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PAPR Reduction in Optical OFDM Using Lexicographical Permutations With Low Complexity

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ABSTRACT Efficient utilization of the spectrum, increased resilience to inter-symbol interference (ISI) and simpler channel equalization are becoming important considerations in the design of wireless communication systems including visible light communication (VLC) systems. In this regard, orthogonal frequency division multiplexing (OFDM) has become a preferred modulation technique in wireless communication systems design. However, one of its major challenges is the high peak-to-average power ratio that leads to major inefficiencies. Symbol position permutation (SPP) is a distortion-less technique that achieves substantial PAPR reduction without BER degradation. However, the existing works focus on PAPR reduction using SPP for the radio frequency (RF) OFDM and the use of this technique in optical OFDM is not properly investigated. Therefore, in this paper, we present a new PAPR reduction technique based on lexicographical permutations called lexicographical symbol position permutation (LSPP) for PAPR reduction in direct current optical OFDM (DCO-OFDM). The proposed scheme is less complex than the conventional selective mapping (CSLM) scheme since there is no multiplication of the phase sequences with the DCO OFDM symbol to generate the candidate signals. We further introduce a new way of reducing the complexity by introducing a threshold PAPR and demonstrate that the complexity in terms of inverse fast Fourier transform (IFFT) operations can be reduced substantially depending on the selected threshold and the number of candidate signals.

INDEX TERMS CCDF, DCO-OFDM, lexicographical permutations, PAPR, VLC.

I. INTRODUCTION

Visible light communication (VLC) has lately attracted consideration from researchers in academia, industry and governments around the globe due to its tremendous advantages such as interference-free communication, high levels of security, low cost due to the utilization of the license-free spectrum and availability of light-emitting diodes (LEDs) used for communication [1]–[3].

To attain the higher data rates required nowadays, multi-carrier modulation techniques such as orthogonal frequency division multiplexing (OFDM) have been considered for practical implementation in VLC systems [4], [5].

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In addition to the higher data rates, OFDM also can combat inter-symbol interference (ISI) in a diffuse optical channel without the need for complex equalization filters at the receiver [6].

Most of the practical VLC systems currently deployed use intensity modulation direct detection (IM/DD) and therefore the optical carrier used for modulating the light intensity must be real and uni-polar. In a VLC based OFDM system, the real signal is obtained by subjecting the frequency domain symbol to Hermitian symmetry and to obtain the uni-polar signal, two well-known techniques have been extensively researched and considered in VLC systems, these are, direct current optical OFDM (DCO OFDM) [7] and asymmetrically clipped optical OFDM (ACO OFDM) [8]. In a DCO OFDM system, the unipolar signal is obtained through the addition of an appropriate

DC bias after the inverse fast Fourier transform (IFFT) operation and clipping the remaining negative peaks. All the subcarriers are used to carry data symbols unlike in an ACO OFDM system where only the odd subcarriers are used and the uni-polar signal obtained by clipping the entire negative signal excursions. Consequently, the DCO OFDM system is more spectrally efficient and is preferred in VLC systems.

Regrettably, despite the advantages of OFDM, the multi-carrier nature of OFDM means that there will be constructive addition at certain instants of the sub-carriers after the IFFT operation leading to a higher peak value [9]. Consequently, this will result in a high peak-to-average power ratio (PAPR). It is important to keep the devices at the transmitter such as the LEDs, the digital-to-analogue converters (DACs) and the power amplifiers (PAs) in the linear region of operation for reliable transmission. However, this is difficult to achieve in practice due to the high PAPR and as a consequence, the high peaks are often clipped leading to signal distortion and an increase in bit error rate (BER).

Therefore, a lot of attention has been put on PAPR reduction and several techniques have been proposed in the traditional OFDM for wireless communication. However, since the transmitted signal in VLC must be real and positive due to the use IM/DD, most of these techniques cannot be directly applied in VLC systems.

Only a few techniques have been proposed for PAPR reduction in VLC systems. One of these techniques is clipping and filtering [10] that can be easily implemented, although it results in significant in-band distortion and out-band radiation which leads to performance degradation in terms of both the spectrum efficiency and the BER. On the other hand, companding transforms [11]–[13] such as μ-law and A-law offer better PAPR reduction performance with less distortion but at the cost of increased average power which is unacceptable in VLC systems.

Selective mapping (SLM) [14]–[17] based techniques have been observed as the most popular techniques for PAPR reduction in VLC systems. This is because they are distortionless and offer significant PAPR reduction without an observable BER degradation. In SLM, multiple candidate signals are generated by multiplying the OFDM symbol in the frequency domain with random phase sequences. The candidate signal after the IFFT operation with the least PAPR is selected for transmission and the side information (SI) associated with this candidate signal is transmitted for efficient recovery at the receiver.

