A Low-Complexity PAPR Reduction for Optical OFDM in Visible Light Communication System Using Partial Transmit Sequence Techniques

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***Abstract*—The high peak to average power ratio (PAPR) was one of the main factors affecting the performance in visible light communication (VLC) system, which was based on the orthogonal frequency division multiplexing (OFDM) technology. This paper proposes a sub-optimization scheme to decrease the high PAPR of optical orthogonal frequency division multiplexing (OOFDM) signals in VLC systems. The method is to combine the partial transmit sequence (PTS) technique to reduce the PAPR which causes nonlinear signal distortions and high power requirements that damages to VLC transmitter (light emitting diode, LED) at the signal transmission as well as increases the complexity in retrieving the original signal at the VLC receiver. The results show that the proposed method improves the PAPR reduction performance.**

Keywords**—**OOFDM, PAPR Reduction, VLC, PTS.

Introduction

Recently, visible light communication (VLC), which is emerging as a promising technology, has gained significant attention in the field of wireless transmission technologies [1]. Compared to conventional radio frequency (RF) communication, VLC enjoys several unique advantages such as abundant unlicensed optical spectrum and extremely high data rates. Orthogonal frequency division multiplexing (OFDM) has been adopted in a large variety of communication standards due to its robustness to channel impairments, simple equalization, and efficient implementation using the fast Fourier transform (FFT). In order to improve data rate and mitigate inter-symbol interference (ISI) caused by a dispersive channel, orthogonal frequency division multiplexing (OFDM) is employed in VLC [2], [3], which is also known as discrete multitone (DMT) in wired communication like asymmetric digital subscriber line (ADSL). A particularly difficult challenge in applying OFDM techniques to visible light communication (VLC) optical wireless systems is the need for wideband high current drivers which can accommodate the large peak-to-average power ratio (PAPR) of OFDM [4]. Visible light communications (VLC) has attracted an increasing interest in the field of next generation wireless transmission technologies. According to recent market research report, the global VLC market size is expected to grow at compound annual growth rate (CAGR) of 87.31% by 2020 [5]. The main property of VLC system is its ability to provide illumination and communication simultaneously as well as it supplements the unlicensed spectrum resource. In addition, the enhancements of power efficiency and cost reduction enable light emitting diode (LED) to be deployed in VLC applications. It is possible to use a LED as a transmitter for optical wireless communication because it can be switched on and off at a relatively high speed compared to conventional lighting sources. Hence, utilizing the OFDM with VLC system is also a research hotspot [6-9] as OFDM is especially suited for an optical wireless communication system like VLC. While OFDM offers many advantages for indoor VLC systems, it has a number of disadvantages. The performance of VLC systems using intensity-modulation direct-detection (IM/DD) along with OFDM modulation is significantly influenced by nonlinear characteristic of the LED. PAPR reduction technique is considered to mitigate the clipping distortion. In the literature of [7]–[14], several low PAPR algorithms designed for DCO-OFDM are proposed to reduce the peak amplitude and the power of clipping noise accordingly. PAPR reduction of VLC-OFDM signals via signal clipping is straightforward and widely used in the literatures due to its simplicity [5-8]. These methods introduce the additional complexity for both the transmitter and receiver and the negative effects such as data rate loss and bit error rate (BER) performance degradation could not be neglectedIn this work, we investigate the performance of an optical OFDM based VLC system and propose a new method for reducing the PAPR. Moreover, the use of PTS technique has not been fully investigated so far in VLC system and only few researches considered the application of PTS method to reduce the PAPR of OFDM signals in VLC system [8-112].

In this paper, we propose a clipping noise mitigation method using partial transmit sequences (PTSs), for OFDM-based Optical wireless communication (OWC) systems. PTS is a well known approach for PAPR mitigation in OFDM systems [13-15]. Basically, input data block is partitioned into several clusters and each cluster is multiplied by a phase factor. Phase values are selected in such a way that the sum of phase shifted blocks gives a time domain signal with minimized PAPR.

