PAPR Reduction in OFDM Signals by Self-Adjustment Gain Method

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Abstract: OFDM in 5G wireless communication networks has the advantages of a high transmission volume and data rate. However, the problem of a high peak-to-average power ratio (PAPR) of OFDM signals may lead to serious performance degradation and distortion in the high-power amplifier at the transmitter. In this paper, with the clipping process, the self-adjustment gain (SAG) method is proposed, to tune up the positions of the clipped signals, for reducing the PAPR of OFDM signals without increasing the error probability. The distance between the estimated and clipped signal points in the signal space is measured. An updated process is developed to produce the new signal points based on the measured distance and the self-adjustment gain that is obtained from the clipping noise power and measurement power. The simulation results show that for QPSK/OFDM, SAG reduces up to 2 dB and 0.7 dB more PAPR than ACE with one and three iterations, respectively. For 16QAM/OFDM, SAG reduces up to 1.3 dB and 0.5 dB more PAPR than ACE with one and three iterations, respectively. SAG also outperforms the active constellation extension, with the projection onto convex sets (ACE-POCS) and gradient project (SGP) methods in first two iterations. Hence, the proposed method really reduces the PAPR value more effectively, within an acceptable error probability, and its computational complexity is also much lower in comparison with those methods based on the active constellation extension (ACE) with iterations.

Keywords: OFDM; PAPR; self-adjustment gain (SAG); ACE; clipping

1. Introduction

The mobile communication system has been evolved to the 5th generation (5G), where OFDM is its main multiplexing modulation technology [1–4]. Although the advantages of OFDM meet 5G’s requirements in the high transmission volume and data rate. The drawback of a high peak-to-average power ratio (PAPR) may cause serious performance degradation with a non-linear high-power amplifier at the transmitter.

To solve for the high PAPR problem, many technologies have been proposed [5–8], which can be classified into the following two categories: distortion-free and distortion. The former includes probabilistic techniques, such as selected mapping (SLM) [9–13], which yields alternative input symbol sequences, obtained by input symbol sequences, multiplied by phase sequences. Then, the sequence with the lowest PAPR is selected as the candidate for transmission. For the partial transmit sequence (PTS) scheme [14–20], the subblocks of the original data signals are optimally combined at the transmitter, for generating a transmission signal of low PAPR. Both the SLM and PTS techniques provide significantly improved PAPR statistics, but involve high computational complexity of a bank of inverse discrete Fourier transforms; besides, side information is required as the indicator of the sequence that is selected for the transmitter. By applying signal processing techniques on block coded or pulse-shaping schemes, the PAPR reduction gains can be obtained at the expense of redundancy in data rates [21–25]. The method of tone reservation (TR) [26–30] basically reserves a small subset of subcarriers not to transmit any data, and by setting proper values on these reserved subcarriers to effectively lower the signal PAPR. However,
searching for these proper values usually requires a large computational complexity. The scheme of non-bijective constellations [31–40] tries to alter or introduce new constellations to combat large signal peaks, such as the active constellation extension (ACE) [31] method, which reduces the PAPR by changing the signal constellation, while preserving the same minimum distance. The distortion-type technologies include clipping [41–44], which is the simplest method, by clipping the peak amplitude of the OFDM signal to some desired maximum level, at the price of introducing in-band distortion and out-of-band radiation. In companding technologies [45–53], the signal contents are either compressed or enlarged, such that the PAPR reduction is obtained. Recently, with the introduction of artificial intelligence (AI) techniques in wireless communication systems, many methods have been developed for further improvement in PAPR performance; such as Sohn et al., who effectively reduced the complexity of the iterative clipping and filtering (ICF), and simplified clipping and filtering (SCF) techniques by employing neural networks [54]. The literature [55] developed an auto encoder-based method based on deep learning for the OFDM system, which provides superior performance in PAPR and bit error rate (BER).

