Three-Layer PAPR Reduction Technique for FBMC Based VLC Systems

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ABSTRACT In this paper, a new non-redundant three-layer peak-to-average power ratio (PAPR) reduction technique is proposed for filter bank multicarrier communication based visible light communication (FBMC based VLC) systems. In the proposed technique, the FBMC based VLC data signal is overlapped with two new non-redundant signals. The initial-layer signals are the FBMC modulated signals. For PAPR reduction, the second-layer signals are constructed to decrease initial-layer large-amplitude signals, while the last-layer signals are used to improve the initial-layer small-amplitude signals. The two non-redundant signals do not overlap with the data signals in the frequency domain, because data signals are distributed on odd subcarriers, while even subcarriers are occupied by the constructed signals. To mitigate the effect of large-amplitude signal reduction in the proposed technique, the negative signals are converted into positive, rather than being clipped off as in conventional FBMC based VLC systems. In order to realize a trade-off between PAPR reduction and bit error rate (BER), we introduce a scaling factor in the converted signals. The performance of the proposed technique is calculated in terms of complementary cumulative distribution function (CCDF) and BER. The obtained results indicate that FBMC based VLC systems with the proposed technique can achieve a good trade-off between PAPR reduction and BER and outperforms the corresponding orthogonal frequency division multiplexing (OFDM) based VLC systems.

INDEX TERMS BER performance, FBMC, OFDM, PAPR reduction, VLC.

I. INTRODUCTION

Recently, visible light communication (VLC) has gained significant attention because it can support high-speed and large-capacity communications compared to traditional wireless radio communications. Also, VLC systems can be used in hospitals, aircraft, and spaceships because they can have a minor impact on electronic devices [1].

Due to their ability to resolve frequency-selective fading impairments at high data rates, multicarrier systems have gotten much attention in recent years. Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation technique that ensures orthogonality of waveforms modulated by different data symbols with a cyclic prefix (CP) and proper spacing between subcarriers [2]. Furthermore, unlike radio communication systems, VLC systems do not have a spectrum mask, so that we may be less concerned about out-of-band radiation. As a result, OFDM is used in VLC systems to communicate quickly, and there is a significant difference between the radio signal and the VLC signal [2].

Nakamura et al. investigated asymmetrically clipped O-OFDM (ACO-OFDM) and direct current (DC) biased O-OFDM (DCO-OFDM) at the transmitter front-end which are clipped double-sided time-domain signals. The time-domain signals of two systems are pre-clipped at different bottom levels. Since the clipping levels in ACO-OFDM assume only non-negative values, the signal is pre-clipped at zero or a positive bottom level. On the other hand, since the clipping levels in DCO-OFDM can be negative or positive, the signal is pre-clipped at the bottom level [3]. However, since the bias value varies with each OFDM symbol, it is essential to estimate the receiver’s bias value as with the traditional technique. Furthermore, it suffers from the dynamic range between each OFDM symbol and less power efficiency [4].
Filter bank multicarrier communication (FBMC) systems are another form of the multicarrier system recently used in optical access networks and VLC systems to reduce the out-of-band interference (OOBI). In FBMC-based systems, each subcarrier is filtered to achieve low OOBI and effectively suppress inter-band interference (IBI). As a result, the necessary guard band (GB) can be reduced, resulting in improved overall spectral performance (SE) [5]. FBMC technique has several advantages compared to the OFDM technique, such as (i) Less radiation outside the required bandwidth, (ii) signal must be transmitted without cyclic prefix (iii) High robust for environmental problems. Furthermore, because of pulse shaping filters, FBMC has lower spectral side lobes than traditional OFDM systems, implying that the FBMC has customizable parameters and asynchronous transmission capabilities [6]. OFDM/offset quadrature amplitude modulation (OFDM/OQAM) has been considered an appealing alternative to traditional OFDM due to higher spectrum efficiency brought about by removing CP and lower out-of-band radiation using a specially designed filter bank [7].

Only in the real domain, the filters utilized in OQAM/OFDM satisfy the orthogonality property. Therefore, we may replace OFDM with FBMC in future intensity modulation/direct detection (IM/DD) based VLCs by integrating VLC and RF communications. For integrated optical transmission, FBMC-offset quadrature amplitude modulation (FBMC-OQAM) with a Mirabbasi-Martin prototype filter is suggested [8]–[10].