Although the methods in [14]–[17] result in significant PAPR reduction, they result in complex systems because of two reasons. Firstly, their PAPR reduction performance capability is proportional to the number of candidate signals that are generated, the higher the number, the better the PAPR reduction performance. The large number of IFFT operations that have to be carried out to generate the candidate signals leads to an increase in complexity. Secondly, the complexity is exacerbated by the generation and multiplication of random phase sequences with the OFDM symbol.

Related to the SLM technique, symbol or bit interleaving technique [18] and the data position permutation (DPP) technique [19] also involve generation of multiple candidate signals for PAPR reduction. In the DPP technique, the OFDM symbol is divided into S sub-blocks which are then permutated to generate the candidate permutation sequences. Just like in SLM, the candidate permutation sequence with the least PAPR is selected for transmission and the SI associated with this candidate permutation sequence is transmitted for efficient recovery at the receiver. However, in the DPP technique, the number of candidate permutation sequences that can be generated is limited since it is given by $S!$ and therefore as the number of sub-blocks increases, the number of permutation sequences increases at a factorial rate of growth leading to a more complex transmitter system as a result of the large number of IFFT operations that have to be performed.

In this paper, we focus our attention on PAPR reduction in DCO OFDM systems using DPP based on lexicographical permutations. We call our scheme lexicographical symbol position permutation (LSPP) method. We concentrate on DCO OFDM because it is more spectrally efficient as compared to ACO OFDM. Unlike in DPP, in our proposed LSPP, the m^{th} permutation sequence can be generated efficiently without generating the previous $m-1$ permutations. From the possible $S!$ sequences,where S is the number of sub-blocks, we determine U random permutation candidate sequences lexicographically using the factorial number system. Just like in DPP, the candidate sequence with the least PAPR is selected for transmission and the SI associated with this candidate sequence is transmitted for efficient recovery at the receiver. Further, we introduce an algorithm for complexity reduction using LSPP by setting a threshold PAPR value and generating the permutation candidate sequences one by one until when a candidate sequence with PAPR below the threshold is reached. In this way, if the $m^{th}(m \leq U)$ permutation sequence satisfies the threshold condition, then $U-m$ candidate sequences are not generated and consequently, $U-m$ IFFT operations are not performed. This new method does not only reduce the PAPR but also results in a significant reduction in computational complexity.

This paper is laid out into five sections together with this introductory part. In the background given in Sec. II, the CSLM scheme is described together with the PAPR problem in DCO OFDM systems. The proposed scheme for PAPR reduction is described in Sec. III. In Sec. IV, we present the results together with a detailed analysis and discussion and finally, the concluding remarks are presented in Sec. V.

II. BACKGROUND

A. PAPR PROBLEM

The peak-to-average power ratio (PAPR) is an indication of the power variations in the transmitted signal and a high PAPR can appear in the transmitted signal when the N independent data symbols modulated on the N orthogonal subcarriers are added to the same phase. Generally, the electrical

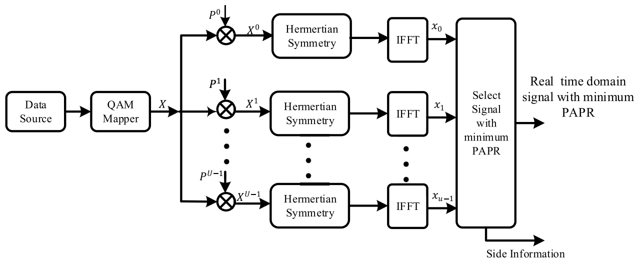

FIGURE 1. Conventional selective mapping scheme.

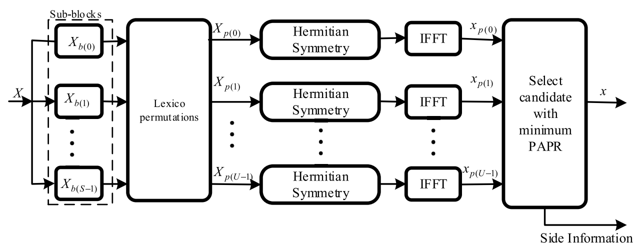

FIGURE 2. Proposed scheme for PAPR mitigation.

PAPR can be defined as the ratio of the peak power to the average power of the transmitted signal and is given by

$$\mathrm{PAPR} = \frac{\max\left\{|x(n)|^2\right\}}{\langle |x(n)|^2 \rangle}, \tag{1}$$

where $x(n)$ represents the time domain signal over-sampled $L-$times and $\langle\cdot\rangle$ denotes the statistical expectation. Usually, the performance of any PAPR reduction technique is normally described using the complementary cumulative distribution function (CCDF) diagram. The CCDF of the PAPR is defined as the probability that the PAPR exceeds a given threshold value PAPR_0 given by

$$\begin{aligned}\mathrm{CCDF} &= 1 - \Pr\{\mathrm{PAPR} \le \mathrm{PAPR}_0\} \\ &= 1 - \left(1 - e^{-\mathrm{PAPR}_0}\right)^N,\end{aligned} \tag{2}$$

where N is the number of subcarriers. In order to obtain a better approximation of the PAPR of the time domain signal, the frequency domain symbol is usually over-sampled L times. This over-sampling is normally performed through padding the frequency domain symbol with $N(L-1)$ zeros. Therefore (2) can be modified as follows:

$$\mathrm{CCDF} = 1 - \left(1 - e^{-\mathrm{PAPR}_0}\right)^{\alpha N}, \tag{3}$$

where α is the over-sampling factor. It was shown in [20] that an over-sampling factor of $L = 4$ is sufficient to obtain accurate PAPR results and this corresponds to $\alpha = 2.8$ [20].