1. SYSTEM MODEL DESCRIPTION

In VLC system, the OFDM baseband signal is used to modulate the intensity of the light, rather than its amplitude and phase. Therefore, the OFDM baseband signal must be real signal. Moreover, the modulated light intensity use the envelope variation of the OFDM signal, instantaneous power of LED light could not be negative, so the input signal is not negative. Hence, modulation signals have to be both real and unipolar. However, conventional OFDM signals are both complex and bipolar in nature. It is possible to obtain a real OFDM signal by imposing Hermitian symmetry (HS) in the inverse fast Fourier transform (IFFT) operation during the signal generation step. To ensure a unipolar signal, a straightforward approach is to add a dc-bias current to the signal to make it positive. This is known as the dc-offset optical OFDM (DCO-OFDM) scheme. The addition of a constant dc-bias current results in a highpower requirement [2]. Performance analysis of DCOOFDM in VLC System can be found in [10]. Nevertheless, for indoor VLC systems that are designed for lighting applications, this power constraint is not very significant as the constant dc-bias current is regardless required to provide a constant level of room illumination. First, the input data bits are mapped based on the considered quadrature amplitude modulation (QAM) constellations. The generated complex QAM are mapped onto a vector $\mathbf{X}_k$ after modulating the odd subcarriers only and setting the even subcarriers to zeros as well as imposing the Hermitian symmetry (HS) to the frequency domain subcarriers. The odd frequency and Hermitian constraint together mean that there are only $N/4$ independent complex input values for an N point IFFT.

$$\mathbf{X}_K = \left[\ X_0,\ \mathrm{X}_1,\ \cdots,\ X_{N/2},\ X^*_{N/2-1}, \cdots, X^*_{2}, X^*_1\right] \quad (1)$$

where N is the number of subcarriers and $(\cdot)^*$ denotes the complex conjugate operation [13], which are fed to the IFFT Cyclic Prefix (CP) blocks where all values of $\mathbf{X}_k = 0$ for k even including $\mathbf{X}_0$ and the $\mathbf{X}_{N/2}$ subcarriers to ensure the HS property whereas the odd indexed subcarriers are mapped with QAM symbols.

$$x_n = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X_i e^{j2\pi ni/LN}, \quad 0 \le n \le N-1 \qquad (2)$$

where can also be written in matrix form $\mathbf{x} = [x_0, x_1, \cdots, x_{N-1}]^T = \mathbf{DX}$, where $\mathbf{D}$ is the DFT matrix with the (n,k) the entry $d_{n,k} = (1/\sqrt{N})e^{j2\pi nk/N})$, where $j = \sqrt{-1}$, and n stands for a discrete time index.

The generated bipolar signal, x_n, is then converted to unipolar through clipping of all negative values at zero before modulating the LED. Since OFDM signals are modulated independently in each subcarrier, the combined OFDM signals are likely to have large peak powers at certain instances. The peak power increases as the number of subcarriers increases. Therefore, in the discrete-time case, the PAPR of the transmitted signals of each antenna is defined as

$$PAPR(x) = 10\log_{10} \frac{\max\limits_{0\le n\le LN-1} |x_n|^2}{E\left[|x_n|^2\right]}, \qquad (4)$$

where the numerator represents the maximum envelope power and the denominator represents the average power, the PAPR should be considered jointly and the signal pair with the lowest PAPR is selected for transmission. Therefore, the PAPR of the OFDM [9-11] system is defined as

$$PAPR(\mathbf{x}) = \max_{i=1,2} \{PAPR(\mathbf{x}_i)\} \qquad (5)$$

where $\mathrm{x} = [\mathrm{x}_1 \ \mathrm{x}_2 \ ]$. Usually, Complementary Cumulative Distribution Function (CCDF) is used to show performance measure for PAPR reduction techniques. It calculates the probability that the PAPR of a data block exceeds a given threshold $PAPR_0$ and computed by Monte Carlo Simulation.

Partial transmit sequence (PTS) is individually applied to each transmitting antenna in a straightforward manner, called ordinary PTS. As it is shown in [15], at each antenna, the frequency domain sequence of OFDM systems with D subcarriers is firstly partitioned into M disjoint subblocks. In the case of O-OFDM, signal in time domain has to be real-valued, and hence if the same procedure is followed, phase factors are constrained to be real, i.e., {+1,-1}. In the PTS method, the data information in the frequency domain $X(n)$ is partitioned into M clusters as $X(n)$, $(1 \le m \le M)$). All sub-carriers for each cluster are multiplied by the weighting factor, $b_k^m = e^{j\varphi_k^m}$ so as to reduce the PAPR performance. Here, the phase value considered in each cluster is given by the following equation.

$$\varphi_k^m = \frac{2\pi i}{W}, \quad i = 1, 2, W-1 \qquad (6)$$

where W is the number of predetermined discrete phase. After multiplying the weighting factor for each cluster, the subcarrier vector is given by the following equation.

