A reduced PAPR hybrid OFDM visible light communication system

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Abstract
Orthogonal frequency division multiplexing (OFDM) is used by visible light communication (VLC) systems. Its main goal is to lessen inter-symbol interference’s negative impacts. As a result, a lot of bandwidth and a high data rate are transmitted. Using OFDM-based VLC systems, nonetheless, have a high peak-to-average power ratio (PAPR). This research presents a new VLC system for indoor applications that reduces the PAPR while maintaining an acceptable bit error rate (BER). To achieve this, a hybrid pre-coding technique-based PAPR reduction solution is proposed; Vander-monde like matrix (VLM) combined with Gaussian matrix (GM). This technique takes advantage of both VLM and GM as a two stages for the signal to simultaneously reduce the PAPR and save the BER from damage. According to the results, the proposed solution (VLM in conjunction with GM) lowers the PAPR to 9.5 dB. Our system performs better when compared to other systems like discrete cosine transform (DCT), GM, VLM, DCT&GM, and original OFDM by 27%, 25%, 11%, 20%, and 34%, respectively.

Keywords Visible light communication (VLC) · Orthogonal frequency division multiplexing (OFDM) · Peak-to-average power ratio (PAPR) · Complementary cumulative distribution function (CCDF) · Discrete cosine transform (DCT) · Vander-monde like matrix (VLM) · Gaussian matrix (GM)
1 Introduction

VLC systems use OFDM to lessen the influence of intersymbol interference (ISI) and achieve high data transmission speeds and large bandwidth. VLC systems based on OFDM, nonetheless, have a high peak-to-average power ratio (PAPR). The LED transmitter clips the optical signal due to the high PAPR, resulting in considerable clipping distortion. Clipping and filtering, selective mapping (SLM), partial transmit sequence (PTS), pre-coding, and post-coding are only a few of the PAPR reduction strategies that have been proposed (Sharif 2019). By using the clipping technique, the signal’s amplitude is lowered to a certain level, resulting in in-band distortion. The techniques of selective mapping (SLM) and partial transmit sequence (PTS) both reduce the likelihood of a high PAPR. Sending side information to the receiver is required, which reduces bandwidth efficiency. Pre-coding and post-coding methods reduce the PAPR without affecting BER performance, requiring more processing, or requiring side information. Some techniques to pre-coding, such as Walsh-Hadamard Transform (WHT), DCT and VLM transform, have been investigated to lower an OFDM signal’s high PAPR (Mhatre and Khot 2015).

VLC is a method that fully utilizes visible LEDs for the simultaneous transmission of data at very high speeds and illumination. It can offer solutions for a variety of applications, including vehicular networks, underground and underwater networks, wireless local area networks (WLAN), wireless personal area networks (WPAN), wireless body area networks (WBANs), heterogeneous networks, indoor localization and navigation (where current GPS is not available), and more (Ahmed et al. 2020).

Optical OFDM modulation techniques have been thoroughly investigated for VLC systems in order to enable high-speed transmission (Chaaban et al. 2022). OFDM provides power efficiency, immunity to frequency selective fading channels, multipath delay spread tolerance, and a noteworthy high spectral efficiency. The signal sent via the VLC link should be both real-valued and positive-valued because a VLC system is based on intensity modulation and direct detection (IM/DD). O-OFDM comes in a variety of forms that are utilized in VLC systems: DC biased O-OFDM (DCO-OFDM), asymmetrically clipped O-OFDM (ACO-OFDM), Flip-OFDM, and asymmetrically clipped DC-biased O-OFDM (ADO-OFDM). In a DCO-OFDM system, the unipolar signal is created by applying a DC bias to the actual optical OFDM signal. Only the odd subcarriers in the ACO-OFDM system transmit data symbols because all of the even subcarriers are zeroed out. In Flip-OFDM, the positive and negative halves of the bipolar OFDM are sent independently over two frames. The advantages of ACO-OFDM and DCO-OFDM are combined in ADO-OFDM. Because of this, the subcarriers are divided into odd and even. For ACO-OFDM, odd subcarriers are assigned, while even subcarriers are used for DCO-OFDM (Hameed et al. 2021).