As with radio frequency (RF) OFDM systems, VLC-OFDM systems suffer from high peak-to-average power ratio (PAPR) [11]. However, some variations between RF-OFDM and VLC-OFDM prohibit traditional PAPR reduction techniques from being directly applied to VLC-OFDM systems. The RF-OFDM baseband signal is complex-valued, whereas the VLC-OFDM baseband signal is real-valued. Therefore, the upper and lower PAPRs of a real-valued OFDM signal must be reduced. Second, in RF communicators, PAPR reduction schemes can compensate for both in-band distortions and out-of-band power leakage [12]. However, since light-emitting diode (LED) functions as a low-pass filter in VLC-OFDM systems, out-of-band subcarriers cannot be used to transfer data to other users. As a result, we do not need to be concerned with out-of-band interferences, which provide us with more flexibility in developing PAPR reduction schemes for VLC-OFDM systems [13]

Furthermore, high PAPR necessitates extensive biasing to transform the bipolar OFDM signal to a unipolar version, rendering the device optically inefficient. As a result, PAPR reduction is also an essential module in a VLC-OFDM system. The distortion-based methods are among the PAPR reduction techniques suggested for RF-OFDM communications [3], [4], [14]–[17] are particularly advantageous for realistic scenarios because receiver alteration is avoided [18], [19]. However, upper and lower PAPR is not distributed separately and are often constrained by asymmetric constraints. Furthermore, prior distortion-based PAPR reduction techniques only limited total distortion capacity, resulting in distortions distributed equally across all in-band subcarriers [3], [16]. However, in bit-loaded OFDM, high-order constellations are often more susceptible to noise than low-order constellations [20], [21].

Clipping was proposed as a technique for reducing the peak amplitude of OFDM signals. Furthermore, if signal distortion occurs due to clipping, out-of-band radiation will occur. As a result, filtering is required to reduce out-of-band radiation, and filtering can result in peak regrowth [2]. However, since there is no spectrum mask for VLC, it is not always necessary to remove distortion in VLC OFDM systems [22]. As a result, the clipping technique will directly obtain the desired PAPR. Furthermore, reduced PAPR will suppress back-off at the transmitter’s power amplifier, allowing the Signal-to-Noise Power Ratio (SNR) of each subcarrier to be comparatively higher. As numerical examples, we evaluate the clipping threshold to minimize BER [23], [24].

In this paper, we used FBMC in VLC with an IM/DD channel more generally, complete with quantized performance analysis. We discovered a significant improvement in BER efficiency in FBMC waveforms with OQAM. The procedure of the proposed non-redundant three-layer PAPR reduction approach is shown in the Algorithm. We go through the transceiver design concepts in-depth and equate them to current VLC-OFDM schemes. Simulations are run to validate the results.

Motivated by the open issues above, we propose a new non-redundant three-layer PAPR reduction technique for FBMC based VLC systems, where two signal streams are superimposed with the FBMC based VLC signals stream. The valuable data signals modulated by FBMC based VLC are the initial-layer signals. We design second-layer signals to reduce the large-amplitude of FBMC based VLC signals and the last-layer signals to enhance the small-amplitude FBMC based VLC signals. An intensive performance analysis was provided. The impact of the scaling factor on PAPR reduction and BER performance was investigated. It is proven that the PAPR is reduced severely by a high value of scaling factor in the small range of LED’s linearity, and the proposed PAPR reduction is independent of the scaling factor in the large range of LED’s linearity. The relationship between the traditional OFDM-based VLC and FBMC based VLC signals with no PAPR reduction and the proposed technique is derived. The second layer and last layer signals are symmetrical to eliminate the interference to the user data on odd subcarriers.

II. SYSTEM MODEL

A. OFDM BASED VLC SYSTEM MODEL

In the OFDM-based VLC system, an inverse fast Fourier Transform (IFFT) of length 128 was performed after the Quadrature amplitude modulation (QAM) block. Traditionally, the step after QAM modulation was to enforce Hermitian
Symmetry (HS) on the IFFT input, which provides a real output result but requires twice the number of IFFT/FFT points in transmitter and receiver, so computational complexity of HS requires higher power consumption and requires higher chip dimensions, as shown in figure 1 [20], [24].

