PAPR Reduction for OFDM/OQAM Signals Using Offset-Symbols Joint SLM Method

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Abstract —A novel offset-symbols joint selective mapping (J-SLM) scheme is proposed for the peak-to-average power ratio (PAPR) reduction in the Orthogonal Frequency Division Multiplexing with Offset Quadrature Amplitude Modulation (OFDM/OQAM) system. By exploiting the dispersive energy of the prototype filter, the proposed J-SLM scheme multiplies the real and imaginary parts of each data block with different phase rotation factors, and then adopts a sequential optimization procedure to jointly optimize the real and imaginary parts for each data block. Simulation results show that the J-SLM scheme could offer much better PAPR reduction and Bit Error Rate (BER) performances than the available SLM-based schemes of OFDM/OQAM signals.

Index Terms—Orthogonal Frequency Division Multiplexing (OFDM), Offset Quadrature Amplitude Modulation (OQAM), Peak-to-Average Power Ratio (PAPR), Selective Mapping (SLM)

I. INTRODUCTION

Recently, Orthogonal Frequency Division Multiplexing with Offset Quadrature Amplitude Modulation (OFDM/OQAM) has drawn much attention [1]-[3]. OFDM/OQAM offers increased bandwidth efficiency as well as low out of band interference by employing a bank of well-defined filters with tight spectral characteristics [4], [5]. However, OFDM/OQAM systems still suffer from high Peak-to-Average Power Ratio (PAPR) inherent in multicarrier systems, such as OFDM. The large PAPR greatly degrades the efficiency of High-Power Amplifiers (HPA) and requires large back off of HPA from its output saturation point in order to operate in the linear region and avoid clipping [6].

Various schemes of OFDM signals have been proposed to tackle the PAPR problem, such as clipping [7], Tone Reservation (TR) [8], Partial Transmit Sequence (PTS) [9], Selective Mapping (SLM) [10], Active Constellation Extension (ACE) [11], among others schemes [12]-[15]. However, the signals of adjacent data blocks are independent in the OFDM system, while they overlap with each other in the OFDM/OQAM system. Therefore, it is not very effective to directly employ these methods in OFDM/OQAM systems.

To reduce the PAPR of OFDM/OQAM signals, several proposals have been studied in the literatures. The clipping methods [16], [17] were introduced to the OFDM/OQAM systems, and these methods increased the Bit Error Rate (BER) and enlarged the sidelobe. To improve the BER performance, the clipping-based iterative PAPR reduction scheme [18] was employed, but it may sacrifice the throughput. An ACE-based linear programming optimization method [19] is discussed to reduce the PAPR of OFDM/OQAM signals, but ACE is an iterative method and the high computational complexity results in an unaffordable implementation. A Sliding Window Tone Reservation (SWTR) technique [20] is proposed to control the peak regrowth and provides good results. However, the addition of reserved tones results in a bandwidth efficiency loss. The PTS-based schemes were presented in [21] and [22] for OFDM/OQAM systems. A multi-block joint optimization (MBJO) with PTS method [21] is proposed and achieves a good PAPR performance. However, the computational complexity of utilizing a trellis for the optimization of the ideal PTS sequence is high and may make this method infeasible in practice. A segmental PTS scheme [22] is proposed with low complexity, but the PAPR performance is poor when the length of segment is long. The SLM-based PAPR method [23]-[25] is another way to reduce the PAPR of OFDM/OQAM signals. The key idea of this method is to reduce the PAPR by imposing the optimal phase rotation vector on the current data block by considering the overlapping feature of multiple data blocks. In [23], an overlapped SLM (OSLM) scheme was introduced to reduce the PAPR of OFDM/OQAM signals. But the PAPR reduction performance was poor because only the current interval of the phase rotated symbol is considered for PAPR calculation. An improved OSLM scheme which is called dispersed SLM (DSLM) is proposed in [24]. For the DSLM method, the current data block and the previous data blocks are jointly considered to choose the optimal phase rotation sequence. Although DSLM method improves the PAPR performance compared to OSLM method, it still uses step-by-step optimization that optimizes each data block separately. A method called as Alternative Signal (AS) method [25] was employed to reduce the PAPR of OFDM/OQAM signals. The independent AS (AS-I) method reduces the PAPR of each OFDM/OQAM symbol independently, and