To generate a positive signal in ACO-OFDM, clipping the signal to zero is required (Chen et al. 2012). The design of the OFDM systems still faces several difficult problems, nevertheless. The high PAPR of transmitted OFDM signals is one of the main issues. The PAPR, which is caused by the sum of orthogonal subcarriers produced at the transmitter by the IFFT operation, is the ratio of maximum power to average power. The OFDM signal should change within a particular range due to the nonlinear properties of the LED in the transmitter, or the PAPR should be reduced accordingly. Otherwise, the signal will be cut at the transmitter, resulting in a poor BER performance. For both original and O-OFDM signals, many PAPR reduction methods have been published. Clipping and filtering, nonlinear
companding, selective mapping (SLM), partial transmit sequence (PTS), and pre-coding are some of the techniques used (Sharif 2019).

Multipath distortion, which results in ISI interference and lowers the signal-to-noise ratio (SNR), is also a problem for VLC. Thus, OFDM was used for VLC to address the ISI problem (Raj et al. 2021). Because OFDM has a high PAPR, some earlier proposed systems used either VLM or GM to reduce PAPR. VLM reduces the autocorrelation of the symbols, lowering the PAPR. Furthermore, GM lowers the signal’s peak and, as a result, lowers the PAPR.

In this study, we introduce a novel hybrid PAPR reduction technique that uses VLM and GM to modify the signal. This method employs both VLM and GM as two signal stages to concurrently lower PAPR and protect the BER from damage. To further increase the PAPR reduction capabilities, we suggest a new OFDM structure based on VLM pre-coding before the IFFT stage and GM after the IFFT. A real Gaussian matrix transform and VLM transform are used to reduce the PAPR of the O-OFDM signal. VLM is one of the pre-coding techniques that minimizes PAPR without compromising BER performance. Other well-known precoding techniques include WHT, DCT and Discrete Hartley Transform (DHT) (Mohammed et al. 2021). Our system is also compared to other systems to show its superiority. After IFFT, the time-domain O-OFDM signal is multiplied with various Gaussian matrices to determine the PAPR of the resulting signals. The receiver is then given side information that includes the matrix’s order that produces the lowest PAPR.

The paper is structured as follows. Section 2 defines the PAPR and explains the O-OFDM system’s basic operating principle. The PAPR reduction techniques are explained in Sect. 3. The VLM pre-coding technique and DCT pre-coding technique and the Gaussian orthogonal matrix transform are investigated for DCO-OFDM in Sect. 4. In Sect. 5, It is demonstrated how to lower the PAPR of an OFDM-based VLC. Mathematical model and simulation results are displayed and discussed in Sect. 6. Finally, concluding comments are presented in Sect. 7.

2 System model

The O-OFDM variations can be categorized as coherent detection optical OFDM (CO-OFDM) or direct detection optical OFDM (DDO-OFDM), depending on how the detection is carried out (DDO-OFDM). There are two varieties of DDO-OFDM: linearly mapped (LM-DDO-OFDM), in which the optical OFDM spectrum is a replica of the OFDM baseband signal, and nonlinearly mapped (NLM-DDO-OFDM), in which the optical OFDM spectrum is distinct from the OFDM baseband spectrum. Systems that fall within the NLM-DDO-OFDM category are intensity modulated optical OFDM systems, the optical signal’s intensity is used to represent the electrical signal. Multimode optical fibers, plastic optical fiber systems, and optical wireless systems are all examples of this approach in action. To be intensity modulated without information loss using the IM/DD approach, the input signal must be true and positive. This is why limitations like Hermitian symmetry are imposed at the IFFT block’s input.

Figure 1 depicts a typical O-OFDM and IM/DD communication circuit. The core of the transmitter/receiver is the IFFT/FFT block. In essence, the Fourier Transform (FT) transforms a time-domain input into a frequency-domain signal. There are different versions of FT used based on the application of the network. In the traditional FT,
boundless time/frequency domain continuous signals are transmitted. To make signal processing simpler, signals are sampled in the traditional transform. Many applications of digital signal processing use the fast algorithms FFT and IFFT to effectively obtain the discrete Fourier transform (DFT) and inverse discrete Fourier transform (IDFT). OFDM systems use the IFFT at the transmitter side for an efficient implementation of the modulated signal, while the FFT is used at the receiver side for efficient demodulation. The IFFT takes a complex vector as input \( X = (X_0, \ldots, X_{N-1}) \), where \( X \) is the modulated data vector, and \( N \) is the number of subcarriers (Kabli and Faqihi 2018).

