A New Weighted Tone Reservation Method for PAPR Reduction in OFDM Systems

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***Abstract*—The tone reservation (TR) technique is an efficient method to reduce the peak-to-average power ratio (PAPR) in orthogonal frequency division multiplexing (OFDM) systems. Although the weighted tone reservation (WTR) approach has been proposed as a potentially promising way to reduce the peak power, it suffers from high peak regrowth in the non-peak region of the transmitted signal. In addition, so far the effective selection of the weights is still an open problem. In this paper, we propose a new weighted tone reservation method that offers two contributions. The first is a reformulation of the traditional weighted least squares optimization that seeks to deeply suppress the peak regrowth of the transmitted signal in the low energy portion while reducing the peak power. The second is a careful study of the optimal weight selection. We provide the general guidelines and propose a class of suitable weights that are easy to implement. Then from this class we find the empirically optimal weights. Simulation results show that the proposed method has much improved performance in terms of both PAPR reduction and bit error rate (BER) than the existing clipping-based TR methods, which represent the state-of-the-art PAPR reduction solutions.

***Index Terms*—Orthogonal frequency division multiplexing (OFDM), peak-to-average-power ratio (PAPR), weighted least squares (WLS), tone reservation (TR), clipping control

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has been widely studied as a promising technique for broadband high speed communications, and has been adopted by many wireless standards such as DAB (digital audio broadcasting), DVB (digital video broadcasting), WLAN (wireless local area networks), and the IEEE's 802.16 family (better known as WiMAX) [1]. However, traditional OFDM systems suffer from severe high PAPR and thus require a high power amplifier (HPA) with a wide linear region at the transmitter. But amplifiers with large dynamic range have very low power efficiency and are expensive. So far many methods have been proposed to reduce the PAPR, including companding [2], coding [3], selected mapping (SLM) [4], partial transmit sequence (PTS) [5], active constellation extension (ACE) [6] and tone reservation (TR) [7], [8].

The tone reservation (TR) technique is an efficient distortionless method and was first presented in [7], [8]. In this approach, a small number of subchannels are reserved to generate peak-canceling signal to reduce PAPR and the signal content at the reserved tones will not affect data signals at other tones and can be discarded at the receiver. Among all the existing TR methods for PAPR reduction, the clipping-based approach may be the simplest with good performance. Clipping-based TR approach utilizes the filtered clipping noise as the desired peak-canceling signal to be approximated by the reserved tones. Since the amplitude of the peak-canceling signal by traditional clipping-based methods is much smaller than that of the clipping noise, iterations are needed for reaching the desired PAPR reduction. So far there are two typical schemes to accelerate the convergence rate of the traditional clipping-based TR method [9], [10]. They both generate the peak-canceling signals by multiplying a scaling factor to obtain a good PAPR reduction with low complexity. However, the scaling factor is a constant multiplied to the peak-canceling signal at each tones. Thus the peak-canceling signal points are equally amplified, which causes high peak-regrowth in the low energy portion of the original signal.

The weighted TR method was first introduced in [11] where a weighted least squares optimization is performed. In this method, higher weights are given to the peak portion of the clipping noise while lower weights are given to the non-peak portion. This will ensure that the peaks of the clipping noise get better approximated. As a result the original peak portion is reduced significantly compared to the optimization procedure in [9] and [10]. However, because less emphasis is now placed on the non-peak portion, large peak regrowth may occur there where the power is low in the original signal. Consequently, the PAPR reduction performance of the weighted TR method is limited. In addition, the weighted TR method also tends to result in a high average power increase which degrades the BER performance. Furthermore, perhaps because of the poor performance of the traditional WTR approach, so far there has been a lack of systematic study on the optimal choice of the weights.