B. CONVENTIONAL SELECTIVE MAPPING AND DCO OFDM

Fig. 1 illustrates the block diagram of DCO OFDM transmitter system using the conventional selective mapping (CSLM) for PAPR mitigation. Let $X = X(k)_{k=0}^{N/2-1}$ denote the input data symbol in frequency domain, where $X(k) \sim \mathcal{N}(0, \sigma^2)$ denotes the M-ary quadrature amplitude modulated (QAM) symbol mapped on the k^{th} sub-carrier with zero mean and variance σ^2.

In CSLM, a set of U pseudo-random phase sequences, $P_{\mathrm{CSLM}}^{(u)} = Ae^{j\theta_k^{(u)}}$ where $\theta_k^{(u)} \in [0, 2\pi]$, $0 \le u \le U-1$ are multiplied component wise with the input data symbol to generate U different candidate sequences. In a DCO OFDM communication system, both the odd and even subcarriers are used and to ensure a real time domain signal, the input to the IFFT is constrained to Hermitian symmetry. Therefore, the input to the IFFT will be given as

$$X_{\mathrm{CSLM}}^{(u)}(k) = X_{\mathrm{CSLM}}^{*(u)}(N-k) \text{ for } 0 < k < \frac{N}{2}, \tag{4}$$

where $X_{\mathrm{CSLM}}^{(u)}(0) = X_{\mathrm{CSLM}}^{(u)}(N/2) = 0$ and X^* is the complex conjugate of X. The U time domain candidate signals are generated by taking the N-point IFFT of the input frequency domain signals as follows:

$$x_{\mathrm{CSLM}}^{(u)}(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_{\mathrm{CSLM}}^{(u)}(k) \exp\left(-j\frac{2\pi kn}{N}\right), \tag{5}$$

where $0 \le n \le N-1$.

The PAPR of the U time domain candidate signals is calculated according to (1) and the candidate signal with the least PAPR is converted from parallel to serial. An appropriate cyclic prefix (CP) is often appended to combat inter-symbol interference (ISI) and inter-carrier interference (ICI) that could be an issue in a dispersive optical wireless communication channel. The continuous time domain signal $x(t)$ is obtained by feeding the discrete time domain signal $x(n)$ to the digital-to-analogue converter (DAC). A DC offset, $\mathrm{DC_{bias}}$ is added to $x(t)$ to ensure that the transmitted signal is unipolar. However, a large DC bias will lead to an increase in optical power and a small DC bias will lead to an increase in clipping noise leading to poor BER performance. Therefore, a suitable DC offset relative to the root mean square (RMS) of the signal $x(t)$ is added [21] and is given by

$$\mathrm{DC_{bias}} = \eta\sqrt{\langle |x(t)|^2 \rangle}, \tag{6}$$

where η is a constant and the $\mathrm{DC_{bias}}$ is defined as a bias of $10\log\left(\eta^2+1\right)$ dB. Next, the remaining negative peaks are clipped resulting into a real and uni-polar signal that is subsequently fed to the LED for transmission in the VLC channel.

III. PROPOSED SYSTEM FOR PAPR MITIGATION

A. LEXICOGRAPHICAL SYMBOL POSITION PERMUTATION

The proposed system for PAPR reduction in DCO OFDM systems using lexicographical permutations is given in Fig. 2.

Let $X = X(k)_{k=0}^{N/2-1}$ denote the input data symbol in frequency domain, where $X(k) \sim \mathcal{N}(0, \sigma^2)$ is the k^{th} M-ary QAM symbol modulated on the k^{th} sub-carrier with zero mean and variance σ^2. The input data block is divided into

S permutation sub-blocks, $X_{b(s)}$ according to (7)

$$X_{b(s)} = X_{S\times 0+s}, X_{S\times 1+s}, X_{S\times 2+s}, \ldots, X_{S\times(S-1)+s}, \quad (7)$$

where $0 \leq s \leq (S-1)$ and $N/2S$ is an integer so that the S permutation sub-blocks have the same size. For example, if the size of the input data sequence, $N/2 = 16$, i.e $X = [X_0, X_1, \ldots, X_{15}]$ and the number of permutation sub-blocks, $S = 4$, then the permutation sub-blocks are given by

$$\begin{aligned} X_{b(0)} &= [X_0, X_4, X_8, X_{12}], \\ X_{b(1)} &= [X_1, X_5, X_9, X_{13}], \\ X_{b(2)} &= [X_2, X_6, X_{10}, X_{14}], \\ X_{b(3)} &= [X_3, X_7, X_{11}, X_{15}]. \end{aligned} \quad (8)$$

The S permutation sub-blocks are then used to generate U random lexicographical permutations, ($U \leq S!$), according to algorithm 1, below.