A scaling factor (s) is implemented, which compresses the converted signals in order to increase the reduction of PAPR. Useful data signals are not interfered by two non-redundant signal streams in the frequency domain, as useful data signals occupy strange subcarriers. In contrast, also subcarriers are occupied by second-layer and last-layer signals. This is different from the conventional OFDM-based VLC signals, where even subcarriers are zero on the transmitter.

The proposed non-redundant three-layer PAPR reduction technique is of high performance in PAPR because superimposed three-layer signals will relax the restricted range of linearity of LEDs to reduce the impact of upper and lower LEDs clipping. Also, the proposed technique is spectrum efficient, as no pilot or side information is needed.

We consider two cases relating to the linearity of LED’s wide and miniature ranges. The optimum PAPR reduction is given when the threshold is equal to the limit boundary in the wide range of LED linearity with the threshold lower than the upper LED clipping level. It is also given when the limit boundary is equal to the upper LED clipping level, with the threshold higher than the upper LED clipping level. In the wide range of LED linearity, the upper and lower limits of the optimal PAPR reduction are derived. The range of lower limits of the optimal PAPR reduction is also derived from the limited range of LED linearity.

A CP was added after IFFT to overcome the effect of inter-symbol interference (ISI). In the discrete-time domain, the generated OFDM symbol can be denoted as:

\[ x(n) = \sum_{l=0}^{N-1} X(k) e^{j2\pi ln/N} \]  

where \( X(k) \) is defined as the data symbols in the frequency domain, \( l \) is the sub-carrier index, and \( N \) is the length of IFFT.

**B. FBMC BASED VLC SYSTEM MODEL**

For the FBMC based VLC system, shown in figure 2, after QAM modulation and IFFT subcarrier loading, each QAM symbol needs to be split into two parts, real and imaginary parts. An up-sampling of \( K \) times for each OQAM-OFDM symbol should be performed, where \( K \) is defined as the FBMC overlapping factor. Each OQAM-OFDM symbol was filtered using a pulse-shaping filter. Individual time domain symbols OQAM-OFDM were overlapped and summed up with \( N/2 \) intervals.

A non-redundant three-layer technique might establish the PAPR reduction transmitted signal of the FBMC-based VLC system. Thus, two non-redundant signal streams superimposed being proposed with the signal stream. First, it is essential to evaluate a synthesis filter bank (SFB) performance, which could be easily satisfied by using Hermitian symmetry before SFB [25].

**FIGURE 1. Structure of OFDM-based VLC with a non-redundant three-layer PAPR reduction technique.**
Even subcarriers are filled with null as \( X(0) = X(2) = \ldots = 0 \), while signals on odd subcarriers satisfy Hermitian symmetry as \( X(k) = X^*(N-k) \).

However, in the VLC system based on OFDM, the throughput that is equal to the standard OFDM-based VLC system doubles because of the symbol rate. Simultaneously, the spectral confinement efficiency of the FBMC based VLC system is far superior to that of OFDM-based VLC and increases with the increasing of K value. As a result, the time-domain FBMC-based VLC signal can define as:

\[
x(n) = \sum_{m=-\infty}^{+\infty} \sum_{k=0}^{N-1} A(m,k) h \left( n - m \frac{N}{2} \right) e^{j\pi k \left( m - \frac{L_p-1}{2} \right)} e^{j\phi_m,k}
\]

(2)

While the symbol rate doubles the OFDM-based VLC system, the output equivalent to the traditional VLC system using OFDM. Where \( n = 0, 1, \ldots, L_p - 1 \), \( N \) is the number of subcarriers and \( L_p \) is the prototype filter’s length and \( L_p = km - 1 \). Simultaneously, the FBMC based VLC system’s spectral containment efficiency is far above OFDM-based VLC and increases as K values grow, when K is defined as the overlapping FBMC factor for each OQAM-OFDM symbol.