In this paper, we propose a new weighted TR method. In this method, we first propose a new optimization

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formulation wherein the peak portion of the clipping noise is approximated as in the traditional weighted TR and more importantly, we add the regularization term that seeks to suppress the portion of the original signal that corresponds to the zero portion of the clipping noise. This will effectively lower the power of the non-peak portion and suppress the peak regrowth in this region, which can result in significantly improved PAPR reduction performance and the BER performance. Then we study the issue of optimal choice of the weights. We provide general guidelines and propose a class of weights, from which the optimal weights are obtained empirically.

The rest of the paper is organized as follows. In Section II, the PAPR problem formulation, the least squares TR (LS-TR) technique and the WTR approach are briefly reviewed. Then the proposed method is developed in Section III. Simulation results are presented in Section IV. Finally Section V draws conclusions.

II. Related Work

In this section, we first review the PAPR problem of OFDM signals. Then, two previous studies concerning our work, i.e., LS-TR and WTR, are briefly described.

A. Tone Reservation (TR) PAPR Reduction

In an operating OFDM system, the transmitted signals are in the analog domain. It is well known that the PAPR of the continuous time signal can be precisely obtained by oversampling the time domain signal [12]. The oversampling factor denoted in this paper is L, and we consider an OFDM system with N subcarriers. The oversampled symbol in the time domain can be obtained by employing the operation of an LN-point inverse Fast Fourier transform (IFFT), i.e.,

$$x_n = \frac{1}{\sqrt{LN}} \sum_{k=0}^{N-1} X_k e^{j\frac{2\pi nk}{LN}}, \quad n = 0,\cdots,LN\text{-}1 \tag{1}$$

where $\mathbf{X} = [X_0, X_1, \cdots, X_{N-1}]$ represents the modulated input data block, and X_k denotes the data in the k-th subcarrier.

The PAPR of an OFDM signal sequence $\{x_n\}$ is generally denoted as the ratio between the maximum power and its average power [8], i.e.,

$$\text{PAPR} = \frac{\max\limits_{0\le n\le LN-1} |x_n|^2}{E[|x_n|^2]} \tag{2}$$

where $E[\bullet]$ is the expected value.

In the tone reservation (TR) approach to PAPR reduction, the basic idea is to subtract a proper time domain peak-canceling signal $\mathbf{c} = [c_0, c_{1,\cdots} c_{LN-1}]$, whose frequency content is confined to the designated tones, from the original signal $\mathbf{x} = [x_0, x_1, \cdots, x_{LN-1}]$ so that the signal PAPR is reduced. The new time domain signal can be written as

$$\tilde{x} = x - c = IFFT(X - C) \tag{3}$$

where IFFT denotes the inverse FFT operator.

For distortionless data transmission, the data block $\mathbf{X}$ and the peak reduction block $\mathbf{C}$ are restricted to lie in disjoint frequency tones, i.e.,

$$X_k - C_k = \begin{cases} -C_k, & k \in R \\ X_k, & k \in R^c \end{cases} \tag{4}$$

where $R = \{r_0, r_1, \cdots, r_{M\text{-}1}\}$ is the index set of the reserved tones, M is the number of the reserved tones, and R^c is the complementary set of R in $\Phi = \{0,1,\cdots,N - 1\}$.

The PAPR of the peak-reduced OFDM signal is defined as [13]

$$\text{PAPR}(\tilde{\text{x}}) = \frac{\max\limits_{0\le n\le LN-1} |x_n - c_n|^2}{E[|x_n|^2]} \tag{5}$$

B. Clipping-based Tone Reservation Using Least-Squares Optimization (LS-TR)

Among all the TR schemes, clipping-based TR method may be the simplest with good performance. It is an iterative clipping and filtering procedure. It first clips the transmitted signal by a threshold A as

$$\hat{x}_n = \begin{cases} x_n, & |x_n| < \text{A} \\ Ae^{j\theta_n}, & |x_n| \ge \text{A} \end{cases} \tag{6}$$

where θ_n is the phase of x_n. The clipping ratio γ is defined as the ratio of the squared clipping level A to the mean squared value of the signal

$$\gamma = A^2 / E[|x_n|^2] \tag{7}$$

Then the clipping noise $\mathbf{f} = [f_0, f_1, \cdots, f_{LN\text{-}1}]$ is

$$f_n = x_n - \hat{x}_n = \begin{cases} 0, & |x_n| < \text{A} \\ x_n - Ae^{j\theta_n}, & |x_n| \ge \text{A} \end{cases} \tag{8}$$