Algorithm 1 An Algorithm to Generate the Lexicographical Permutations

Input: Permutation sub-blocks, $X_{b(s)}$, $0 \leq s \leq (S-1)$; Choose U, $(U \leq S!)$; set $i = 1$;
Output: Permutation sequences $X_{p(0)}, X_{p(1)}, \ldots, X_{p(U-1)}$

for $i = 1 : U$ **do**
  Randomly generate the m^{th} permutation sequence index, β $(1 \leq \beta \leq S!)$
  Set $X_{p(u)} := []$
  while $X_{b(s)} \neq []$ **do**
    $d := \left(\left|X_{b(s)}\right| - 1\right)!$
    $j := \lfloor \beta/d \rfloor$
    $x := X_{b(j)}$
    $\beta := \beta \bmod d$
    Append x to $X_{p(u)}$
    Remove x from $X_{b(s)}$
    Return $X_{p(u)}$
  end while
end for

In order to obtain real-valued time domain signals after the IFFT operation, the permutation sequences are constrained to Hermertian symmetry according to (9)

$$X_{p(u)}(k) = {X^*}_{p(u)}(N-k) \;\text{ for } 0 < k < \frac{N}{2}, \quad (9)$$

where $X_{p(u)}(0) = {X^*}_{p(u)}(N/2) = 0$ and X^* is the complex conjugate of X.

The time domain output candidate signals are generated by taking the $N-$point IFFT of the input frequency domain sequences

$$x_{p(u)}(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_{p(u)}(k) \exp\left(-j\frac{2\pi kn}{N}\right), \quad (10)$$

where $0 \leq n \leq N-1$ and $X_{p(u)}(k)$ is obtained from algorithm 1. The PAPR values of the time domain candidate signals is calculated using (1) and the candidate signal with the least PAPR is selected for transmission.

It is important to note that in our proposed LSPP just like in CSLM, the number of bits required for the SI is $\log_2(U)$ for each block of information that is transmitted. This SI is normally transmitted in a separate channel, or it can be embedded in the transmitted signal and is usually protected by error control codes to prevent erroneous detection at the receiver [19]. In this paper, we assume that the SI is transmitted and received correctly.

B. COMPLEXITY REDUCTION

The PAPR reduction performance of LSPP is proportional to the number of candidate signals leading to high computational complexity as a result of a large number of IFFT operations to be performed. If the first permutation sequence has the least PAPR, then $U-1$ unnecessary permutations will be generated leading to $U-1$ unnecessary IFFT operations which makes the system complex. If the m^{th} $(m < U)$ permutation sequence has the least PAPR, then $U-m$ unnecessary permutation sequences are generated and ultimately $U-m$ unnecessary IFFT operations are generated.

In order to reduce the computational complexity of LSPP, we set a threshold PAPR, γ and then generate the candidate permutation sequences one by one while computing the PAPR of the corresponding candidate signal until we obtain a candidate signal whose PAPR is less or equal to γ. That candidate signal is considered for transmission. If all the U permutation sequences have a PAPR that is more than the threshold, γ then the one with the smallest PAPR among them will be considered for transmission. Algorithm 2 describes our complexity reduction method.

Algorithm 2 The Proposed Algorithm for Complexity Reduction

Input: Choose S and $U(U \leq S!)$; select a predetermined PAPR, γ; set $i = 1$;
Output: Transmitted candidate signal, X_p

1: **while** $i \leq U$ **do**
2:   Randomly generate a permutation sequence, $X_{p(i)}$ using algorithm 1
3:   Calculate the PAPR of $X_{p(i)}$, PAPR_i
4:   **if** $\text{PAPR}_i \leq \gamma$ **then**
5:     Set $X_{p(i)}$ as X_p and consider it for transmission
6:   **else**
7:     $i++$ and go to step 2
8:   **end if**
9:   **if** $i = U$ **then**
10:     Select X_p from $X_{p(1)}, X_{p(2)}, \ldots, X_{p(U)}$ whose PAPR is the smallest and consider it for transmission
11:   **end if**
12: **end while**

C. COMPLEXITY REDUCTION ANALYSIS

The generation of candidate permutation sequences can be modelled as a Bernoulli distribution with only two possible outcomes, i.e PAPR below the threshold or PAPR above

TABLE 1. Simulation parameters.

Simulation Parameter	Value
Number of sub-carriers	$N = 512$
Number of data blocks	10^6
Over-sampling factor	$L = 4$
Modulation scheme	16-QAM
No. of sub-blocks for LSPP	$S = 8, 16$
No of candidate signals	$U = 4, 8, 16, 32$

the threshold [22]. If the maximum number of permutation sequences U approaches infinity, the number of tries Y whose PAPR is less than the threshold can be modelled as a Geometric distribution.