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the joint AS (AS-J) algorithm applies joint PAPR reduction among M OFDM/OQAM symbols. AS-J can yield a better performance than AS-I, but the computation complexity of AS-J exponentially increases with M. To reduce the computation complexity of AS-J method, a sequential AS (AS-S) algorithm is proposed and which adopts a sequential optimization procedure over time with the complexity linearly increasing with M. Duo to the OFDM/OQAM signal spreading beyond one symbol period, the PAPR performance of AS-S degrades substantially with the dispersive energy of the prototype filter. This is a possible indication that the overlapping nature of OFDM/OQAM symbols is not addressed fully.

In this paper, we propose a novel offset-symbols joint SLM scheme, termed as J-SLM scheme for simplicity, to reduce the PAPR of OFDM/OQAM signals. Unlike existing SLM-based PAPR reduction schemes of optimizing each data block, the proposed J-SLM scheme exploits the dispersive energy of the prototype filter and the real and imaginary parts offset modulation feature of QAM symbols, and multiplies the real and imaginary parts of each data block with different phase rotation factors, and then adopts a sequential optimization procedure to jointly optimize the real and imaginary parts of each data block. Simulation results verify that the proposed J-SLM scheme could offer better PAPR reduction and BER performances than the available SLM-based schemes for OFDM/OQAM systems.

The rest of this paper is organized as follows. The OFDM/OQAM signal model is introduced in Section II. The J-SLM scheme for the PAPR reduction of OFDM/OQAM signals is proposed in Section III. The simulation results to illustrate the performance of our proposed scheme are presented in Section IV. Finally, the conclusions are drawn in Section V.

II. System Description and Signal Model

OFDM/OQAM systems consist of a bank of well defined filters with tight spectral characteristics. These filters are frequency and phase-shifted versions of an original prototype filter satisfying the perfect reconstruction condition [2]. In an OFDM/OQAM system, the complex symbols are modulated based on OQAM, and the M complex data blocks with N subcarriers at the transmitter can be written as

$$\mathbf{C} = [\mathbf{C}_0, \cdots, \mathbf{C}_m, \cdots, \mathbf{C}_{M-1}] \tag{1}$$

where $\mathbf{C}_m$ is the mth data block and which is defined as $\mathbf{C}_m = [C_{m,0}, \cdots, C_{m,n}, \cdots, C_{m,N-1}]^T$ with $C_{m,n} = a_{m,n} + jb_{m,n}$ for $0 \le m \le M-1, 0 \le n \le N-1$. OQAM is a staggering technique used to transform complex input data symbols into real symbols at twice the sampling rate [4]. OQAM is used in OFDM to ensure that only real symbols are fed into the filter bank. The real and imaginary components of each modulated symbol are staggered in the time domain by $T/2$, where T denotes the complex symbol interval. Then, the real and imaginary parts of modulated symbol are passed through a bank of transmission filters and modulated with N subcarriers where the spacing between every two sub-carriers is $1/T$. The baseband signal of the mth data block over the nth sbcarrier for OFDM system can be written as

$$s_{m,n}(t) = \begin{Bmatrix} \theta_n a_{m,n} h(t-mT) + \\ \theta_{n+1} b_{m,n} h(t-mT-\dfrac{T}{2}) \end{Bmatrix} e^{j\frac{2\pi}{T}nt} \tag{2}$$

with

$$\theta_n = \begin{cases} 1 & \text{if } k \text{ even} \\ j & \text{if } k \text{ odd,} \end{cases}$$

where $h(t)$ is the impulse response of the prototype filter and the length of $h(t)$ is KT where K is the oversampling factor. The OFDM/OQAM signal of the mth data block in the time domain can be written as

$$s_m(t) = \sum_{n=0}^{N-1} \begin{Bmatrix} \theta_n a_{m,n} h(t-mT) + \\ \theta_{n+1} b_{m,n} h(t-mT-\dfrac{T}{2}) \end{Bmatrix} e^{j\frac{2\pi}{T}nt}$$
$$mT \le t \le (m+K+\frac{1}{2})T \tag{3}$$