The goal of this PAPR reduction approach is to find a peak-canceling signal $\mathbf{c}$, whose frequency content is confined to tones in the set R, to approximate the clipping noise $\mathbf{f}$. The traditional way (e.g., in [9][10]) in clipping-based TR algorithm utilizes the filtered clipping noise as the peak-canceling signal. We can summarize the procedure as obtained from an optimization problem, i.e,

$$\mathbf{C}_R^* = \arg\min_{\mathbf{C_R}} \| \mathbf{f} - \mathbf{Q_s C_R} \|_2^2 \tag{9}$$

where $\mathbf{C_R} = [\text{C}_{r_0}, \text{C}_{r_1}, \cdots \text{C}_{r_{M-1}}]$, $\mathbf{Q_s} = \mathbf{Q}(:, \text{R})$ is the submatrix of $\mathbf{Q}$ corresponding to the reserved tones, $\mathbf{Q}$ is the IDFT matrix with the (n,k)th entry $\text{Q}_{n,k} = (1/\sqrt{LN})\,\text{e}^{j2\pi nk/LN}$, and $\mathbf{c} = \mathbf{Q_s C_R}$ is the peak-canceling signal. We call this approach (9) LS-TR in this paper. Notice that the major advantage of such formulation is that it jointly considers the two steps in the traditional clipping-based TR approach---one step to approximate the clipping noise $\mathbf{f}$, and the other one to confine the frequency domain peak reduction signal to the reserved tones. Specifically, the independent variable vector $\mathbf{C_R}$ is only the reserved tone signal and thus any out-of-band distortion can never occur. On the other hand, (9) also tries to find suitable $\mathbf{C_R}$ so that the clipping noise $\mathbf{f}$ is approximated. The well-known closed form optimal solution of (9) can be readily obtained as

$$\mathbf{C}_R^* = (\mathbf{Q}_s^H \mathbf{Q}_s)^{-1} \mathbf{Q}_s^H \mathbf{f} \tag{10}$$

where $\mathbf{Q}_s^H$ is the complex conjugate transpose matrix of $\mathbf{Q}_s$. Since the matrix $\mathbf{Q}_s$ is known to the transmitter, $(\mathbf{Q}_s^H \mathbf{Q}_s)^{-1} \mathbf{Q}_s^H$ can be calculated offline.

C. The Weighted TR Approach (WTR)

The main drawback of the clipping noise approximation in the LS-TR approach is that it tries to equally faithfully approximate the entire clipping noise vector $\mathbf{f}$. As a result its peak-canceling capability is severally limited, since usually the non-zero peak part of $\mathbf{f}$ occupies only a small portion of the entire signal. The WTR method proposed in [11] applies some weights when generating the peak-canceling signal and can be formulated as

$$\begin{aligned} \mathbf{C}_R^* &= \arg\min_{\mathbf{C}_R} \sum_{n=0}^{LN-1} w_n \mid f_n - \mathbf{Q}_s(n,:)\mathbf{C}_R \mid^2 \\ &= \arg\min_{\mathbf{C}_R} \sum_{n=0}^{LN-1} (\mathbf{f} - \mathbf{Q}_s \mathbf{C}_R)^H \mathbf{W} (\mathbf{f} - \mathbf{Q}_s \mathbf{C}_R) \end{aligned} \tag{11}$$

where $\mathbf{Q}_s(n,:)$ denotes the n -th row of $\mathbf{Q}_s$ and $\mathbf{W} = \mathrm{diag}([\mathrm{w}_0, \mathrm{w}_1, \cdots, \mathrm{w}_{LN-1}])$ is the diagonal weighting matrix. The advantage of using weighted least squares approximation is that the peak portion of the clipping noise will be more precisely approximated with relatively larger weights, compared to the least squares approximation in (9). This will reduce the peak portion power by a larger extent. The optimal solution in (11) can also be easily derived as

$$\mathbf{C}_R^* = (\mathbf{Q}_s^H \mathbf{W} \mathbf{Q}_s)^{-1} \mathbf{Q}_s^H \mathbf{W} \mathbf{f} \tag{12}$$