Let p be the probability that the PAPR is less or equal to the threshold PAPR γ, Then $p = \Pr(\text{PAPR} \leq \gamma) = \left(1 - e^{-\gamma}\right)^{\alpha N}$. According to Geometric distribution, the probability of exactly generating m sequences using algorithm 2 is

$$\Pr(Y = m) = (1 - p)^{(m-1)} p. \tag{11}$$

The above (11) is applicable when $m < U$. Therefore, the probability distribution of the random variable Y can be given as follows

$$\Pr(Y = m) = \begin{cases} (1-p)^{(m-1)} p, & 1 \leq m \leq (U-1) \\ 1 - \sum_{k=1}^{U-1} (1-p)^{(m-1)} p = (1-p)^{(U-1)}, & m = U. \end{cases} \tag{12}$$

The average number of tried candidates (trials before a success is obtained) is

$$\langle Y \rangle = \sum_{m=1}^{U} \Pr(Y = m) m = \frac{1}{p} - \frac{1-p}{p}(1-p)^{U-1}. \tag{13}$$

In order to generate a candidate sequence, $2N$ point IFFT operations are required in DCO OFDM, where N is the number of data subcarriers. Therefore, the total number of IFFT operations is

$$\text{IFFT}_{\text{Proposed}} = 2N\langle Y \rangle [\frac{1}{p} - \frac{1-p}{p}(1-p)^{U-1}]. \tag{14}$$

IV. RESULTS AND DISCUSSIONS

In this section, the PAPR reduction performance of our proposed LSPP for DCO OFDM communication system is evaluated through conducting simulation experiments using MATLAB®. In our simulations, we consider a 16-QAM DCO OFDM communication system with $N = 512$ subcarriers and 1,000,000 data blocks were generated with each data block over-sampled by $L = 4$ which is sufficient to approximate the true value of the PAPR [20]. For comparison purposes, we obtained simulation results for the original DCO OFDM without PAPR reduction, the CSLM and our proposed LSPP for the same number of candidate signals. The simulation parameters are given in Table 1.

Fig. 3 shows the PAPR reduction performance of the original DCO OFDM system, the CSLM and the proposed LSPP using CCDF defined by (3). It can be seen that at a CCDF $= 10^3$, the PAPR reduction achieved by our proposed LSPP is quite significant with values of 1.6, 2.4, 2.7 and 3dB respectively for $U = 4, 8, 16$ and 32 candidate signals compared to the original DCO OFDM.

As compared to the CSLM, our proposed LSPP, achieves almost the same PAPR reduction performance with our scheme slightly inferior by 0.36, 0.01, 0.1, 0.05dB for $U =$ 4, 8, 16, 32 candidate signals respectively at a CCDF $= 10^3$ for $S = 8$ sub-blocks. However, as the number of sub-blocks is increased from 8 to 16, it can be observed from Fig. 4 that the PAPR reduction performance of our proposed LSPP almost approaches that of CSLM. This is because, as the number of sub-blocks, S increases, the candidate permutation sequences become more uncorrelated leading to low PAPR values.

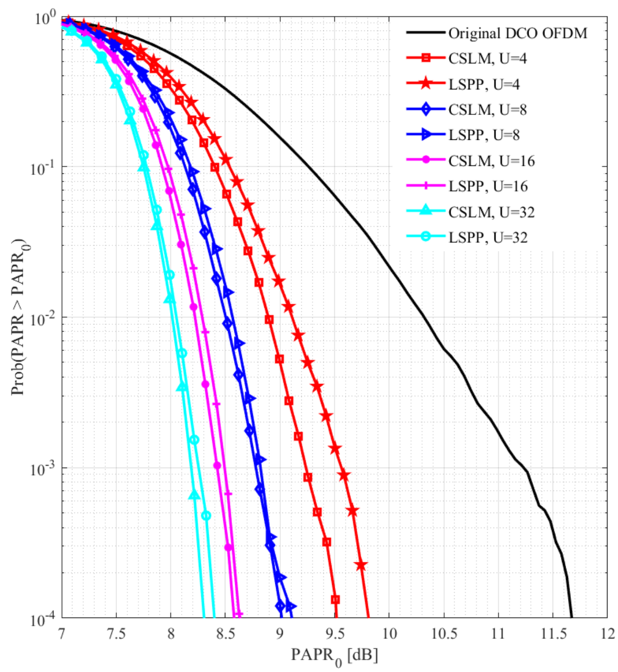

FIGURE 3. PAPR performance comparison between the original DCO OFDM, LSPP and CSLM for $S = 8$ sub-blocks.

Fig. 5 compares the BER performance of the proposed technique to that of CSLM and the original DCO OFDM signal over additive white Gaussian noise (AWGN) channel. From Fig. 5, it can be observed that our proposed LSPP and CSLM have almost the same BER performance with negligible BER degradation. It is quite clear from the results that the PAPR reduction performance of our proposed scheme is proportional to the number of candidate signals. However, when the number of candidate signals is increased, the complexity in terms of IFFT operations increases, hence there is a trade off between PAPR reduction performance and system complexity.