For all M data blocks, the transmitted OFDM/OQAM signals in the time domain for $0 \le t \le (M+K-\frac{1}{2})T$ is

$$s(t) = \sum_{m=0}^{M-1} s_m(t) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} \begin{Bmatrix} \theta_n a_{m,n} h(t-mT) + \\ \theta_{n+1} b_{m,n} h(t-mT-\dfrac{T}{2}) \end{Bmatrix} e^{j\frac{2\pi}{T}nt} \tag{4}$$

Since the OFDM/OQAM signals are overlapped with adjacent data blocks caused by the bank of filters, the general definition of PAPR for OFDM systems is no longer applicable to OFDM/OQAM systems [15]. Let $I_m = [m, (m+1)T]$ be the mth interval for $m \in [0, M-1]$, the PAPR for $s(t)$ on the interval I_m is defined as

$$\text{PAPR}(s_m) = \frac{\max\limits_{mT \le t \le (m+1)T} |s(t)|^2}{E\{|s(t)|^2\}} \tag{5}$$

where $E\{\cdot\}$ denotes the expectation operator and the denominator in (5) represents the average power of OFDM/OQAM signals.

III. Proposed Method for the PAPR Reduction

In this section, the effect of prototype filter for peaks of OFDM/OQAM signals is discussed. Then, we propose a novel J-SLM method to reduce the PAPR of OFDM/OQAM signals and explain its implementation with complexity analysis.

A. Effect of Prototype Filter forPAPR of OFDM/OQAM Signals

From (4), the OFDM/OQAM signals of adjacent data blocks overlap with each other and the peak power of OFDM/OQAM signals will affected by the energy of prototype filter due to the fact that, the impulse response of prototype filters in OFDM/OQAM systems has longer time duration than T. The impulse response of prototype filter $h(t)$ is set as the same as those in [4], [5], which is given as

$$h(t)=\begin{cases}\dfrac{1}{\sqrt{A}}[1+2\displaystyle\sum_{k=1}^{K-1}(-1)^k F_k\cos(\frac{2\pi kt}{KT})] & t\in[0,KT]\\ 0 & \text{otherwise}\end{cases} \quad (6)$$

where $A=KT[1+2\sum_{k=1}^{K-1}F_k^2]$ is the normalization factor, $K=4$ is the oversampling factor and F_k, $k=1,\cdots,K-1$, are given as

$$F_1=0.97195983,\ F_2=1/\sqrt{2},\ F_3=0.23514695 \quad (7)$$

The normalized amplitude of $h(t)$ with $T=64$ is shown in Fig. 1. From this figure, it can be seen that a given OFDM/OQAM symbol overlaps over its next three symbols while it significantly impacts two symbols which are the immediate preceding and succeeding symbols since the prototype filter has a time period of $4T$. Moreover, the large amplitude samples of $h(t)$ are located within $1.5T\le t\le 2.5T$. For $h(t-T/2)$, its large amplitude samples are located within $2T\le t\le 3T$. According to (3), we could obtain that the large-amplitude samples of $s_m(t)$ are located within $(m+1.5)T\le t\le(m+3)T$.

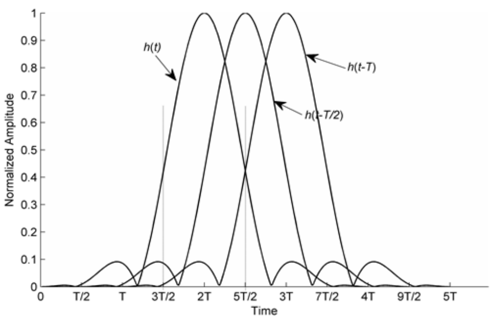

Fig. 1. Normalized amplitude of the impulse response of prototype filter.

Since most of the energy of prototype filter lies in the main lobe, the superposition of the real and imaginary parts of one complex symbol which passed through the prototype filter with time staggered $T/2$ makes the most contribution to the peaks of the OFDM/OQAM signals. Therefore, to obtain a good PAPR reduction performance of OFDM/OQAM signals, joint optimization of the real and imaginary parts of offset QAM symbols is a good choice.