The filter coefficients are

\[
H(0) = 1, \quad H \left( \frac{1}{L_p} \right) = 0.97169,
\]

\[
H \left( \frac{2}{L_p} \right) = \frac{1}{\sqrt{2}}, \quad H \left( \frac{3}{L_p} \right) = 0.235147
\]

\[
H \left( \frac{i}{L_p} \right) = 0, \quad 4 \leq i \leq L_p - 1
\]

(4)

The bipolar signal \( y \) is sent to an analysis filter bank (AFB) for sub-band processing of an analysis filter after the intensity of light was detected through a photodiode (PD) at the receiver. The transmitted signal is clipped to fit in the dynamic working area of LED as [26]:

\[
x_{\text{clip}}(n) = \begin{cases} 
A_{\text{top}}, & x(n) > A_{\text{top}} \\
A_{\text{bottom}}, & A_{\text{bottom}} \leq x(n) \leq A_{\text{top}} \\
A_{\text{bottom}}, & x(n) < A_{\text{bottom}}
\end{cases}
\]

(5)

The normalized bottom and top clipping ratios relative to a regular normal distribution are \( A_{\text{bottom}} \) and \( A_{\text{top}} \), respectively. Thus, the received OFDM signal with the impulse response \( h(t) \), propagated through the wireless optical channel, is given by:

\[
y_t(t) = R x(t) \otimes h(t) + w(t)
\]

(6)

R is the photodetector’s responsivity, \( \otimes \) denotes circular convolution. \( w(t) \) is the additive white Gaussian noise (AWGN) applied to the electrical domain. This paper considers the performance in a flat channel, and we assume that
The designed signal structure on the second layer has a time-domain symmetry property, as:

\[ x_2 (n) = x_2 (\tilde{n}) \]  

Let \( \tilde{n} \) denote the time index of the symmetrical position, \( x_2 (n) \) and \( x_2 (\tilde{n}) \) share the same value on the second layer. Any initial-layer signals above the threshold \( A_2 \) and without being reversed and compressed are clipped, and the reduced symmetrical signals are non-negative. Using Eq. 7, the symmetrical signal is not reduced to be negative, when a large-amplitude signal is cut off to the threshold, we consider two cases related to the large and small ranges of LED’s linearity. We define the clipping threshold as:

\[ A_2 = (1 - s) x_1 (n_{pk}) \]  

Let \( n_{pk} \) denote the time index with peak signal.

The superposition of initial and second layer signals is written as:

\[
(x_1 (n) + x_2 (n)) = \begin{cases} 
A_2, & x (n) > A_2 \\
(1 - s)[x_1(n_{pk}) - x_1(\tilde{n})], & x (\tilde{n}) < A_2 \\
x_1 (n), & \text{Otherwise.}
\end{cases}
\]  

\[ (10) \]

**C. LAST-LAYER SIGNAL DESIGN**

Unlike the second-layer signal designed for large-signal reduction, the last-layer signal design aims to increase the small amplitude of OFDM-VLC or initial-layer FBMC-VLC signals. Like the second-layer signal design, the last-layer signals on odd subcarriers do not conflict with the initial-layer signals. Thus, on odd subcarriers, the last-layer signals are null, while even subcarriers increase the small amplitude of OFDM-VLC or FBMC-VLC signals on the initial layer. Let \( x_3 (k) \) denote the last-layer signal on the \( k \)-th subcarrier. Odd subcarriers are filled with null information \( x_3 (1) = x_3 (3) = \ldots = 0 \), whereas Hermitian symmetry satisfies the last-layer signals on even subcarriers. Therefore, the superposition of the symmetric signal to the enhancement is less than \( A_3 \) as:

\[ [(A_3 - x_1 (n)) + x_1 (\tilde{n})] < A_3 \]  

\[ (11) \]

The last-layer signal design, therefore, is given by:

\[
x_3 (n) = x_3 (\tilde{n}) = \begin{cases} 
A_3 - x_1 (n), & 0 < x (n) < A_3 \\
0, & \text{Otherwise.}
\end{cases}
\]  

\[ (12) \]

The superimposition between the initial and last layers of the signals is given by:

\[
(x_1 (n) + x_3 (n)) = \begin{cases} 
A_3, & 0 < x(n) < A_3 \\
A_3 - x_1 (\tilde{n}) + x_1 (n), & 0 < x(\tilde{n}) < A_3 \\
x_1 (n), & \text{otherwise}
\end{cases}
\]  

\[ (13) \]

Accordingly, the resulting transmitted signal is the superimposition of the initial, second and last layer signals as:

\[ x_f (n) = x_1 (n) + x_2 (n) + x_3 (n) \]  

\[ (14) \]

**Algorithm:** The proposed non-redundant three-layer PAPR reduction for OFDM based VLC and FBMC based VLC systems

Input: Data at the initial layer.