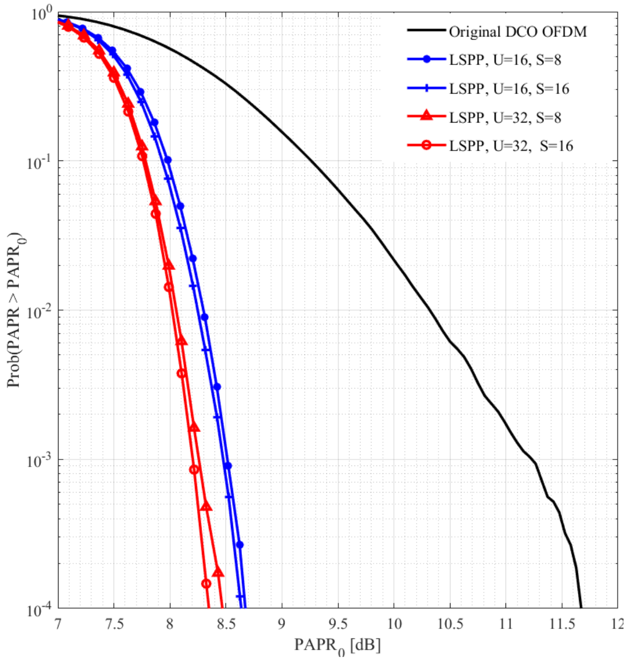

FIGURE 4. PAPR comparison for LSPP with $U = 16$ and 32 candidate signals for $S = 8$ and 16 sub-blocks. For the same number of candidate signals, increasing the number of sub-blocks improves the PAPR reduction performance.

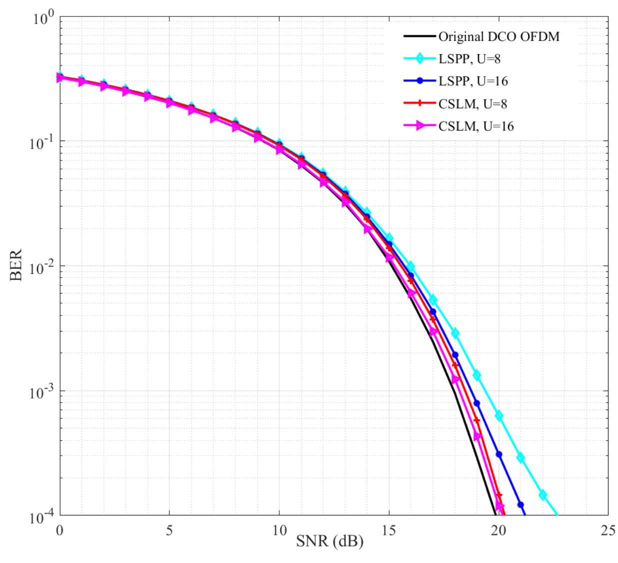

FIGURE 5. Comparison of BER performance of the original OFDM system, the CSLM and LSPP for $U = 8$ and 16 candidate signals.

A. COMPLEXITY REDUCTION ANALYSIS

In Fig. 6, we plot the number of IFFT operations required to generate a candidate signal. The total number of IFFT operations is given by (14). We can observe that the number of total IFFT operations reduces as the threshold, γ increases. This is because, as γ increases, the number of candidate signals with PAPR above γ will increase and hence will not be generated by algorithm 2 leading to a reduction in the number of IFFT operations. This reduction in IFFT operations can be analysed using the complexity reduction equation given by (15).

$$\text{Complexity Reduction} = \frac{2NU - \text{IFFT}_{\text{Proposed}}}{2NU} \times 100\%, \quad (15)$$

TABLE 2. Complexity reduction.

No. of candidate signals, U	Complexity Reduction %		
	8.0 dB	8.5 dB	9.0 dB
4	10.5	36.6	59.5
8	22.3	60.6	79.2
16	40.0	79.1	89.6
32	61.2	89.5	94.8

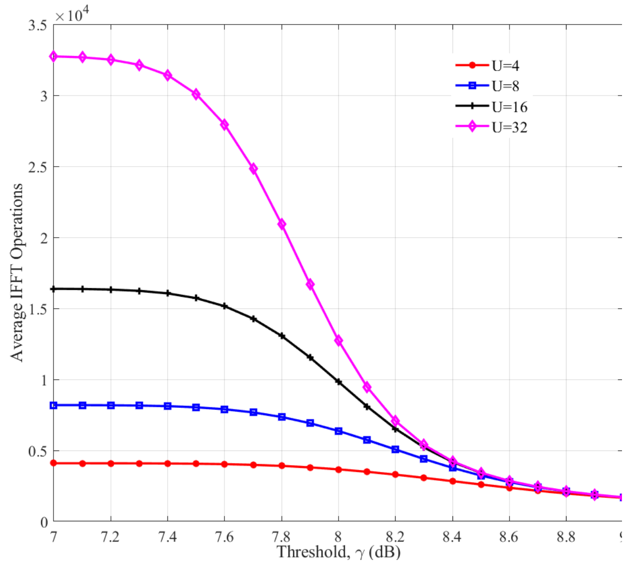

FIGURE 6. IFFT operations for different γ and U.