B. Proposed J-SLM Method

Based on above analysis, a novel J-SLM method is proposed to reduce the PAPRA of OFDM/OQAM signals. We firstly divide each data block into real and imaginary parts, and each of which multiply the rotation phase vector from U sets. Then, two parts signals are taken into account to select the optimal phase rotation combination. Denote the set of candidate phase rotation vectors as

$$\mathbf{b}=\{\mathbf{b}^0,\mathbf{b}^1,\cdots,\mathbf{b}^u,\cdots,\mathbf{b}^U\} \quad (8)$$

where U is the size of $\mathbf{b}$, and $\mathbf{b}^u, 0\le u\le U-1$ is the u^{th} phase rotation vector with $\mathbf{b}^u=[b_0^u,\cdots,b_v^u\cdots,b_{N-1}^u]^T$.

The phase rotation factors b_v^u for all v and u are chosen from $\{1,-1\}$, since $\{1,-1\}$ is easily implemented and as good as any other phase sequence in terms of the PAPR reducing capability [26]. Define the mth data block as $\mathbf{C}_m=\mathbf{R}_m+j\mathbf{I}_m$ where $\mathbf{R}_m=[R_{m,0},\cdots,R_{m,n},\cdots,R_{m,N-1}]^T$ for $R_{m,n}=\Re(C_{m,n})$ and $\Re\{\ \}$ denotes the real part of a complex quantity. $\mathbf{I}_m=[I_{m,0},\cdots,I_{m,n},\cdots,I_{m,N-1}]^T$ for $I_{m,n}=\Im(C_{m,n})$ and $\Im\{\ \}$ denotes the imaginary part of a complex quantity. Let $\mathbf{b}_{m.R}^p=[b_0^p,\cdots,b_n^p,\cdots,b_{N-1}^p]^T$ be the pth phase rotation vector corresponding to $\mathbf{R}_m$, and $\mathbf{b}_{m,I}^q=[b_0^q,\cdots,b_n^q,\cdots,b_{N-1}^q]^T$ be the qth phase rotation vector corresponding to $\mathbf{I}_m$. Then, the mth data block with $\mathbf{R}^m$ and $\mathbf{I}^m$ multiplied by $\mathbf{b}_{m,I}^q$ and $\mathbf{b}_{m,I}^q$ for $p,q\in[0,U-1]$ can be expressed as

$$\bar{\mathbf{C}}_m^{p,q}=\mathbf{R}_m\otimes\mathbf{b}_{m,R}^p+j\mathbf{I}_m\otimes\mathbf{b}_{m,I}^q \quad (9)$$

where $\otimes$ denotes vector element-wise product and $\bar{\mathbf{C}}_m^{p,q}=[\bar{C}_{m,0}^{p,q},\cdots,\bar{C}_{m,n}^{p,q},\cdots,\bar{C}_{m,N-1}^{p,q}]^T$ is a $N\times 1$ vector with $\bar{C}_{m,n}^{p,q}=R_{m,n}b_{m,n}^{(p)}+jI_{m,n}b_{m,n}^{(q)}$.

Next, by using (3) and (4), the output signal for $0\le t\le(m+K+\frac{1}{2})T$ by considering the overlap of previous data blocks is

$$\hat{s}^{p,q}(t)=\sum_{l=0}^{m-1}\hat{s}_l(t)+\sum_{n=0}^{N-1}\begin{Bmatrix}\theta_n R_{m,n}b_n^{(p)}h(t-mT)+\\ \theta_{n+1}I_{m,n}b_n^{(q)}h(t-mT-\dfrac{T}{2})\end{Bmatrix}e^{j\frac{2\pi}{T}nt} \quad (10)$$

where $\hat{s}_l(t)$ is the output signal of the lth data block for $l\in[0,m-1]$ with the least peak power.

