power, indicating more energy effectiveness in PM-DCO-OFDM system. Further, the PM-DCO-OFDM system overwhelms the DCO-OFDM system in terms of clipping error probability, as shown in Fig. 5b). In Fig. 4, the benefit of precoding matrix gets smaller when SNR is increased.

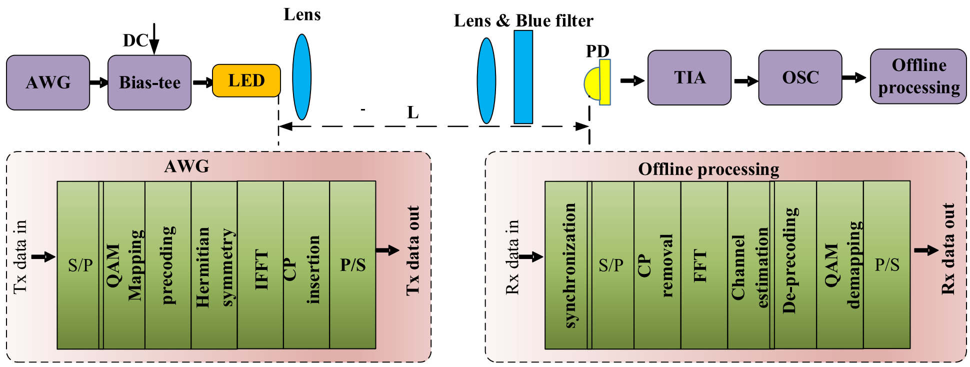


Fig. 5. Illustration of block diagrams of PM-DCO-OFDM VLC system (L is the distance between LED and PD).

The large SNR leads to a very high PAPR of most OFDM symbols. What's worse, when the high PAPR is far beyond the LED work range, even precoding matrix can't reduce the very high clipping noise. Therefore, similar clipping distortion can be found in the DCO-OFDM VLC systems with high SNR, regardless of precoding or not.

8. Experimental Results and Discussions

Figure 5 shows the experimental setup of the PM-DCO-OFDM VLC system. At the transmitter, the DSP for OFDM modulation can be depicted as follows. The original bit sequence is divided into parallel binary streams for QAM mapping and then multiply the precoding matrix. Hermitian symmetry is compulsory to generate the real-valued OFDM signal. After IFFT, enough length of cyclic prefix (CP) is inserted to mitigate the effect of inter symbol interference (ISI). After offline signal processing at the transmitter, the generated signal was feed into an arbitrary waveform generator (AWG, Tektronix AWG7122B) to generate the analog OFDM signal. The electrical OFDM signals from AWG is then superimposed on the DC bias via a bias-tee. The optical light source is a commercial phosphor-LED. In order to achieve light-path collimation, a pair of bi-convex lenses are fixed in front of the LED and PD. At the receiver end, a blue filter is placed in front of the commercial large-area PD (Hamamatsu S6968) to eliminate the slow phosphorescent components. The detected signal from PD is amplified by a trans-impedance amplifier (TIA) circuit and then captured by a real-time oscilloscope (Tektronix DPO4104B) for offline signal processing. During the offline DSP, CP of the electrical signal is removed after synchronization and S/P. In order to estimate channel frequency response and SNR of received signals on subcarriers, channel estimation is adopted after fast Fourier transform (FFT).

Based on the theoretical analysis, the precoding matrix method can achieve a uniform distribution of SNR among subcarriers which is beneficial to improve the BER performance of high frequency subcarriers. However, it will deteriorate the overall BER performance when the channel quality cannot support the SNR equalization in M-QAM OFDM transmission. In the experiments, we aim to investigate the validity of precoding matrix method, as well as the application scenario in VLC. Transmitting power, modulation format and transmission distance are the three key factors that affect the performance of precoding matrix. For the modulation, we adopt three kinds of format, i.e., 16 QAM, 32 QAM and 64 QAM. For the transmitting power, we set different values of bias current to emulate the different initial SNR with the consideration of dimming/brightness control. Furthermore, we repeat the experiments in different transmission distance to emulate the different application scenarios of VLC. For various OFDM schemes, the experimental parameters remain the same for a fair comparison, including 256 block size for FFT, 107 data subcarriers, training sequence (TS) with length of 10, and CP with length of 11. For the precoding matrix, $M = 1$, $N = 107$ and $q = 0$. The AWG has the sampling rate of 200 MSa/s, which loads the 2 times upsampled OFDM signal