Most of these methods mentioned above make use of complicated algorithms or require additional devices in the receiver, to get a better effect of the reducing PAPR, or repeat the defined procedure until the required PAPR reduction is reached. In Table 1, the comparison of different features for various PAPR reduction schemes are summarized.

| Item                  | Method            | Power Increasing | BER Increasing | Data Rate Loss | Signal Distortion | Computational Complexity |
|-----------------------|-------------------|------------------|----------------|----------------|-------------------|------------------------|
|                       | Amplitude Clipping| No               | Yes            | No             | Yes               | Low                    |
|                       | Partial Transmit Sequence | No   | Yes            | Yes            | No               | High                   |
|                       | Selective Mapping  | No               | Yes            | Yes            | No               | Medium                 |
|                       | Active Constellation Extension | Yes  | No             | Yes            | No               | Medium                 |
|                       | Coding             | No               | Yes            | Yes            | Yes               | Low                    |

It is known that the clipping technique for PAPR reduction of OFDM systems will cause nonlinear distortion, and hence degrade the BER performance. In order to minimize the peak magnitude, the ACE method dynamically extends outer constellation points in active channels within margin-preserving constraints, to reach the required PAPR reduction performance without increasing the error probability, and hence is adopted in the digital video broadcasting—second generation terrestrial (DVB-T2) system, as the part of the DVB-T2 standard for terrestrial television signal transmission, as well as cellular telephone and wireless data signal transmission [31,32]. The algorithm that is implemented on field-programmable gate array (FPGA), with fixed-point and floating-point architectures, has been demonstrated [34]. The repeated clipping (ACE-RE) method was used in [35] for improving the convergence rate of the conventional ACE method. For a higher level constellation, by mapping the disseminative constellation onto the points of extended constellation, the clipping-based optimum and suboptimal methods, through solving the constrained quadratic problem (QCQP), were given for PAPR reduction in the ACE scheme [36]. The algorithm of the active constellation extension, with a projection onto convex sets (ACE-POCS), adjusts the signal amplitude and phase for increasing the average power, following the minimax rule to attain the optimum effect [37,38]. By combining the self-adaption clipping strategy and special extension rules, the extension projection onto convex sets (ACE-EPOCS) designed the correction factor to adjust the scheme for its flexibility [38,39]. To reform the active constellation extension, a pre-distortion scheme, by defining expendable regions, was proposed for reducing the PAPR with only one iteration [40].

Generally, ACE-based methods concern both the schemes for peaks clipping and the criterions for constellation extension. By setting different clipping thresholds for
varied PAPR levels, typical ACE techniques concentrate on the corresponding constellation adjustment. Optimum ACE technologies, on the other hand, involve the trade-off between getting considerable PAPR reduction gains and complexity within reasonable BER, or the trade-off between PAPR reduction and BER performance. To make the clipping and the constellation extension concurrently effective, the optimization procedure is required to be performed iteratively, to modify the associated parameters until the required condition is satisfied. These processes result in an increase in the computational complexity and a decrease in the operation efficiency. However, the constellation extension rules in these optimum schemes maintain the conventional way, i.e., each clipped signal point is relocated to the new position, according to the zone it drops and the extension criterion that is complied with. Obviously, these rules are constellation-dependent. With the increase in the modulation order, these rules become complicated, so they must be carefully defined. Motivated by the observations, the self-adjustable scheme is proposed in order to make the extension rule systematic and adaptable. The basic idea behind the proposed scheme is to measure the distance between the clipped signal point and its original location. It is possible to write an equation for the new assignment position by combing the clipped signal point with a displacement that is proportional to the measured distance, with a proportionality constant defined as the self-adjustment gain (SAG). Motivated by the adaptive filtering algorithms, such as the recursive least-squares (RLS) and Kalman filter [56], the self-adjustment gain can be made as the ratio that is proportional to the reciprocal of the squared measurement distance and the clipping error power. Hence, each signal point can be moved dynamically, which will effectively smooth the clipped noise and diminish errors. In this paper, we assume a fixed clipping threshold, and consider designing a simple and adaptive constellation extension scheme to reduce the PAPR of OFDM signals and improve the BER performance owing to the clipping process. In our scheme, let the clipped signals be fed back into the signal space, through the fast Fourier transform (FFT), and the distance between the clipped signal and its original position is measured and weighted by the chosen self-adjustment gain. A movement method for the clipped signals is developed, and the self-adjustment gain is derived heuristically. The updated process tends to make the new signal point more accurate. Similarly to ACE, the position adjustment of the signal points does not require an additional device in the receivers, also no iteration is required, such that the scheme consumes much less computation time in comparison with ACE in PAPR reduction. We, hence, can achieve approving PAPR reduction with acceptable BER.