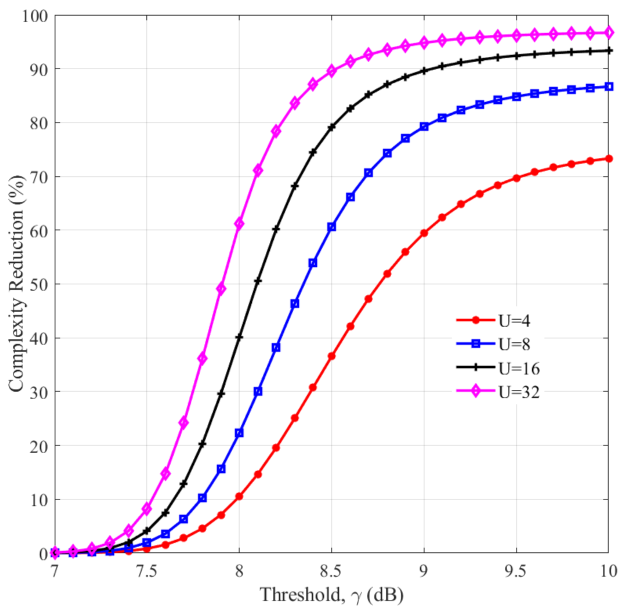

FIGURE 7. Complexity reduction performance for different γ and U.

where $\text{IFFT}_{\text{Proposed}}$ is given by (14), N is the number of subcarriers and U is the number of candidate signals.

In Fig. 7, we plot the complexity reduction performance for our proposed LSPP. The complexity reduction is calculated using (15) and the results are summarised in Table 2. We can observe that the complexity reduction is proportional to γ when the number of candidate signals U is constant. When γ is fixed, the number of candidate signals, U has an influence on complexity reduction. For instance, as given in Table 2 and Fig. 7, when γ is 8dB, the complexity reduction is 10.5, 22.3, 40.0 and 61.2% for $U = 4, 8, 16$ and 32 respectively. When $\gamma = 9$dB and $U = 16$, the complexity reduction that is achieved is 90% and when γ is increased to 10dB, the complexity reduction achieved increases to 96% for $U = 32$ candidate signals. The increase in complexity reduction as γ is increased corresponds to the reduction in the number of IFFT operations as γ increases given in Fig 6.

V. CONCLUSION

Direct current optical orthogonal frequency division multiplexing (DCO-OFDM) is an attractive modulation technique in visible light communication (VLC) due to its high spectral efficiency compared to asymmetrically clipped optical OFDM (ACO-OFDM) and its ability to combat inter-symbol interference (ISI) as a multi-carrier modulation technique. However, one of the major shortcomings of DCO-OFDM is the high peak-to-average power ratio (PAPR) of the transmitted signal which affects the system performance due to the presence of non-linear components like the digital-to-analog converters (DACs), power amplifiers (PAs) and light emitting diodes (LEDs) whose performance is highly influenced by the PAPR.

In this paper, we have proposed and experimentally demonstrated through computer simulations a new PAPR reduction technique called LSPP that effectively reduces the PAPR compared to the original DCO OFDM with no PAPR mitigation. The proposed technique has almost the same PAPR reduction performance compared to the conventional selective mapping (CSLM) with less complexity since there is no multiplication of the phase sequences at the transmitter to generate the candidate signals as is done in CSLM.

Further, we also present and analyse a new way to further reduce the complexity by introducing a threshold PAPR, since different applications require different PAPR performance. We show through our results that the complexity in terms of IFFT operations can be reduced substantially depending on the selected threshold γ and the number of candidate signals, U. For example, when $\gamma = 9$dB and $U = 16$, the complexity reduction that is achieved is 90% and when $\gamma = 10$dB, the complexity reduction achieved is 96% for $U = 32$ candidate signals.

REFERENCES

[1] S. Arai, M. Kinoshita, and T. Yamazato, "Optical wireless communication: A candidate 6G technology?" *IEICE Trans. Fundam. Electron., Commun. Comput. Sci.*, vol. 104, no. 1, pp. 227–234, Jan. 2021.

[2] L. E. M. Matheus, A. B. Vieira, L. F. Vieira, M. A. Vieira, and O. Gnawali, "Visible light communication: Concepts, applications and challenges," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3204–3237, 4th Quart., 2019, doi: 10.1109/COMST.2019.2913348.

[3] A. Al-Kinani, C.-X. Wang, L. Zhou, and W. Zhang, "Optical wireless communication channel measurements and models," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1939–1962, 3rd Quart. 2018, doi: 10.1109/COMST.2018.2838096.