TABLE 2
Key Parameters of Experiments

Parameter	Value
Modulation scheme	64/32/16-QAM
IFFT/FFT size	256
Cyclic prefix length	11
Training sequence length	10
AWG sampling rate	200 MS/s
DPO sampling rate	1 GS/s
Peak-to-peak voltage (Vpp)	1V
Number of data subcarriers	107
OFDM symbols per frame	130
Oversampling factor	2
LED maximum allowed forward current	500mA
Bias current	0.01~0.18A
Bias voltage	5.215~6.283V
Transmission distance	1/0.8/0.6m

with 41.8 MHz signal bandwidth. The detected signal are recorded by a DPO at a sampling rate of 1 GS/s. The key parameters of experiment are given in Table 2.

8.1 BER Performance of DCO/PM-DCO-OFDM VLC

Figure 6a), b), c) show the BER comparison of system (i) DCO-OFDM, (ii) PM-DCO-OFDM under different transmission distances. It is seen that with the increase of bias current, the PM-DCO-OFDM system can provide enhanced BER performance compared to the system without precoding matrix. In Fig. 6a), for 16 QAM, even though the value of bias current is very low, the BER performance also can be improved in PM-DCO-OFDM. However, for 32 and 64 QAM, the precoding matrix can't improve or even degrades the BER performance in the case of low bias current. Compared with 16 QAM, 32 and 64 QAM need more SNR to achieve the same BER performance. However, under the low bias current, all subcarriers have a relatively low SNR which leads to a poor average SNR. What' worse, the average SNR is insufficient to support 32 or 64 QAM decoding, so it could not help to improve the BER performance of high frequency subcarriers significantly. Instead, precoding matrix degrades the BER performance of low frequency subcarriers. Therefore, without enough bias current, the precoding matrix can degrade the BER performance of VLC OFDM transmission. When we decrease the transmission distance, the channel quality can be improved due to the decrease of signal power attenuation and thus the ability of precoding matrix in improving the BER performance is more obvious. The validity of precoding matrix is most evident in Figure 6c) and the BER performance of three kinds of QAM modulation can be reduced from 1.17×10^{-3} to 2.47×10^{-4}, 2.63×10^{-3} to 3.89×10^{-4}, and 2.76×10^{-3} to 4.89×10^{-4}, respectively.

The SNR profiles of the 64 QAM DCO/PM-DCO OFDM system is depicted in Fig. 6d). Compared with DCO-OFDM technique, precoding matrix can achieve a relatively uniform SNR profile, which improves the robustness to high frequency fading in the band-limited system and results in the BER reduction in a), b), c). The uniform SNR profile is attributed to the channel noise and clipping noise equalization which means the precoding also can be used in frequency-selective fading systems.