The organization of this paper is as follows: The OFDM systems model and PAPR are described and defined in Section 2. The proposed PAPR reduction scheme by the SAG algorithm is derived in Section 3. The simulation results are provided in Section 4. Finally, the conclusions are given in Section 5.

2. PAPR Properties of OFDM Signals

The OFDM modulation that is considered here consists of a total of $N$ orthogonal subcarriers of equal frequency separation of $1/T$, where $T$ is the time duration of the OFDM signal. Assume that $X = [X[0], X[1], \ldots, X[N-1]]^T$ is a complex data block, where the complex data symbols $X[k]$, $k = 0, 1, \ldots, N-1$, are mapped from an input bit stream, through QPSK or QAM modulations, and the transpose of a matrix is denoted by $[\cdot]^T$. The modulated stream is then transformed into a discrete-time signal $x[n]$ via the inverse discrete Fourier transform, i.e., IFFT, as follows:

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{j2\pi nk/N}, \quad n = 0, 1, \ldots, N-1,$$

where $j = \sqrt{-1}$ and the sequence $\{x[n]\}$ are the OFDM signals in the time domain, and are represented as a vector $x = [x[0], x[1], \ldots, x[N-1]]^T$. 

The PAPR of the transmitted signal is defined as the ratio of the maximum instantaneous power to the average power of the OFDM signals. Hence, the PAPR value for discrete time signals can be defined as follows:

$$\text{PAPR} \triangleq 10 \log_{10} \left( \frac{\max |x[n]|^2}{E[|x[n]|^2]} \right),$$  \hspace{2cm} (2)

where $E[\cdot]$ denotes the expectation operator.

High PAPR will introduce errors in quantization, nonlinear distortion in the power amplifier, such that the applications are subject to many restrictions.

3. The Self-Adjustment Gain Method for PAPR Reduction in OFDM Signals

In the ACE-based PAPR reduction methods, the constellation extension rules are conventional, which are dependent on the constellation structure and modulation orders. Each clipped signal point, from the place it stands, is reassigned to the new position, along the extension criterion as planned. As the modulation order is increased, or the constellation topology comes to be complicated, these extension rules will fall into obscure, and thus must be specified carefully. The self-adjustment gain (SAG) method, hence, is proposed in this paper to provide a systematic procedure for moving the clipped signals properly to the corresponding locations, in a well-ordered course. This section presents the procedure and formulas of SAG.

3.1. Clipping and Error Power Measurement

The block diagram of the SAG method is shown in Figure 1, where the procedure includes the amplitude clipping, measurement, and adjustment of the constellation points. The data symbols $X[k], k = 0, 1, \cdots, N - 1,$ mapped with QPSK or QAM modulation, are passed through IFFT, to obtain the time domain signals $x[n]$. The peak value and average power $E[|x[n]|^2]$ of the OFDM signals can be calculated or measured to obtain the PAPR values, which are given in (2).