Layer-1: Signal reversal and linear compression.
1. Time-domain signal after IFFT at case of OFDM based VLC or SFB at FBMC based VLC: \( x (n) \)
2. Negative signal reversal and linear compression:
   3. If \( x (n) < 0 \) then \( x_1 (n) = s \cdot |x (n)| \);
   4. Else \( x_1 (n) = x (n) \);
   5. End if

Layer-2: Second-layer signal design for large-amplitude signal reduction.
6. Two conditions of the second-layer signal design: 1) $x_2(n) = x_2(\hat{n});$ 2) $x_2(n) < 0, x_2(\hat{n}) < o$.
7. The selection of the peak signal on the initial layer: $[x_1(n_{pk}), n_{pk}] = \arg\max_{0 \leq k \leq N-1} (x_1(\hat{n})).$
8. The clipping threshold: $A_2 = (1-s) x_1(n_{pk}).$
9. The second-layer signal design as:
  10. If $x_1(n) > A_2$ then
  11. $x_2(n) = A_2 - x_1(n); x_2(\hat{n}) = x_2(n);
  12. Else
  13. $x_2(n) = 0; x_2(\hat{n}) = 0;
  14. End if

Layer-3: Last-layer signal design for small-amplitude signal improvement.
15. Two conditions of the last-layer signal design: 1) $x_3(n) = x_3(\hat{n});$ 2) $x_3(n) > 0, x_3(\hat{n}) > 0$.
16. The limit boundary that small signals can reach as: $A_3$, subject to two conditions: $0 < A_3 < A_{top}$ and $A_3 < A_2$.
17. The last-layer signal design as:
  18. If $x_3(n) > 0$ and $x_1(n) < A_3$ then
  19. $x_3(n) = A_3 - x_1(n); x_3(n) = x_3(n);
  20. Else
  21. $x_3(n) = 0; x_3(\hat{n}) = 0;
  22. End if

Output: The three-layer superimposed transmitted signal: $x_f(n) = x_1(n) + x_2(n) + x_3(n)$.

The PAPR of the three-layer superimposed signals becomes [24]:

$$\text{PAPR (dB)} = 10 \log_{10} \frac{\max_{0 \leq n \leq N-1} |x_f(n)|^2}{E[|x_f(n)|^2]}$$

Figure 3 shows the CCDF performance of the proposed non-redundant three-layer PAPR reduction scheme for OFDM-based VLC and FBMC based VLC systems with $s = 0.3$ and $A_3 = 0.6$. The original VLC_FBMC and VLC_OFDM signals with no PAPR reduction provide high PAPR up to 7.5 dB and are affected by the limited range of LED’s linearity at CCDF = $10^{-3}$.

### IV. RESULTS AND DISCUSSION

Results of simulations are obtained in this section in order to assess the efficiency of the proposed techniques in terms of CCDF and BER performance for 128 subcarriers with 4-QAM. The overlapping factor $K = 4$ was implemented with a CP of length $l_p = 16$ of OFDM. The range of scaling factor is $0 \leq s \leq 0.5$. Implementing FBMC will improve spectrum efficiency while addressing the challenges of complexity and high PAPR [6]. In a traditional VLC scheme based on OFDM or FBMC, bias values equal to the absolute minimum value are applied. Several state-of-the-art methods are used for comparison: Hadamard transform with clipping ratio=1.8 [20], Discrete cosine transform, and clipping ratio=1.8 [24] in term of PAPR and BER performance.

### A. PAPR REDUCTION PERFORMANCE

The proposed non-redundant three-layer PAPR reduction technique is shown to provide CCDF performance more than 3.1 dB better than original VLC_OFDM signals with no PAPR reduction techniques [28]. The proposed technique in the case of FBMC based VLC provides CCDF performance slightly better than that in VLC_OFDM by 0.2 dB. The proposed scheme is shown to provide CCDF performance more than 4 dB better than hadamard transform with CR=1.8 [20] and 3.3 dB better than DCT with CR=1.8 [24], respectively.