It is self-evident that the output of the IFFT block is a complex vector in the general situation, which is inappropriate for intensity modulation, since the modulating signal should be real and positive. It is necessary to confine the input vector \( X \) to have Hermitian symmetry in order to meet this condition. As a result, the input vector \( X \) has the shape (Sharif 2019)

\[
X_i = X^*_i, 0 < i < \frac{N}{2}
\]  

(1)

where \( X^* \) is the complex conjugate of \( X \).

The active subcarriers’ transpose-conjugate duplicate is then added to finish the other half of the IFFT frame, where the new IFFT input vector’s components \( X_H \) are

\[
X_H = [X_0, X_1, X_2, \ldots, X_{N-1}, X_N, X^*_N, X^*_{N-1}, \ldots, X^*_2, X^*_1]
\]  

(2)

and the DC component is \( X_0 = X_N = 0 \).

As a result, the OFDM symbol produces a 2 N-point IFFT output. In the time domain, the IFFT algorithm outputs of the discrete OFDM symbol vector, \( x_k \), are provided by

\[
x_k = \frac{1}{N} \sum_{h=0}^{N-1} X_{H,h} e^{2\pi i k h / N} \text{ for } 0 \leq k \leq N - 1
\]  

(3)

where \( h \) is the \( h \)th subcarrier symbol of \( X_H \).

The OFDM symbol, \( x_k \), is a period-based periodic function, \( T_p = 1/\Delta f \), and \( \Delta f \) the subcarrier spacing, as determined by \( \Delta f = B/(N - 1) \) and \( B \) is the signal modulation bandwidth. Consequently, a high PAPR still exists in the real-valued time-domain OFDM signal envelope (Tahkoubit et al. 2021).

The continuous time PAPR OFDM is the transmitted signal’s maximum instantaneous power divided by its average power.
\[ PAPR = 10 \log_{10} \frac{\max|x_k|^2}{E|x_k|^2} \]  

where \( \max|x_k|^2 \) is the greatest OFDM signal power value and \( E[.] \) is the average of those \( (x_k) \) values.

The most common statistic for showing a drop in PAPR is known as the CCDF of a PAPR, and it measures the likelihood that the PAPR of an OFDM frame would surpass a particular threshold value, \( PAPR_0 \) (Abdulkafi et al. 2017). Hence, it is defined as (Freag et al. 2018)

\[ CCDF = \text{Prob}(PAPR > PAPR_0) \]  

### 3 PAPR reduction techniques

Indoor VLC systems can benefit greatly from OFDM, however there are still several problems that need to be fixed. Because of the enormous PAPR of the OFDM signal, the nonlinear characteristics of LED have a significant impact on the effectiveness of VLC systems using IM/DD with OFDM modulation. Given the Gaussian distribution and significant PAPR of the signal, OFDM needs a large linear operational dynamic range.

### 4 PAPR reduction in OFDM systems using pre-coding with Gaussian matrix

Pre-coding and post-coding methods that don’t impair BER performance and don’t call for side information or extra processing are used to lower the PAPR. The discrete cosine transform (DCT) and the VLM transform are two pre-coding methods, have been considered to lower the high PAPR of an OFDM signal (Sharif 2019). The VLM pre-coding approach for optical OFDM signals is recommended in this research.