$$x_k = \sum_{m=1}^{V} (b_k^m X_n^m) \qquad (7)$$

where, b_k^m is the weighting factors, which are required to inform the receiver as the side information. The set of weighting factor for M clusters are optimized in the time domain so as to achieve the better PAPR performance, by

$$\hat{x}_k = \sum_{m=1}^{V} (b_k^m \cdot X_k^m) \qquad (8)$$

Finally, at each transmitting antenna, there are (V-1) subblocks to be optimized, and the candidate sequence with the lowest PAPR is individually selected for transmitting. Assume that there are W allowed phase weighting factors. To achieve the optimal weighting factors for each transmitting antenna, W^{V-1} combinations should be checked in order to obtain the minimum PAPR. From (5) to (6), it can be seen that the weighting factor can be multiplied either in the frequency or time domains and the optimized PAPR performance is the same as that given by

$$\xi(\mathbf{b}) = \arg \min_{0 \le w \le W} \max_{0 \le n \le L-1} \left| \sum_{m=1}^{M} (b_k^m x_n^M) \right| \qquad (9)$$

where ξ is optimized argument that can reduce to the lowest PAPR performance. Then, among all the alternative signals, we choose the signal with the lowest PAPR as the transmitted signal. Therefore the optimal phase rotation sequence $\{ \ \hat{b}_0, \hat{b}_1, \cdots, \hat{b}_{M-1} \ \}$ is chosen as

$$f(\mathbf{b}_i) = \arg \min_{b_M \in [-1,1]} (\max_{0 \le w \le W} |\tilde{Q}(b_i)|) \ (10)$$

As mentioned above, in each cycle of our proposed method, at the initial step, phase factor optimizations memorize a global optimum phase vector with the best fitness from the randomly produced phase vectors. Next, phase factor test sets produce the neighbor candidate phase vector around the optimum phase vector and its fitness value is evaluated. If the fitness value of the new phase vector is better than that of the previous one, they memorize the new one, otherwise they keep the previous one. After phase factor test sets complete the search process, they will share the fitness value of the phase vector and the phase vector information with the phase factor optimizations. The phase factor optimizations determine a phase vector with a high probability based on its fitness value and produce the neighbor candidate phase vector around the optimum phase vector. The phase factor optimizations use the greedy selection process in that if the fitness of the candidate phase vector is better than that of the present one, they forget the present one and memorize the candidate phase vector. Otherwise, they keep the present one in the memory. After all phase factor optimizations are distributed, they compare the fitness of the global optimum phase vector with that of the final best candidate phase vector. If the fitness of the final best candidate phase vector is better than that of the global optimum one, they will memorize the final best candidate phase vector as the new global optimum phase vector for the next cycle. Otherwise, they keep the global optimum phase vector in memory for the next cycle. After the phase vector test sets and the phase factor optimizations complete their searches, if the fitness value of the phase vectors cannot be improved by a predetermined number that is called limit, a renew phase factor set is produced to replace the exhausted phase vector associated with that fitness value. This prevents the algorithm from being trapped in the same phase vector for the whole cycles. All these steps will be repeated until the maximum number of cycles K is reached. The fitness value of the phase vector bi is determined as:

3. PAPR Reduction Scheme for OOFDM Systems

Firefly algorithm (FA) is a novel nature-inspired algorithm inspired by social behavior of fireflies. The FA was developed by Yang [16-17], and is proposed for several different optimization applications. FA is based on this exclusive flashing behaviour of the fireflies. Fireflies are a family of insects which are commonly found in tropical environment. The fireflies are also called lighting bugs, because of their apparent use of bioluminescence during twilight to attract mates or prey. In the case that the brightness of fireflies has the same value, they will move randomly. The brightness of a firefly at some distance r of its location varies with the value of an objective function, which can be defined as

$$I(r) = I_0 e^{-\gamma r^2} \tag{11}$$

where I_0 is the maximum brightness when $r = 0$; it is related to the value of the objective function, and a larger value means brighter. Here, γ is the light absorption coefficient. The attractiveness of a firefly at some distance r of its location is proportional to its light brightness observed by adjacent fireflies; it can be expressed as attractiveness β of the fireflies varies according to the equation given by

$$\beta(r) = \beta_0 e^{-\gamma r^2}, \tag{12}$$

where β_0 is the attractiveness when the distance between two fireflies is zero. In this paper, we simply set $I(r) = \beta(r)$. The distance between two fireflies i and j at positions x_i and x_j can be defined as

$$r_{ij} = \left\| X_i - X_j \right\| = \sqrt{\sum_{k=1}^{l} \left(x_{i,k} - x_{j,k} \right)^2} \tag{13}$$

The equation that updates the jth firefly's location based on the ith firefly's attraction can be described as

$$x_i^j = x_i + \beta_0 e^{-\gamma r_{ij}^2} (x_i - x_j) + \alpha(rand - \frac{1}{2}) \tag{14}$$

where x_i and x_j are the initial position of the jth and ith fireflies, respectively, α is a constant within [0, 1], *rand* is a random number within [0, 1], and x_{ij} is the distance between the ith and jth fireflies. At each iterative step, the brightness and the attractiveness of each firefly is computed. The brightness of each firefly is compared with all other fireflies and the positions of the fireflies are updated using equation (14). In the following, we employ the FA method to search the optimal phase factor for the PTS technique in order to reduce the PAPR.