### B. BER PERFORMANCE

Figure 4 demonstrates the BER performance of the proposed three-layer PAPR reduction technique for FBMC based VLC systems with $s = 0.3$. The proposed Three-layer PAPR reduction scheme provides BER performance better than conventional FBMC based VLC [29].

The scaling factor $s$ in Eq. (7) plays an important trade-off between PAPR reduction and BER performance.
The proposed technique provides BER as low as 3 dB, 2 dB and 1 dB than conventional OFDM-based VLC, conventional FBMC based VLC, and proposed OFDM-based VLC systems, respectively.

The conventional OFDM-based VLC and conventional FBMC based VLC signals with no PAPR reduction technique are affected by the limited range of LED's linearity, resulting in signal distortion. The signals out of the scope of LED's linearity are clipped and cannot be transferred over LED for transmission. The proposed non-redundant three-layer PAPR reduction scheme is shown to provide BER performance better than existing methods: Hadamard transform with CR = 1.8 [20] and DCT with CR = 1.8 [24], respectively.

C. EFFECT OF SCALING FACTORS

Figures 5, 6 demonstrate the effect of scaling factor $s$ on the CCDF performance of the proposed non-redundant three-layer PAPR reduction technique for VLC-OFDM and FBMC based VLC systems, respectively. In the OFDM-based VLC system, Fig. 5 is shown to provide improved CCDF performance of the proposed PAPR reduction technique with a higher value of scaling factor $s$ used. This verifies the performance analysis in terms of the impact of $s$ on the CCDF performance. The best value of CCDF performance at $s = 0.3$.

The scaling factor $s$ plays a necessary trade-off between PAPR reduction and BER performance. The higher the scaling factor's value, the severer the PAPR reduction is, verified by figures 5, 6. However, the increasing value of the scaling factor reduces transmitted signal power, resulting in worse BER. Therefore, there is a selection of $s$ to achieve good PAPR reduction and good BER performance.

In VLC-FBMC, fig. 6 is shown to provide consistent CCDF performance of the proposed PAPR reduction technique with the varying value of $s$. The CCDF performance is better in VLC-OFDM, which verifies the performance analysis in terms of the effect of $s$, shown in fig. 7. Therefore, in order to provide a good trade-off between PAPR reduction and BER performance, we set $s = 0.3$ in the simulation results.

D. EFFECT OF LIMIT BOUNDARY $A_3$

Figure 8 demonstrates the effect of limit boundary $A_3$ on the CCDF performance of the proposed non-redundant
three-layer PAPR reduction technique for OFDM-based VLC and FBMC based VLC systems in the cases with $A_3 = 0.3$, $A_2 = 0.6$, and $s = 0.3$. Fig. 8 is shown to provide CCDF performance of the proposed PAPR reduction technique improved with a higher value of $A_3 = 0.6$ than $A_3 = 0.3$ by $0.5$ dB. As for computational complexity, the FBMC-based VLC system’s computational complexity is greater than that of the OFDM-based VLC system, primarily due to the increased FFT size and additional filtering processes.

**V. CONCLUSION**

In this paper, we proposed a non-redundant three-layers PAPR reduction technique for FBMC based VLC systems, in which the FBMC based VLC data signal is overlapped with two new non-redundant signals. One to decrease the large amplitude of FBMC modulated signals, while the other is used to improve its small-amplitude signals. Comparisons were made between the FBMC based VLC system and OFDM-based VLC using the proposed technique. The results show that the proposed technique can achieve good CCDF performance, especially when using $A_3 = 0.6$. Moreover, we can achieve a good trade-off between PAPR reduction and BER performance when selecting a scaling factor of $s = 0.3$. Thus, the proposed PAPR reduction scheme outperforms some state-of-the-art methods [20] and [24], in terms of BER performance. With the FBMC based VLC system, the proposed non-redundant three-layer PAPR reduction technique gives good values for different values of $s$ and $A_3$ is compared with the OFDM-based VLC system. However, FBMC-based VLC system’s computational complexity is greater than that of the OFDM-based VLC system, primarily due to the increased FFT size and additional filtering processes.

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