#### 4.1 Discrete cosine transform (DCT)

The majority of the signal energy is concentrated in the first few samples because of the exceptional energy compression property of the DCT, leaving the remaining samples with very little energy. The ISI resulting from such small amplitude samples is anticipated to be very small when DCT pre-coding is used prior to data transmission, leading to enhanced BER performance. The primary premise of the DCT approach is that the transferred data is first transformed by the DCT matrix. The IFFT unit subsequently processes the modified data. The input to the IFFT stage must have a Hermitian symmetric structure in order to produce a real output. The DCT is a real transform that uses the \( K \times K \) DCT matrix to turn modulated data, \( X \), into a new transform-domain signal, \( F_{n,m} \) is given by (Wang et al. 2014)

\[
F_{n,m} = \begin{cases} 
\frac{1}{\sqrt{K}} & n = 0, \quad 0 \leq m \leq K - 1 \\
\sqrt{2/K} \cos \left( \frac{(2m+1)n\pi}{2K} \right) & 1 \leq n \leq K - 1, \quad 0 \leq m \leq K - 1 
\end{cases}
\]  

(6)
$F$ stands for the DCT matrix, where the row and column entries are denoted by $n$ and $m$, respectively. The DCT pre-coding matrix follows the new sequence $X_{DCT}$ that can be represented as (Wang et al. 2014).

$$X_{pre} = X_{DCT} = FX$$  \hspace{1cm} (7)

where $X_{pre}$ is the new sequences after the pre-coding process.

### 4.2 Vander-monde like matrix (VLM)

The goal of PAPR reduction utilizing the VLM transform is to lower the input sequence’s autocorrelation before the IFFT operation is used, hence lowering the PAPR of the OFDM signal. At the specified nodes, the monomials $(1, x, x^2, \ldots, x^n)$ can be used to generate the VLM. A VLM is created by replacing monomials with polynomials $(p_0(x), p_1(x), \ldots p_n(x))$

The following are two types of VLMs that can be created (Sharif. 2019)

$$p_{mn} = \sqrt{\frac{2}{N+1}} \cos\left(\frac{\pi}{N-1} (m-1)(n-1)\right)$$  \hspace{1cm} (8)

$$p_{mn} = \sqrt{\frac{2}{N+1}} \cos\left(\frac{\pi}{N-1} (m-1)\left(n - \frac{1}{2}\right)\right)$$  \hspace{1cm} (9)

where $p$ is Vander-monde matrix in the $m$th row and $n$th column ($0 \leq m, n \leq n - 1$).

The PAPR reduction performance of both matrices is the same. Therefore, in our simulation, we simply use the first kind of VLM transform. After the VLM precoding matrix, the new sequences $X_{VLM}$ can be represented as (Sharif 2019)

$$X_{pre} = X_{VLM} = p_{mn}X$$  \hspace{1cm} (10)

### 4.3 Gaussian matrix

The proposed GM approach is based on the 1-dimensional weighted method concept. To begin, we create a sequence of 2-dimensional random Gaussian matrices called $G$. Each is a $m \times n$ matrix, where $i$ is the number of candidate matrices, and the pseudorandom values are drawn from the standard normal distribution. After that, the time-domain O-OFDM signal is created and multiplied by multiple matrices to improve performance. All obtained sequences’ PAPRs are calculated, and the candidate matrix that minimizes the PAPR is chosen as shown in (Zhang et al. 2017; Sharifi and Azarnia 2020)

$$G \times x = s$$  \hspace{1cm} (11)

where $G = \begin{bmatrix} g_{1,1} & g_{1,2} & \cdots & g_{1,n} \\ \vdots & \vdots & \ddots & \vdots \\ g_{m,1} & \cdots & g_{m,n} \end{bmatrix}, x = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}, s = \begin{bmatrix} s_1 \\ \vdots \\ s_m \end{bmatrix}$.

The parameter $s$ has a length of $m$ and is the new OFDM frame.

To create each discrete signal $s$ in the new OFDM a row from $G_{M \times N}$ is multiplied by the corresponding element of the original $x(n)$. The performance of the suggested technique is determined by the Gaussian matrix element. Depending on the Gaussian matrices employed, there are different levels of PAPR reduction, however such a reduction is...
possible for all DCO-OFDM signals. $S_i(n)$ only selects the produced sequence with the minimum PAPR for transmission. Meanwhile, $G_i$ that corresponds to the minimum PAPR of $S(n)$ is chosen and delivered as side data. Furthermore, when evaluating the OFDM system’s transmission efficiency, Because the generated $S(n)$ has similar length as the original $x(n)$ The Gaussian matrix in the time domain is selected as a square matrix, $G_{M\times N}$, to avoid bandwidth penalty.