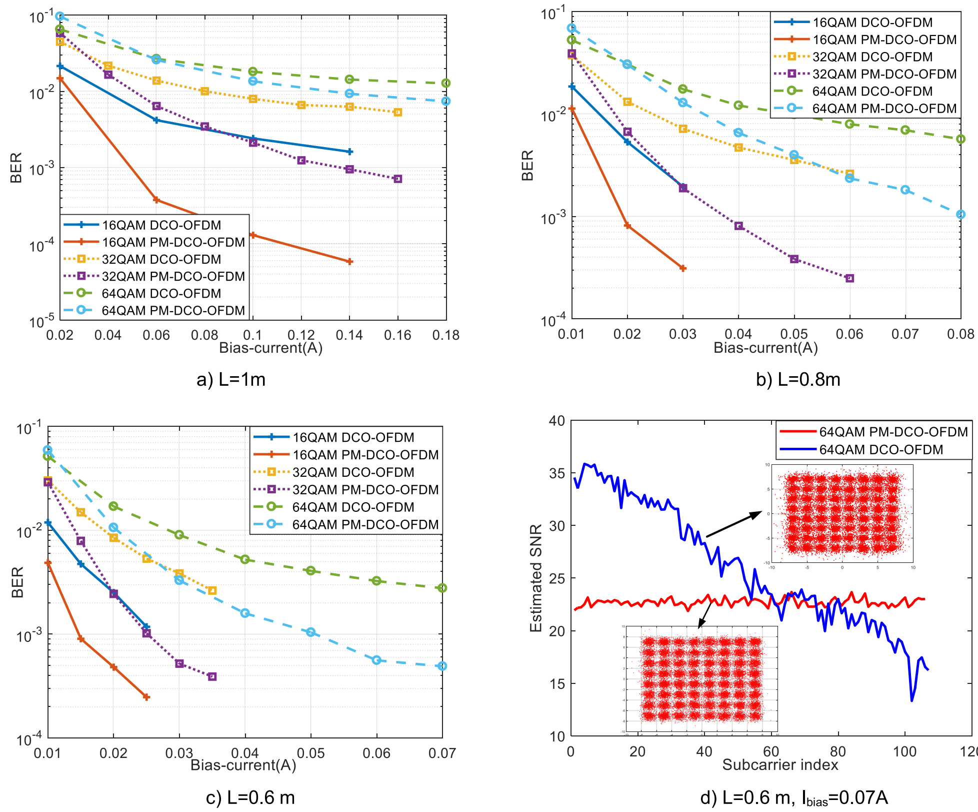


Fig. 6. a), b), c) BER of PM-DCO/DCO-OFDM VLC system; d) the Estimated SNR profile after transmission.

From the experimental results, we can get some basic conclusions: 1) with enough bias current, precoding matrix is beneficial to improve the BER performance in OFDM VLC system; 2) considering the dimming/brightness control, not all cases of VLC can support precoding operation; 3) the precoding matrix used in the VLC of high-order QAM or long transmission distance need more bias current.

8.2 Performance of PM-DCO/DFT-Spread OFDM VLC

DFT-Spread also can be regarded as a precoding method to realize the uniform SNR distribution among subcarriers, so we compare the precoding matrix with DFT-Spread in the aspects of PAPR, BER performance and complexity. Figure 7 shows the PAPR comparison of two methods under different kind of modulation format. It is seen that two methods provide approximately the same capability in reducing the high PAPR. The PAPR can be reduced about 2∼3 dB by these two methods.

Figure 8a) shows the BER comparison of two methods under different values of bias current. It is seen that two methods can provide approximately the same boost in BER performance for all cases of VLC OFDM transmission. The SNR profiles of the 64 QAM PM-DCO/DFT-Spread OFDM system is depicted in Fig. 7b). Most the SNRs of subcarriers are maintained around 20 which means the two method have the same effect on SNR equalization. The experiment results demonstrate that the two methods have roughly equivalent ability of improving the BER performance in OFDM VLC systems.

In the experiments, both methods just need an extra matrix operation in the DSP of transmitter and receiver side, so we think two methods have similar implementation complexity in most cases. In some cases when the FFT can be used, the DFT-Spread method has lower implementation