4. Simulation Results

Performance improvement gained with PTS approach is presented in this section. In this section, some simulations have been conducted to evaluate the capability of the proposed FA-PTS scheme including the PAPR reduction of performance. The phase rotation factors are chosen as $b_V \in \{-1, +1\}$. the 16-QAM modulation is employed with M=2, 4 and 8, respectively. The side information is assumed to be known at the receiver. PTS is flexible as the number of blocks and phase rotations can be increased providing more alternative transmit signals to choose from. The disadvantage of this scheme is the complexity, especially with an increase in V and W. Also, a large amount of memory is required to store the alternative transmit signals (if check performed in parallel) in order to compare them to find the one with the lowest peak value. Alternatively the optimization can be performed in an iterative fashion where the current best transit signal is stored until a better one is found, at the cost of increased latency.

It should also be noted that the data can be divided into sub blocks in different ways as noted in reference [15] and shown in Figure 1. Different PTS sub block structures have varying performance with pseudo random having the best and interleaving having the worst. Of course there is a trade off with complexity, interleaved sub blocks are the least complex PTS structure to implement and pseudo random PTS is the most complex (random sequences require more hardware complexity to implement in this case). Also computationally efficient IFFT's can be used to exploit the number of zero's in the PTS sub-blocks. Results from reference [15] indicate that pseudo-random partitioning is 0.5 to 0.9dB better than adjacent partitioning. It should be noted that no guaranteed level of PAPR reduction can be provided with FA-PTS techniques, all they can do is reduce the probability of large peaks. Figures 1 and 2 show CCDF results with varying factors of V and W.

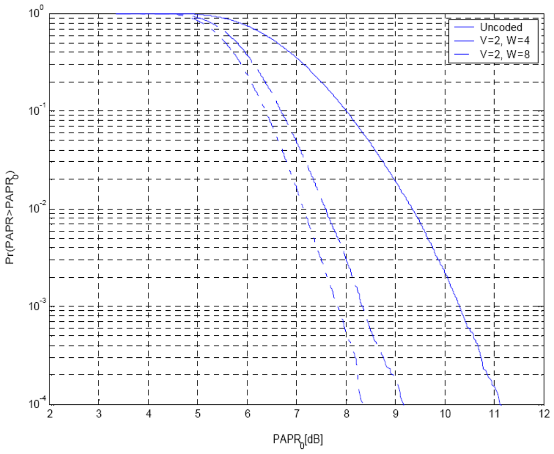

Fig. 1 Simulated CCDF for PTS-OOFDM with V=2 and varying W.

From this fact, we could confirm that the PAPR performance of OOFDM signal would be depend on the number of iterations as the same as the conventional OFDM system. The PAPR performance of proposed method can be converged firstly as compared with the CPTS method. Fig. 2, as the maximum number of M is increased, then, the CCDF of the PAPR has a better performance From the Figure 1, it can be seen that the $PAPR_0$ of FA-PTS is 6.8 dB, 7.53dB, 9.2 dB, and OFDM is 11.2 dB at CCDF of 10^{-4}, respectively. The proposed FA-PTS method shows the better performance.

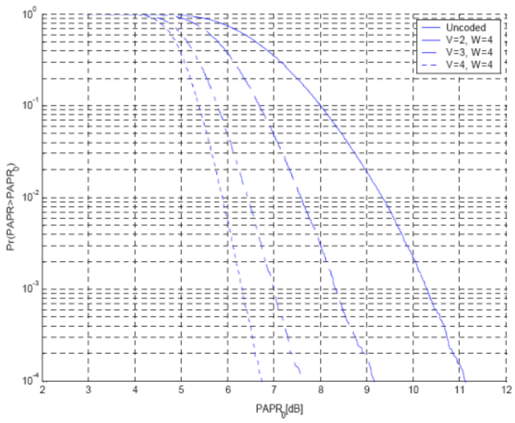

Fig.2 Simulated CCDF for PTS-OFDM with W=4 and varying V.

So, it is observed that quantity improvement in PAPR is dependent on the number of V and W used for OOFDM generation, and the optimization algorithms provide improvement in PAPR performance in each case. From the above descriptions, we can see that FA-PTS is a effective technique for reducing the PAPR of OOFDM system, even with the large number of V and W.

5. Conclusion

In this paper, a new PAPR reduction method for an optical OFDM-based VLC system is developed. OOFDM transmission schemes are compared in terms of PAPR and error rate performance. Finally, FA based PTS scheme is proposed to search the optimal combination of phase weight factor of OOFDM signals. In order to further improve the BER performance of the proposed system, future works will initially include the channel estimation methods and investigate their impact on the PAPR of the optical OFDM signals in the proposed VLC model.

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