![Figure 1. Block diagram of the PAPR reduction in OFDM signals by the proposed SAG method.](image)

Applying the signals $x[n]$ to the recursion scheme, the OFDM signals are usually oversampled by a factor for approximating the real PAPR values in the clipping procedure. Let the signals $x[n]$ be clipped to a preset threshold value $M_{\text{max}}$, given by the following:

$$M_{\text{max}} = (\max|x[n]|) \cdot \eta,$$  \hspace{2cm} (3)
where \( \eta \) is the compression ratio of the peak value. Any OFDM signal with a peak envelop of \( |x[n]| \) is limited to the predetermined value \( M_{\text{max}} \), such that the clipped signal \( x_c[n] \) is given as follows:

\[
x_c[n] = \begin{cases} 
x[n], & |x[n]| < M_{\text{max}} \\
M_{\text{max}} e^{j\theta[n]}, & |x[n]| \geq M_{\text{max}}
\end{cases}
\]

(4)

where \( \theta[n] \) is the phase of \( x[n] \). An illustration of the clipping procedure is shown in Figure 2.

**Figure 2.** An illustration of the original OFDM signal and its clipped counterpart. Orthogonal frequency-division multiplexing (OFDM).

Let the clipping error power \( P_s \) be the difference between \( P_0 \) and \( P_{\text{clip}} \) in the following:

\[
P_s = P_0 - P_{\text{clip}}.
\]

(5)

where \( P_0 = E[|x[n]|^2] \) is the average power of the original OFDM signal and \( P_{\text{clip}} = E[|x_c[n]|^2] \) is the average power of the clipped signal. The PAPR value is determined both by the average power and the instantaneous maximum power of the OFDM signals. Controlling the clipping error power, for lessening the symbol errors caused by clipping, is much more difficult. This is because we naturally do not have the ability to directly manage the status of signals after IFFT transformation [57].

### 3.2. Signal Detection and Distance Measurement

The new data symbol \( X[k] \) is produced after the clipped signal \( x_c[n] \) is fed into FFT in the feedback loop, since the clipped signal is corrupted by clipping noise, and will deviate from the original constellation point. To actually perform management for reducing system errors, the original data symbols \( X^v \), with \( v \) denoting the number of symbols in modulation, are required, which was actually unknown. Hence, signal detection is carried out on the signal space where the decision criterion is specified. In the maximum likelihood detection, the detection of signals is achieved by finding the closest symbol on the constellation map to the clipped symbol \( X[k] \). Hence, instead of \( X^v \), the estimated state \( \hat{X}^v \) is determined
through a proper detection procedure. If the corresponding original data were retained in advance, we can set $X^v[k] = X[k], k = 0, \cdots, N -1$ straightaway.

As the given example of QPSK, the original data symbol $X^v$ is one of the four quadrant points.

$$X^v \in \left\{ \pm \frac{1}{\sqrt{2}} \pm j \frac{1}{\sqrt{2}} \right\},$$

where $v$ is the quadrant index with $v \in \{I, II, III, IV\}$. The detector determines the estimated state $\hat{X}^v$ according to the following rule:

$$v = \begin{cases} 
I, & \Re\{\bar{X}[k]\} > 0, \Im\{\bar{X}[k]\} > 0 \\
II, & \Re\{\bar{X}[k]\} \leq 0, \Im\{\bar{X}[k]\} > 0 \\
III, & \Re\{\bar{X}[k]\} \leq 0, \Im\{\bar{X}[k]\} \leq 0' \\
IV, & \Re\{\bar{X}[k]\} > 0, \Im\{\bar{X}[k]\} \leq 0
\end{cases}$$

(7)

where the operators $\Re\{\cdot\}$ and $\Im\{\cdot\}$ take the real part and the imaginary part of the clipped state, respectively.