After $\mathbf{C}_R^*$ is obtained, the peak-canceling signal $\mathbf{c}$ in the time domain can be obtained through the IFFT of $\mathbf{C}$.

The PAPR reduction of the WTR and the LS-TR is illustrated in Fig. 1 and Fig. 2. The horizontal axis is the sample sequence number, the vertical axis denotes the signal amplitude. The weights in WTR are chosen to be $w_n = \mid x_n \mid^2$ $(0 \le n \le LN-1)$ according to [11]. The number of the subcarrier $N = 256$, the oversampling factor $L = 4$, and the example signal is QPSK modulated. Since each signal point is treated equally in the LS-TR and the zero portion of the clipping noise covers a large portion, overall the LS-TR method approximates the clipping noise $\mathbf{f}$ better than the WTR method (Fig. 1), but the latter is better if confined to just the non-zero portion of $\mathbf{f}$. When this approximation is added to the original clipped signal, we see in Fig. 2 that the WTR method effectively brings the signal peak portion down. By contrast, the LS-TR method causes just minor perturbation of the signal and as a result provides little peak reduction performance.

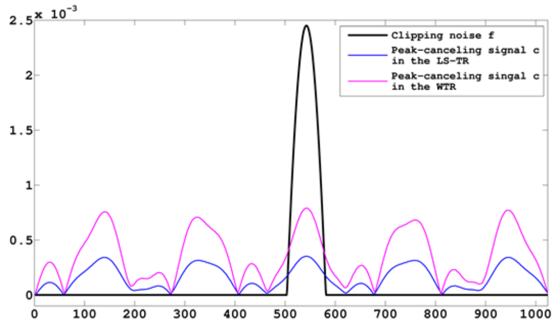

Fig. 1. Clipping noise approximation.

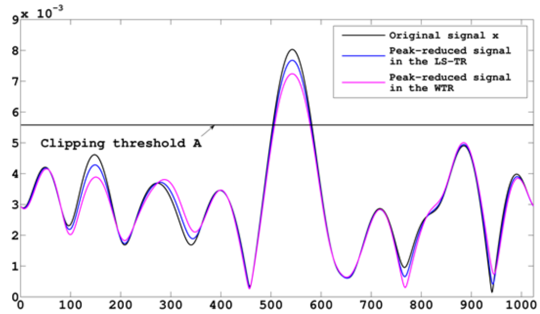

Fig. 2. Transmitting signal PAPR reduction.

III. Proposed Algorithm

We see from the previous section that by using the bigger weights assigned to the peak portion, WTR has better performance than LS-TR in peak portion approximation of the clipping noise. This algorithm, however, may result in high peak regrowth and high average power increase which lead to high PAPR and poor BER performance. Moreover, the PAPR reduction performance is also affected to a large extent by the choice of the weights. In this section, we propose a new optimization procedure based on the weighted least squares to reduce PAPR and at the same time suppress the high peak regrowth in WTR. We also carry out an in-depth study on the choice of the weights when generating the peak-canceling signal.

A. Weighted Tone Reservation with Peak Regrowth Suppression

In the WTR method, weights are assigned to the approximation procedure to obtain the peak canceling signal. The cost function can be rewritten as

$$\mathbf{C}_R^* = \arg\min_{\mathbf{C}_R} \sum_{n=0}^{LN-1} w_n \mid f_n - \mathbf{Q}_s(n,:)\mathbf{C}_R \mid^2 \tag{13}$$

When setting all the weights $w_n = 1$, (13) becomes the special case of the ordinary least squares optimization.