The PAPR reduction of OFDM/OQAM signals should come from the peak power reduction rather than the average power increasing, so the PAPR reduction problem can be formulated as

$$\min_{\mathbf{b}_{m,R}^{(p)},\mathbf{b}_{m,I}^{(q)}}\ \max_{mT\le t\le(m+K+\frac{1}{2})T}\left|\hat{s}^{p,q}(t)\right|^2,\ s.t.\ \mathbf{b}_{m,R}^{(p)},\mathbf{b}_{m,I}^{(q)}\in\mathbf{b} \quad (11)$$

To solve above problem in (11) and obtain the optimal phase rotation vectors $\mathbf{b}_{m,R}^{(p')}$ and $\mathbf{b}_{m,I}^{(q')}$ of real and imaginary parts of the mth data block, respectively. Thus, the output signals of the mth data block with the minimum peak power as

$$\hat{s}_m(t)=\sum_{n=0}^{N-1}\begin{Bmatrix}\theta_n R_{m,n}b_n^{(p')}h(t-mT)+\\ \theta_{n+1}I_{m,n}b_n^{(q')}h(t-mT-\dfrac{T}{2})\end{Bmatrix}e^{j\frac{2\pi}{T}nt},$$
$$mT\le t\le(m+K+\frac{1}{2})T \quad (12)$$

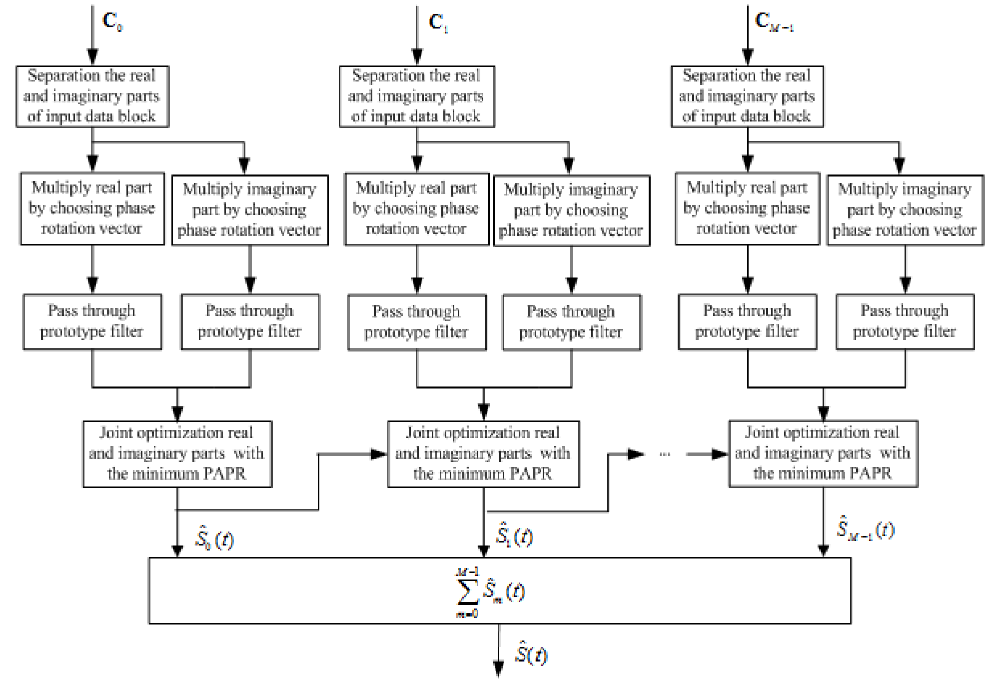

Fig. 2. Block of J-SLM PAPR reduction method.

From (12), by taking account of the previous overlapped signals, we adopt a sequential optimization procedure to jointly optimize the real and imaginary parts for each data block. Fig. 2 illustrates the key idea of the proposed J-SLM scheme.

Define $\mathbf{b}_{m-1}=[\mathbf{b}^{p'}_{m-1,R},\mathbf{b}^{q'}_{m-1,I}]$ are the selected rotation vectors for the real and imaginary parts of the (m-1)th data block and let $\mathbf{B}_m=(\mathbf{b}_0,\mathbf{b}_1,\cdots,\mathbf{b}_{m-1})$. Supposed that $\hat{s}_l(t)$ is the output signal of the lth ($l\in[0,M-1]$) data block with the least peak power. The proposed J-SLM algorithm can be described as follows:

1) Initialize the index of modulated data block $m=0$. Denote $\mathbf{B}_m$ as an empty matrix and $\hat{s}_l(t)=0$ for $l\le 0$.