After transformed back to the frequency domain in the iteration loop, the clipped data symbols at the output end of FFT are obviously different from the original ones. Prior to further processing, the clipped signal point is measured and the residual $d[k] = \hat{X}^v - \bar{X}[k]$ is computed, for reflecting the discrepancy between the clipped state and the original state in the detection procedure. The instantaneous residual power $P_m$ is then calculated as follows:

$$P_m[k] = ||\hat{X}^v - \bar{X}[k]||^2.$$  

(8)

3.3. Self-Adjustment Gain and Signal Position Update

The OFDM signals usually become too noisy to control, due to the inevitable clipping process. It is necessary to smooth the clipped OFDM signals with a measurement and adjustment scheme. However, a straightforward operation on the clipped signals is not an easy work. Instead, in the time domain, moving the signal point to the new position on the constellation map, after applying the FFT transform on the signals, is controllable. Motivated by the observations that the fast dynamics of a system require an adjustable gain to give large influence on the move of the signal point on the constellation, the self-adjustment gain scheme is proposed in order to define a systematic and adaptable rule on the constellation extension. The SAG method tunes the constellations in terms of clipping adjustment gain as follows:

$$G[k] = \frac{P_m[k]}{P_m[k] + P_s},$$

(9)

where the denominator term is the instantaneously residual power that represents the uncertainty of the data symbol after clipping. Let $\hat{X}[k]$ be the updated constellation point of the data symbol $\bar{X}[k]$. The adjustment procedure can be accomplished by the combination of $\bar{X}[k]$ and the scaled residual $\hat{X}^v - \bar{X}[k]$, as follows:

$$\hat{X}[k] = \bar{X}[k] + (1 - G[k]) \cdot (\hat{X}^v - \bar{X}[k])$$

(10)

It can be seen from Figure 3 that the constellation point $\bar{X}[k]$ of the data symbol after clipping is moved to $\hat{X}[k]$, using the residual scaled by $1 - G[k]$. An increase in the clipping noise power gives a decrease in the adjustment factor $G[k]$, which yields $\hat{X}[k]$ and relies on
the residual. It is obvious, from the illustration of QPSK shown in Figure 4, that the clipping process reduces the PAPR at the price, blowing up the error power and consequently the system error probability. The proposed procedure, on the other hand, smoothens the errors by moving each clipped signal point appropriately, according to the self-adjustment gain. Finally, the updated signal symbol $\tilde{X}[k]$ is applied to IFFT to obtain the OFDM signals $\hat{x}[n]$.

Figure 3. Update procedure with the self-adjustment gain for the constellation point.

Figure 4. Constellation adjustment by the proposed SAG method for QPSK–OFDM signals.

3.4. Summary of SAG Procedure

The SAG scheme may also be part of the ACE-based methods, as the constellation extension regulation for reducing the PAPR values may allow iterations between the clipping and adjustment of signal points. Our study, however, focuses on the effects of the SAG scheme on the PAPR reduction without iterations. The flowchart of the SAG method is shown in Figure 5, and the procedure of the algorithm is summarized as follows:

1. The modulated data symbols $X[k], k = 0, 1, \ldots, N - 1$ are passed through IFFT to generate the OFDM signal $x[n]$. The peak value and average power $P_0$ of $x[n]$ are calculated to obtain the PAPR value;
2. The clipping process is performed according to (4) for all $x[n]$ to obtain the clipped signal $x_c[n]$. The clipped average power $P_{\text{clip}}$ of $x[n]$ is calculated;
3. The $x_c[n]$ is fed into FFT, to obtain the new signal point $\tilde{X}[k]$;
(4) The detection procedure is performed on $X[k]$, to determine the estimated signal point $\hat{X}^v$;
(5) The residual for each $X[k]$ is measured. The corresponding residual power $P_m$ is calculated based on (8) and the self-adjustment gain $G[k]$ in (9);
(6) The self-adjustment procedure in (10) is performed, to obtain the updated signal point $\hat{X}[k]$;
(7) The updated signal point $\hat{X}[k]$ is passed to IFFT, to obtain the modified OFDM signal $\hat{x}[n]$;
(8) The modified OFDM signal $\hat{x}[n]$ is transmitted. The new PAPR value is examined, by calculating the peak value and average power of $\hat{x}[n]$.