In (13), if w_n is large, the approximation error between fn and c_n is small. On the other hand, if w_n is small, the approximation error between f_n and c_n tends to be large. Usually the nonzero peak part of $\mathbf{f}$ occupies only a small portion of the entire signal, which is the part beyond the clipping level and need to be faithfully approximated to reduce the PAPR and assigned with higher weights. Yet the smaller weight assigned to the zero part of $\mathbf{f}$ introduces large error between the clipping noise and the peak-canceling signal. Hence, although the obtained peak-canceling signal, when added to the original signal, may reduce the original peaks, newly generated peaks may appear in the non-peak portion. Furthermore, the WTR approach is associated with high power increase at the reserved tones which causes poor BER performance.

To overcome the drawbacks mentioned above, we propose a new cost function to obtain the peak-canceling signal as

$$\mathbf{C}_R^* = \arg\min_{\mathbf{C}_R} \left\{ \sum_{n=0}^{LN-1} w_n \mid f_n - \mathbf{Q}_s(n,:)\mathbf{C}_R \mid^2 + \lambda \| \mathbf{x}_0 - \mathbf{Q}_0 \mathbf{C}_R \|_2^2 \right\} \quad (14)$$

where $\mathbf{x}_0$ is the part of the transmitted signal $\mathbf{x}$ which is below the clipping level, $\mathbf{Q}_0$ denotes the corresponding rows of the matrix $\mathbf{Q}$. $\lambda > 0$ is a regularization parameter. In (14), to suppress the peak regrowth at the zero portion of the clipping noise, we add a regularization term to (13). The objective of the proposed optimization procedure is to deeply suppress the peak regrowth and at the same time to reduce the peak values. In the WTR method (13), when searching for the optimal peak canceling signal, only the characteristics of the transmitted signal at the peak portion is considered, since at the nonpeak portion $\mathbf{f} = 0$. In (14), instead of approximating 0, $\mathbf{c}_0$ approximates the transmitted signal $\mathbf{x}_0$. Hence, when calculating the peak reduced signal $\mathbf{x}_{new}$ ($\mathbf{x}_{new} = \mathbf{x} - \mathbf{c}$), the peak value of $\mathbf{x}_0$ will be deeply suppressed. The regularization parameter λ allows the tradeoff between the PAPR reduction and the peak-regrowth suppression and the optimum value can be obtained by simulation. In the simulations, we show that compared with the WTR method, the proposed method can not only improve the PAPR reduction performance but also decrease the final signal power. By solving (14) above, we can obtain the optimal solution as

$$\mathbf{C}_R^* = (\mathbf{Q}_s^H \mathbf{W} \mathbf{Q}_s + \lambda \mathbf{Q}_0^H \mathbf{Q}_0)^{-1} (\mathbf{Q}_s^H \mathbf{W} \mathbf{f} + \lambda \mathbf{Q}_0^H \mathbf{x}_0) \quad (15)$$

In Fig. 3 and Fig. 4 we show the details of the WTR and the proposed methods. The parameters α and δ in (16) are chosen as $\alpha = 1$ and $\delta = 1\times 10^{-4}$. The regularization parameter in (15) $\lambda = 1\times 10^{-4}$. We see in Fig. 3 that although the WTR approximates the clipping noise $\mathbf{f}$ better than the proposed method in the peak portion, when this approximation is added to the original clipped signal, it causes larger peak regrowth at the non-peak portion which can be observed in Fig. 4. From Fig. 3 and Fig. 4, we can conclude that the proposed method effectively brings the signal peak portion down, meanwhile the rest part of the signal varied by a smaller extent than that from the WTR method which will suppress the peak regrowth.