5 PAPR of OFDM-based VLC

The PAPR of discrete time VLC-OFDM signal $\hat{x}_n$ is calculated as

$$PAPR(dB) \approx 10 \log_{10} \frac{\max_{0 \leq n \leq N_{\text{max}}} \left| \hat{x}_n \right|^2}{E \left[ \left| \hat{x}_n \right|^2 \right]}$$

(12)

$E \left[ \cdot \right]$ stands for statistical expectation.

Figure 2 shows the new proposed hybrid system for VLC, which uses both pre-coding techniques and Gaussian matrix together to reduce the PAPR. The proposed blocks are drawn in grey.

At the transmitter, IM is employed. To create the new complex symbols $X = [X_0, X_1, \ldots, X_{N-1}]^T$ the incoming binary data are transferred to a digital modulator (M-QAM). The vector $X$ is transformed into a new vector $X_{\text{pre}}$ by a pre-coder matrix.

$$X_{\text{pre}} = V \times X = [X_{\text{pre}0}, X_{\text{pre}1}, \ldots, X_{\text{pre}M-1}]^T$$

(13)

$V$ is the pre-coding matrix. $V = F$ when using DCT and $V = \mu_{mm}$ when using VLM. The complex vector is subjected to Hermitian symmetry, $X_{\text{pre}}$, to create a real-valued OFDM signal. The output from Hermitian symmetry when it comes to the IFFT operation $x_{\text{IFFT}} = \text{IFFT}(X_{\text{pre}})$ to create the time-domain symbols. The Gaussian matrix is used to multiply the IFFT output symbols. A cyclic prefix (CP) is added to eliminate the ISI. Due to the fact that the OFDM time-domain signal must be both real and positive, a DC bias is

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**Fig. 2** New hybrid OFDM-based VLC system block diagram
used. The forward signal, \( y(t) \), turns the magnitude of the input electric signals, \( y(t) \), into optical intensity.

A wireless optical channel with impulse response, \( h(t) \), transmits the received OFDM signal. So, \( h(t) \) is defined as

\[
y_f(t) = Rx(t) \otimes h(t) + w(t)
\]

where \( x(t) \) is the optical power, \( R \) is the photodetector (PD) responsivity, \( \otimes \) represents the circular convolution, and \( w(t) \) is the electrical domain’s additive white Gaussian noise (AWGN).

The most common paradigm for wireless infrared communication systems is one in which high amounts of ambient infrared radiation are the main source of degradation. It is possible to filter out the ambient signals, which are primarily DC. They do, however, cause shot noise in the detector, which is well-modeled as AWGN. The performance in a flat channel is the topic of this paper. As a result, we suppose that \( h(t) = 1 \) (Freag et al. 2018).

Direct detection (DD) is used on the receiver side. The PIN PD converts the received optical power into an electrical signal’s amplitude. The CP has been deactivated. The inverse of a Gaussian matrix is used. After that, FFT is used. After the FFT, the inverse pre-coding is done. M-QAM demodulation is carried out. After the parallel to serial (P/S) conversion, data signals are successfully received.

### 6 Simulation results and discussion

Table 1 shows the values of parameters used in our simulation.

| Simulation parameters               | Value(s) |
|------------------------------------|----------|
| Modulation type                    | 4 QAM    |
| OFDM symbols                       | 10,000   |
| No. of data subcarriers            | 48       |
| FFT size                           | 128      |
| Guard interval                     | 16 samples |
| Total number of subcarriers        | 144      |

The CCDF of the PAPR for the GM technique is shown in Fig. 3. The efficiency of various PAPR reduction approaches is evaluated by CCDF, as previously stated. The GM method is compared to the traditional OOFDM system in this simulation (without utilizing the PAPR reduction method). In comparison to the typical OOFDM system, CCDF \( = 10^{-3} \) results in a 14% PAPR reduction.