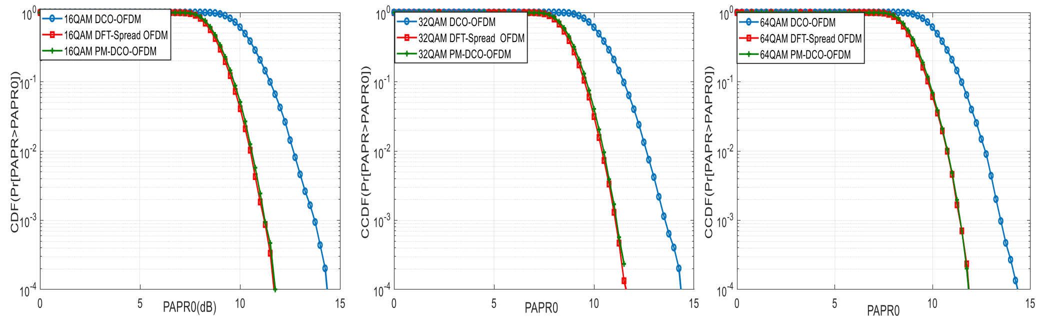
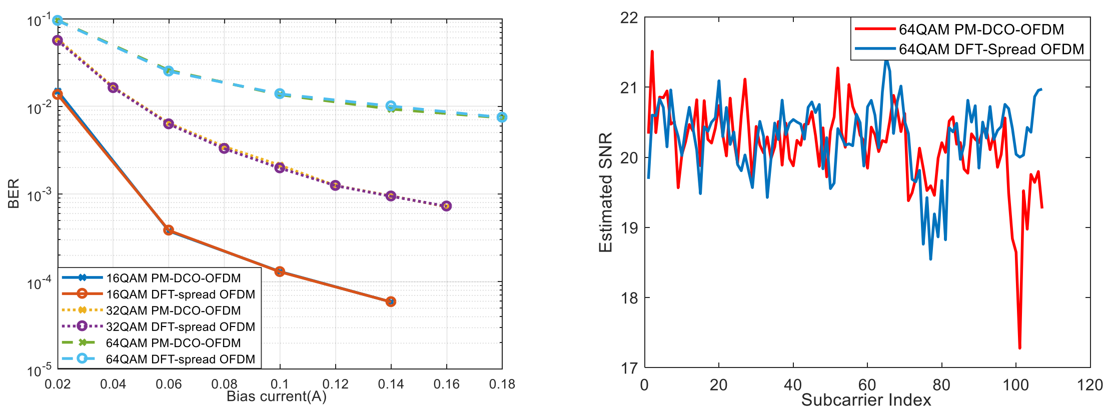


Fig. 7. CCDF of PM-DCO/DFT-Spread OFDM VLC system.



a) L=1m

b) L=1 m, I_{bias}=0.18A

Fig. 8. a) BER of PM-DCO/DFT-Spread OFDM VLC system; b) the estimated SNR profile after transmission.

complexity. In terms of method improvement, both methods can be designed and updated according to the channel configuration.

9. Conclusions and Discussions

In this paper, we investigate the theory of precoding matrix used in DCO-OFDM VLC system. Based on the theoretical analysis, the precoding matrix with zero autocorrelation can reduce the possibility of high PAPR and clipping distortion, as well as achieve uniform SNR distribution among subcarriers. Furthermore, the relatively uniform SNR distribution can relieve the fading of the high frequency subcarriers which is beneficial to improve the BER performance. However, the use of precoding method should consider whether the channel quality can support the SNR equalization in M-QAM OFDM transmission. From the simulation results, the PAPR is decreased about ∼3 dB in PM-DCO-OFDM VLC system. Furthermore, experimental results demonstrate that the BER performance is improved significantly by precoding matrix in the case of OFDM VLC transmission with enough bias current. The low value of bias current can't support predcoding matrix under 32 QAM or 64 QAM OFDM transmission. For 16 QAM at a distance of 0.6, 0.8 and1 m, system BER can be significantly reduced from $\sim 10^{-3}$ to $\sim 10^{-5}$ by precoding matrix. For 32 QAM or 64 QAM, not all case of VLC can support predcoding matrix. Compared with DFT-Spread method, the precoding matrix can provide much of the same BER performance and complexity. From the experiment results, only with enough transmitting power, PM-DCO-OFDM is an effective technique to realize high-speed transmission in VLC system.

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