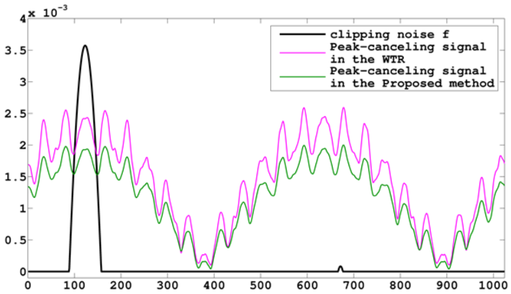

Fig. 3. Clipping noise approximation.

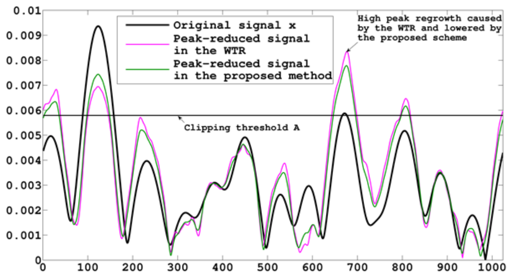

Fig. 4. Transmitting signal PAPR reduction.

B. Optimal Weights Selection

We next study the optimal weights in $\mathbf{W}$. In the proposed method (14), weighted least squares optimization is utilized to reduce the peaks and the regularization term is to suppress the peak regrowth. The most direct rule of thumb is that more weights should be assigned for bigger values of $| f_n |$. Although this was mentioned in [11], detailed analysis is more involved but is missing there. In our case, if the weights for the zero portion of $\mathbf{f}$ are fixed, then the weights for the peak portion of $\mathbf{f}$ should be chosen with care. If they are too big, then very accurate approximation in the peak portion will result. But then a higher likelihood of peak regrowth will also happen in the zero portion of $\mathbf{f}$ as in the traditional WTR approach. If they are too small, then the signal peak will not likely to be sufficiently brought down. Note that the weights for the zero portion of $\mathbf{f}$ cannot be zero, which would then mean to tolerate any amount of error and would tend to cause large peak regrowth. For the peak portion of $\mathbf{f}$, it seems reasonable to differentiate various samples according to their peakiness, meaning that the higher an $\mathbf{f}$ value gets, the bigger the weight that should be assigned to it. Because of the difficulty in searching for the optimal solution among all weight assignment possibilities, we restrict the searching space to be of the following form as

$$w_n = | f_n |^{\alpha} + \delta \tag{16}$$

where δ is a very small positive constant. We find empirically that $\delta = 1\times10^{-4}$ is a generally good choice and we fix this value throughout the paper. Since the derivation of the optimal choice of α is still difficult, in this paper we search for the near optimal value of α by simulation. In Fig. 5, we compare the complementary cumulative density function (CCDF) [14] curves with different choices of α from (16). As shown in Fig. 3, the best PAPR reduction performance is obtained when $\alpha = 1$ and in this paper we will choose $\alpha = 1$ for all simulations.

It is interesting to note that the result of this weight assigning scheme may be understood as a type of water filling in redistributing signal power. Specifically, the signal power in the peak part of $\mathbf{f}$ is made to flow into the lower places, mostly the zero part of $\mathbf{f}$. The lower the $| f_n |$ value, the more the error margin (water) is allowed in the approximation, which corresponds to less weight.

C. Computational Complexity

The complexity of the proposed method mainly depends on the calculation of $\mathbf{C}_R^*$ in (15), wherein the matrix $\mathbf{W}$ is diagonal. In (15) the computation of the $M \times M$ matrix $(\mathbf{Q}_s^H \mathbf{W} \mathbf{Q}_s + \lambda \mathbf{Q}_0^H \mathbf{Q}_0)$ has the complexity of $O(M^2 LN)$, and it needs $O(M^3)$ to compute its inverse. The computation of $(\mathbf{Q}_s^H \mathbf{W} \mathbf{f} + \lambda \mathbf{Q}_0^H \mathbf{x}_0)$ has the complexity of no more than $O(MLN)$. In addition, it is well-known that the IFFT needs $O(LN\log(LN))$ multiplications. Thus the total computational complexity of the proposed algorithm is $O(LN(\mathrm{M}^2 + \log(LN)))$, which is the same as the WTR algorithm.