In Figs. 4 and 5, we apply the pre-coding method, which involves multiplying the frequency domain base band modulated signals by an adjustable square matrix. The main objective is to minimize the autocorrelation of the symbols in order to lower the high PAPR. For a DCO-OFDM system, Fig. 4 demonstrates the CCDF of the PAPR for the original OOFDM (without PAPR reduction), the DCT, and the suggested DCT with a Gaussian matrix. As shown, the suggested system outperforms the traditional O-OFDM signal and DCT pre-coding ways in terms of PAPR. When CCDF \( = 10^{-3} \), the suggested scheme’s PAPR is approximately 3 dB (18%) lower than the original O-OFDM signal and 1.2 dB (9%) lower than the DCT pre-coding approach.
For a DCO-OFDM system, Fig. 5 illustrates the CCDF of the PAPR for original O-OFDM (without PAPR reduction), VLM, and the suggested VLM with a Gaussian matrix. It should be mentioned that the suggested strategy outperforms the traditional O-OFDM signal and VLM pre-coding ways in terms of PAPR. The PAPR of the proposed approach is roughly 5 dB (34%) less than the original O-OFDM signal and 1.2 dB (11%) less than the VLM pre-coding method when CCDF = $10^{-3}$.

Table 2 summarizes the comparison between the proposed scheme, the OOFDM signal, the GM method, the DCT method, the VLM method and the new proposed ones which are the DCT with GM method and the VLM with GM method.

We need to know how the system affects the BER, thus Fig. 6 displays the BER performance of the suggested technique versus signal-to-noise ratio (SNR) for $N=128$ and 4-QAM modulation for OFDM, OFDM with DCT and OFDM-DCT with GM. The SNR ranges from 0 to 21 dB on the AWGN channel. As demonstrated, the suggested approach not only drastically lowers the PAPR but also maintains the BER performance.
Figure 7 demonstrates the proposed method’s BER performance vs signal-to-noise ratio (SNR) for N = 128 with 4-QAM modulation for OFDM, OFDM with VLM, and OFDM VLM with GM for OFDM, OFDM with VLM, and OFDM VLM with GM. On the AWGN channel, the SNR values range from 0 to 21 dB. It is evident that the suggested technique not only reduces the PAPR but also enhances BER performance.

The collected findings show that the proposed approach greatly minimizes the PAPR in the transmitter without impairing the BER performance.

### 7 Conclusion

This research provides new hybrid strategies for lowering the PAPR of OFDM-based VLC systems without sacrificing their BER performance. When DCT is used only with OFDM, the PAPR is decreased by approximately 10%, and when VLM is used only, the PAPR is lowered by about 26%, making it better than DCT. When GM is used only after IFFT, the PAPR is reduced by about 12%. The DCT or VLM transform is combined

![Performance comparison of the original and suggested OFDM-based VLC systems employing a Gaussian matrix-based VLM](image)

### Table 2 PAPR reduction for the new hybrid system

| System type | PAPR value (dB) | % Reduction compared to original OFDM | % Reduction of proposed system as compared to other systems |
|-------------|----------------|---------------------------------------|----------------------------------------------------------|
| Original OFDM | 14.5 | – | 34 |
| DCT | 13.1 | 10 | 27 |
| GM | 12.8 | 12 | 25 |
| VLM | 10.7 | 26 | 11 |
| DCT and GM | 11.9 | 18 | 20 |
| VLM and GM (present work) 4-QAM | 9.5 | 34 | – |
| Reference (Hameed et al. 2021) 16-QAM | 1.8 | 71 |
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To further increase the PAPR reduction, a new OFDM structure is proposed based on DCT or VLM pre-coding before the IFFT stage and Gaussian matrix after the IFFT stage. The PAPR is reduced by 34% for VLM with GM and 18% for DCT with GM with the new structure. When compared to existing systems such as DCT, GM, VLM, DCT & GM, and original OFDM, our system outperforms them by 27%, 25%, 11%, 20%, and 34%, respectively. This guarantees the proposed system’s superiority.

Authors’ contribution BT, HAF, MHA, MM have directly participated in the planning, execution, and analysis of this study. BT drafted the manuscript. All authors have read and approved the final version of the manuscript.

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Data availability  The data used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest  The authors declare that they have no competing interests.

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