[4] Y. Sun, F. Yang, and L. Cheng, "An overview of OFDM-based visible light communication systems from the perspective of energy efficiency versus spectral efficiency," *IEEE Access*, vol. 6, pp. 60824–60833, 2018, doi: 10.1109/ACCESS.2018.2876148.

[5] X. Zhang, Z. Babar, P. Petropoulos, H. Haas, and L. Hanzo, "The evolution of optical OFDM," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 3, pp. 1430–1457, 3rd Quart., 2021, doi: 10.1109/COMST.2021.3065907.

[6] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling With MATLAB*. Boca Raton, FL, USA: CRC Press, 2019.

[7] J. M. Kahn and J. R. Barry, "Wireless infrared communications," *Proc. IEEE*, vol. 85, no. 2, pp. 265–298, Feb. 1997.

[8] J. Armstrong and A. J. Lowery, "Power efficient optical OFDM," *Electron. Lett.*, vol. 42, no. 6, pp. 370–372, Mar. 2006.

[9] T. Jiang and Y. Wu, "An overview: Peak-to-average power ratio reduction techniques for OFDM signals," *IEEE Trans. Broadcast.*, vol. 54, no. 2, pp. 257–268, Jun. 2008, doi: 10.1109/TBC.2008.915770.

[10] Z.-R. Tong, Y.-N. Hu, and W.-H. Zhang, "PAPR reduction in CO-OFDM systems using IPTS and modified clipping and filtering," *Optoelectron. Lett.*, vol. 14, no. 3, pp. 209–211, May 2018.

[11] M. Mounir and M. B. El-Mashade, "On the selection of the best companding technique for PAPR reduction in OFDM systems," *J. Inf. Telecommun.*, vol. 3, no. 3, pp. 400–411, 2019.

[12] N. Ali, R. Almahainy, A. Al-Shabili, N. Almoosa, and R. Abd-Alhameed, "Analysis of improved μ-law companding technique for OFDM systems," *IEEE Trans. Consum. Electron.*, vol. 63, no. 2, pp. 126–134, May 2017, doi: 10.1109/TCE.2017.014753.

[13] J. Kim and Y. Shin, "An effective clipped companding scheme for PAPR reduction of OFDM signals," in *Proc. IEEE Int. Conf. Commun.*, Beijing, China, May 2008, pp. 668–672, doi: 10.1109/ICC.2008.131.

[14] W.-W. Hu and D.-H. Lee, "PAPR reduction for visible light communication systems without side information," *IEEE Photon. J.*, vol. 9, no. 3, pp. 1–11, Jun. 2017, doi: 10.1109/JPHOT.2017.2700400.

[15] S. P. Valluri, V. Kishore, and V. M. Vakamulla, "A new selective mapping scheme for visible light systems," *IEEE Access*, vol. 8, pp. 18087–18096, 2020, doi: 10.1109/ACCESS.2020.2968344.

[16] S. Y. L. Goff, S. S. Al-Samahi, B. K. Khoo, C. C. Tsimenidis, and B. S. Sharif, "Selected mapping without side information for PAPR reduction in OFDM," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3320–3325, Jul. 2009, doi: 10.1109/TWC.2009.070463.

[17] Y. Wu, C. He, Q. Zhang, Y. Sun, and T. Wang, "Low-complexity recombined SLM scheme for PAPR reduction in IM/DD optical OFDM systems," *Opt. Exp.*, vol. 26, no. 24, pp. 32237–32247, 2018.

[18] A. D. S. Jayalath and C. Tellambura, "Reducing the peak-to-average power ratio of orthogonal frequency division multiplexing signal through bit or symbol interleaving," *Electron. Lett.*, vol. 36, no. 13, pp. 1161–1163, Jun. 2000.

[19] J.-H. Wen, S.-H. Lee, and C.-C. Kung, "SLM-based data position permutation method for PAPR reduction in OFDM systems," *Wireless Commun. Mobile Comput.*, vol. 13, no. 11, pp. 985–997, 2013, doi: 10.1002/wcm.709.

[20] J. Tellado-Mourelo, "Peak to average power ratio reduction for multicarrier modulation," Ph.D. dissertation, Dept. Elect. Eng., Stanford Univ., Stanford, CA, USA, Sep. 1999.

[21] J. Armstrong and B. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN," *IEEE Commun. Lett.*, vol. 12, no. 5, pp. 343–345, May 2008, doi: 10.1109/LCOMM.2008.080193.

[22] D. Bi, P. Ren, and Z. Xiang, "A novel joint PAPR reduction algorithm with low complexity using LT codes," *IEEE Wireless Commun. Lett.*, vol. 7, no. 2, pp. 166–169, Apr. 2018, doi: 10.1109/LWC.2017.2762312.

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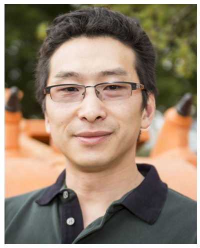

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