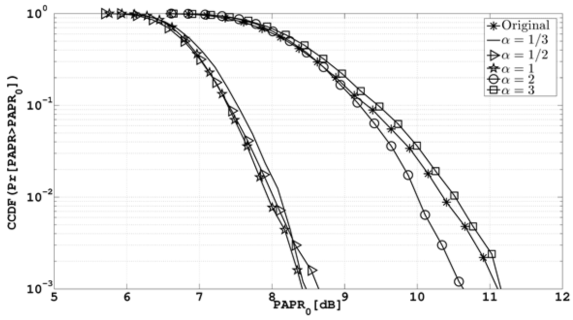

Fig. 5. Comparison of PAPR reduction for different α when $N = 256$, $r = 5\%$ and QPSK is used.

IV. Simulation Results

In this section we compare the proposed method with the controlled clipper TR (CC-TR) algorithm [15], the adaptive scaling TR (AS-TR) algorithm [9], [16], the adaptive amplitude clipping (AAC-TR) algorithm [17] and the WTR method [11]. When obtaining the complementary cumulative density function (CCDF) as the performance measure [14], 10^4 random OFDM symbols are generated. The transmitting signal is oversampled by a factor of $L = 4$. The set R is randomly generated as proposed in other works (e.g., [10], [16]). We define the tone reservation ratio $r = M/N$.

We compare the five algorithms for the clipping ratio $\gamma =$ 4dB (Simulations on different γ were also conducted and the comparison results were similar) and the tone reservation ratio $r = 5\%$ with $N = 256$ and $N = 1024$ in Fig. 6 and Fig. 7, respectively, and the OFDM symbol is QPSK modulated. For the CC-TR, the AS-TR and the AAC-TR algorithms, the numbers of iterations are chosen to be 20, 16 and 2, respectively. The WTR algorithm and the proposed method iterate just once. The weights in WTR are chosen to be $w_n = | x_n |^2$ $(0 \le n \le LN - 1)$ as suggested in [11]. For the proposed method, $\alpha = 1$, $\lambda = 1\times10^{-4}$. When $N = 256$, $\Pr(\mathrm{PAPR} > \mathrm{PAPR}_0) = 10^{-3}$, the PAPR of the original OFDM is 11.1dB. For the CC-TR algorithm, the WTR algorithm, the AS-TR algorithm and the AAC-TR algorithm, the PAPRs are approximately reduced to 9.5dB, 9.7dB, 9.1dB and 8.8dB, respectively, while the proposed algorithm achieves the best performance of the PAPR value of about 8.4dB. When $N = 1024$, the PAPR of the original OFDM is 11.6dB. For the WTR algorithm, the CC-TR algorithm, the AS-TR algorithm and the AAC-TR algorithm, the PAPRs are approximately reduced to 9.9dB, 9.8dB, 9.5dB and 8.9dB, respectively, while the proposed algorithm also achieves the best performance of the PAPR value of about 8.5dB.

Fig. 8 compares the power spectral density between different clipping-based TR algorithms. The peak reduced OFDM signal is passed through a soft limiter (SL) nonlinearity, where the input-output profile is represented by

$$y = \begin{cases} x, & |x| < l \\ l\dfrac{x}{|x|} & |x| \ge l \end{cases} \tag{17}$$

where l is the amplifier clip level. The input backoff (IBO) is defined as

$$\mathrm{IBO} = 10\log_{10}\left(\frac{l^2}{\sigma^2}\right) \tag{18}$$

In our simulations, we choose IBO = 5 dB and 64QAM modulated OFDM symbols. From Fig. 8 we can see that the out-of-band radiation at the normalized frequency $fn = 4MHz$ of the proposed algorithm is -33dB, which is lowest among the five algorithms and

3dB lower than that of the original signal without using any PAR-reduction techniques.