2) Multiply $\mathbf{R}_m$ and $\mathbf{I}_m$ of the mth data block $\mathbf{C}_m$ by different phase vectors $\mathbf{b}^p_{m,R}$ and $\mathbf{b}^q_{m,I}$ for $p,q\in[0,U-1]$. The new OFDM/OQAM data block is expressed by

$$\bar{\mathbf{C}}^{p,q}_m=\mathbf{R}_m\otimes\mathbf{b}^p_{m,R}+j\mathbf{I}_m\otimes\mathbf{b}^q_{m,I} \tag{13}$$

3) Generate the OFDM/OQAM signal of the mth ($m\in[0,M-1]$) data block $\bar{\mathbf{C}}^{p,q}_m$ for $p,q\in[0,U-1]$ as

$$s^{p,q}_m(t)=\sum_{n=0}^{N-1}\left\{\begin{matrix}\theta_n R_{m,n}b^{(p)}_n h(t-mT)+\\ \theta_{n+1}I_{m,n}b^{(q)}_n h(t-mT-\dfrac{T}{2})\end{matrix}\right\}e^{j\frac{2\pi}{T}nt} \tag{14}$$

4) Select the optimal rotation vectors of real and imaginary parts of the mth data block by considering the overlap of previous data blocks as:

$$\{\mathbf{b}^{p'}_{m,R},\mathbf{b}^{q'}_{m,I}\}=\underset{\mathbf{b}^p_{m,R},\mathbf{b}^q_{m,I}\in\mathbf{b}}{\arg\min}\ \max_{mT\le t\le(m+K+\frac{1}{2})T}\left|\sum_{l=0}^{m-1}\hat{s}_l(t)+s^{p,q}_m(t)\right|^2 \tag{15}$$

5) Update the mth data block with the optimal phase rotation vectors:

$$\bar{\mathbf{C}}^{p',q'}_m=\mathbf{R}_m\otimes\mathbf{b}^{p'}_{m,R}+j\mathbf{I}_m\otimes\mathbf{b}^{q'}_{m,I} \tag{16}$$

The output signals of the mth data block with the minimum peak power is determined by

$$\hat{s}_m(t)=\sum_{n=0}^{N-1}\left\{\begin{matrix}\theta_n R_{m,n}b^{(p')}_n h(t-mT)+\\ \theta_{n+1}I_{m,n}b^{(q')}_n h(t-mT-\dfrac{T}{2})\end{matrix}\right\}e^{j\frac{2\pi}{T}nt},\quad mT\le t\le(m+K+\frac{1}{2})T \tag{17}$$

If $m+1>M$, the PAPR procedure stops, calculate $s(t)=\sum_{l=0}^{M-1}\hat{s}_l(t)$ and output the OFDM/OQAM signals of all M symbols. Otherwise, increase the index m and go to step 2).

When the sequential optimization procedure finishes, one obtains phase rotation vectors $\mathbf{B}_M=(\mathbf{b}_{0,R},\mathbf{b}_{0,I},\cdots,\mathbf{b}_{M-1,R},\mathbf{b}_{M-1,I})$ for all M data blocks. For the PAPR-reduced OFDM/OQAM signal, $\mathbf{B}_M$ is transmitted as side information for perfect recovery of the signal at the receiver. Obviously, $M\log_2(2U)$ bits are needed for SI transmission in total. At the receiver, if the SI is correctly received, the original data blocks can be successfully recovered.

C. *Computational Complexity*

The computational complexity of the J-SLM method can be evaluated in terms of number of real multiplications (RMs) and real additions (RAs) required for all M data blocks. As indicated in (12), the $2NU^2$ RMs are required of one data block where U is the number of phase rotation sequences and $2U^2$ phase rotated real and imaginary parts are passed through the filters with $2NU^2KT$ RMs. Next, NU^2KT complex multiplications (CMs) and (N-1)U^2KT complex additions (CAs) are needed for subcarrier modulation in (13). Then, U^2 candidate signals of each data block are added to the previous signal with U^2KT CAs in (14). Finally, NU^2KT $|\ |^2$ operations are needed in (15) to compute the power of output samples of OFDM/OQAM signals. Consider that one CM is equivalent to four RMs and two RAs, one CA is translated into two RAs, and $|\ |^2$ represents two RMs and one RA. Thus, the numbers of the RMs and RAs for all M data blocks are $MNU^2(2+8KT)$ and $5MNU^2KT$, respectively.