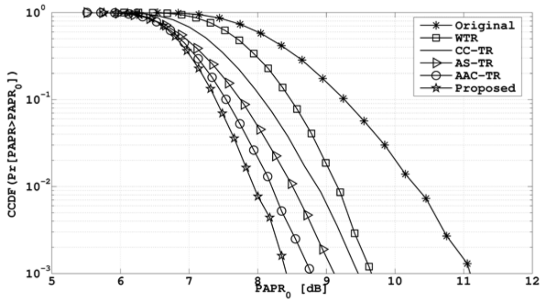

Fig. 6. Comparison of PAPR reduction for different methods when $N = 256$, $r = 5\%$ and QPSK is used.

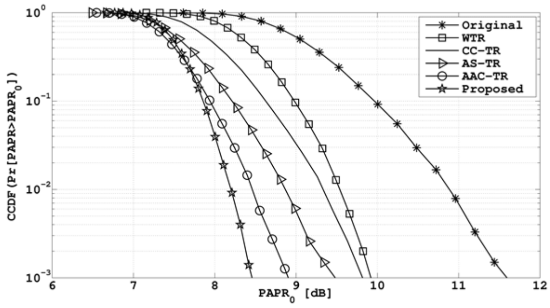

Fig. 7. Comparison of PAPR reduction for different methods when $N = 1024$, $r = 5\%$ and QPSK is used.

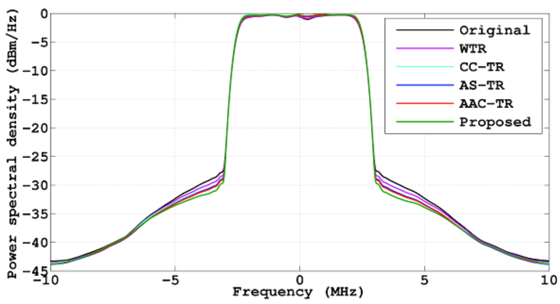

Fig. 8. Comparison of power spectral density of the output signal from the SL nonlinearity at IBO = 5 dB.

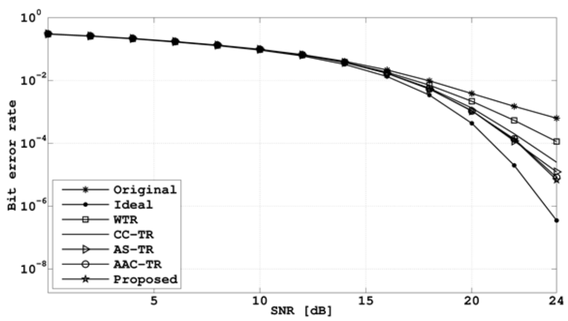

Fig. 9. Comparison of BER of the different algorithms.

Fig. 9 shows the bit error rate curves of the different algorithms. In this simulation, the OFDM symbols are 64QAM modulated and the linear AWGN channel is adopted. The nonlinearity is also a soft limiter and the IBO = 5dB. Due to the average power increase, the BER performance of the WTR scheme is limited compared to the AAC-TR algorithm, AS-TR algorithm and the CC-TR algorithm. Since the proposed approach has the ability to obtain high PAPR reduction and lowest average power increase, compared with the other four algorithms and the original OFDM symbols, the proposed scheme can offer better BER performance. Note that the "Ideal" curve is the BER of the original signal without passing through the SL.

V. Conclusion

In this paper, we propose a novel weighted tone reservation method for PAPR reduction in OFDM systems. It uses the weighted least squares to approximate the clipping noise and an additional regularization term to lower the average power increase and suppress the high peak regrowth in the traditional WTR. The issue of the optimal choice of the weights is also studied and an efficient formula is empirically obtained. Simulation results confirm these advantages and show a large performance improvement over typical state-of-the-art methods in terms of both PAPR and BER.

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