The complexity of the J-SLM scheme is summarized in the first line of Table I. For comparisons, in the second line and the third line of Table I we report the computational complexity of the AS-S and AS-I methods in [25].

TABLE I: COMPLEXITY COMPARISONS FOR DIFFERENT PAPR SCHEMES

Algorithm	Number of RAs	Number of RMs
Proposed J-SLM	$MNU^2(2+8KT)$	$5MNU^2KT$
AS-S	$MNU(2+7KT)$	$5MNUKT$
AS-I	$MNU(2+7KT)$	$(5N-2)MUKT$

IV. SIMULATION RESULTS

The performance of the proposed J-SLM method has been assessed by computer simulations. The considered OFDM/OQAM system has $N=64$ subcarriers with 16QAM modulation. The oversampling factor is $K=4$ and the length of prototype filter is $4T$. There are 10^3 data blocks randomly generated and the PAPR observation interval is set to be T. Transmission of the side information of the phase factors is not considered in the simulation. The Rapp model in [14] is used to describe the nonlinearity of solid state power amplifier (SSPA) in the transmission. When the time-domain samples at the SSPA input is $s(n)=\rho_n e^{j\theta_n}$, the output of the SSPA model can be expressed as

$$y_n = A(\rho_n)e^{j\theta_n} \tag{18}$$

where $\rho_n = |s_n|$, $\theta_n = \arg(s_n)$ and $A(\cdot)$ denotes the amplitude conversion of SSPA. A typical SSPA introduces amplitude distortion, which can be described as

$$A(\rho_n) = \rho_n \left[1+\left(\frac{\rho_n}{A_{sat}}\right)^{2p}\right]^{\frac{-1}{2p}} \tag{19}$$

where A_{sat} denotes the maximum output and p is the smoothness factor of the transition from the linear region to the limiting region of SSPA. The input back-off (IBO) parameter is defined as

$$IBO = 10\log_{10}\frac{A_{sat}^2}{P_{in}} \tag{20}$$

where P_{in} denotes the average power of OFDM/OQAM signals at the SSPA input. We assume that the SSPA simulated with a smoothness parameter p = 3 and $IBO = 6dB$.

Comparisons are made with the AS-I and AS-S methods in [25] under a common simulation setup. The channel between the transmitter and the receiver is modeled as an additive white Gaussian noise channel. The complementary cumulative density function (CCDF) of PAPR is employed as the measurement for the PAPR reduction, which is defined as the probability that the PAPR of the discrete-time signal exceeds beyond a given threshold $PAPR_0$ and it can be evaluated as $\Pr\{PAPR \geq PAPR_0\}$.

Fig. 3 shows the PAPR reduction performance of the proposed J-SLM scheme with the phase rotation sequences U=2, 4 and 6, respectively. As noted based on this figure, compared with the PAPR of original OFDM/OQAM signal, the J-SLM scheme of the PAPR could be reduced by 2.4dB, 4.2dB, and 4.7dB with U=2, 4, 6 for $\Pr\{PAPR \geq PAPR_0\} = 10^{-4}$, respectively. Therefore, the proposed J-SLM scheme could significantly reduce the PAPR of the OFDM/OQAM signals. As expected, the J-SLM method achieves better PAPR reduction with U increasing.

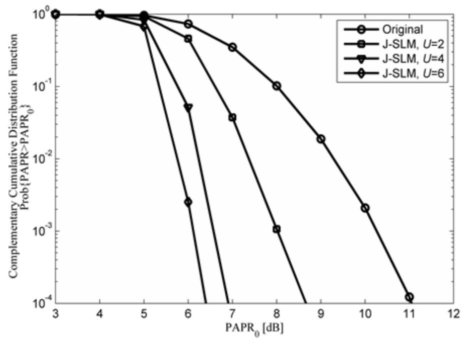

Fig. 3. PAPR reduction of the J-SLM method for different U.

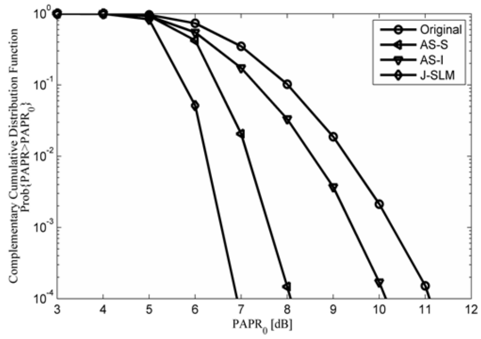

Fig. 4. PAPR reduction of different schemes for U=4.

Fig. 4 illustrates the PAPR reduction performance of the J-SLM, AS-S and AS-I schemes with U=4, respectively. As noted based on the figure, the gain in PAPR of the J-SLM method over the AS-S and AS-I schemes are 1dB and 3.1dB for $\Pr\{PAPR \geq PAPR_0\} = 10^{-4}$. It is observed that the PAPR reduction performance of the J-SLM method is much better than that of the AS-S and AS-I methods. The reason is that, for the J-SLM method, the high amplitude samples of the prototype filter are located within the optimization duration and the energy of the real and imaginary parts of one data block are jointly taken into account. Thus, the good PAPR performance is achieved for the J-SLM method.

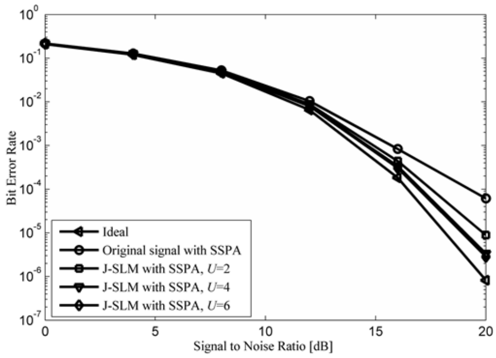

Fig. 5. BER performances of the J-SLM method for different *U*.

Fig. 5 depicts the BER performances of the proposed J-SLM scheme. For ideal situation, "Ideal" denotes the BER performance of the original signals without nonlinear distortion through the SSPA. As noted based on the figure, the signals operated by the J-SLM scheme achieve much better BER performances than the original signals with the SSPA. Moreover, to reach a BER of 10^{-4}, the SNRs are 17.5dB, 17.1dB and 16.9dB for the J-SLM scheme with *U*=2, 4, 6, respectively. When the SNR is 20dB, the J-SLM scheme with *U*=2, 4, 6 provides 85%, 94%, 95% BER improvement compared to original signals with the SSPA. However, the J-SLM scheme for *U*=4 has a slightly BER improvement compared to that for *U*=6. Thus, there is a tradeoff between the PAPR reduction and the computational complexity as well as the BER performance.

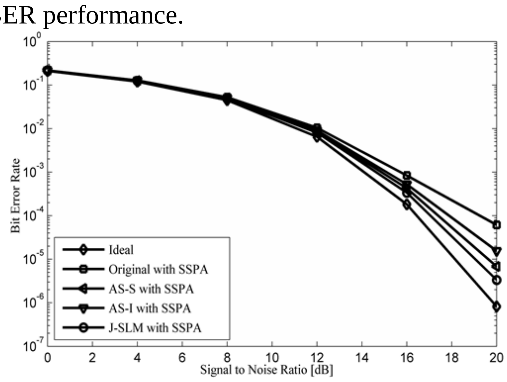

Fig. 6. BER performances of different methods for *U*=4.

Fig. 6 shows the comparison of the BER performances among the J-SLM, AS-S and AS-I methods with *U*=4. As noted based on the figure, the BER performance of the J-SLM method is much better than that of the other considered techniques. Specifically, to reach a BER of 10^{-4}, the SNRs are 17.1dB, 17.4dB and 17.9dB for the J-SLM, AS-S and AS-I methods, respectively. When the SNR is 20dB, the J-SLM scheme provides 51% and 78.5% BER improvement compared to the AS-S and AS-I methods, respectively.

V. Conclusions

In this paper, a novel J-SLM scheme has been proposed for the PAPR reduction of OFDM/OQAM signals. By using the offset modulation feature of QAM symbols, the proposed J-SLM scheme adopts a sequential optimization procedure to jointly optimize the real and imaginary parts of each data block. Simulation results showed that the J-SLM algorithm is an efficient method to reduce the PAPR performance of OFDM/OQAM signals. Moreover, it can improve the BER performance caused by the nonlinear characteristics of the SSPA utilized in OFDM/OQAM systems.

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