4. Simulation Results and Discussion

In this section, computer simulations are performed in order to compare the performance of the proposed SAG method with the other method, in PAPR reduction in OFDM signals. Throughout all the simulations, the OFDM system with $N = 256$ subcarriers is used. Both the QPSK and 16QAM for symbol mapping are used in the simulations. Figure 6 shows the simulation results of the PAPR performance of the QPSK–OFDM with the SAG method and ACE method with one to three iterations. It can be seen that the PAPR performance of the SAG method is 8.5 dB at the CCDF of $10^{-4}$, which is an improvement of 3.2 dB compared to the original OFDM. Compared to the ACE method, which is 10.5 dB at the CCDF of $10^{-4}$ for one iteration, 9.5 dB for two iterations, and 9.2 dB for three iterations, the proposed method obviously has better performance. Similar results of the PAPR performances for the 16QAM–OFDM of the SAG method and ACE method with one to three iterations, respectively, can be seen in Figure 7. The PAPR performance of the SAG
method is 9.7 dB at the CCDF of $10^{-4}$, which has an improvement of 1.9 dB compared to the original OFDM. Compared with the ACE method, an improvement of 1.3 dB for one iteration, 0.9 dB for two iterations, and 0.5 dB for three iterations are obtained, respectively. The proposed method does not require the performance of iterations, and hence saves computational costs.

Figure 6. PAPR reduction performance comparisons of the QPSK–OFDM with the SAG and ACE method with one to three iterations.

Figure 7. PAPR reduction performance comparisons of the 16QAM–OFDM with the SAG and ACE method with one to three iterations.

Three schemes that are relevant to the ACE involved with the constellation rules, i.e., the projection onto the convex set (ACE-POCS), the smart gradient projection (ACE-SGP), and the modified ACE (mACE) [38–41], are considered for comparison with the PAPR reduction performance. Tables 2 and 3 show the PAPR reduction performance for various
schemes at the third iteration, compared to the proposed SAG scheme for QPSK–OFDM and 16QAM–OFDM, respectively, at CCDF $= 10^{-4}$. Obviously, SAG significantly drops the PAPR values with only one iteration, to attain the required PAPR level. It is clear that the convergence rate of SAG is much faster than the other schemes; besides, the implementation for the SAG scheme in system complexity is much lower. Consequently, SAG can achieve the required PAPR reduction more effectively.

Table 2. PAPR performance comparison for QPSK–OFDM with $N = 256$.

| Item       | Method   | Original | Proposed SAG | ACE   | ACE-POCS | ACE-SGP | mACE |
|------------|----------|----------|--------------|-------|----------|--------|------|
| # of Iterations | -       | 1       | 3             | 3     | 3        | 3      | 3    |
| PAPR(dB)    | 11.6     | 8.5      | 9.2           | 9.7   | 7.7      | 7.2    |      |

Table 3. PAPR performance comparison for 16QAM–OFDM with $N = 256$.

| Item       | Method   | Original | Proposed SAG | ACE   | ACE-POCS | ACE-SGP | mACE |
|------------|----------|----------|--------------|-------|----------|--------|------|
| # of Iterations | -       | 1       | 3             | 3     | 3        | 3      | 3    |
| PAPR(dB)    | 11.6     | 9.8      | 10.2          | 10.8  | 8.6      | 8.5    |      |

The BER performances of the SAG method and ACE method with different iterations are shown in Figures 8 and 9, respectively, for QPSK/OFDM and 16QAM/OFDM. For ACE, each signal point of the clipped data is moved into the specified position inside the decision boundary, and hence the error probability curves are consistent with the original OFDM. The SAG method, in contrast, moves each constellation point according to the self-adjustment gain, which depends on the instantaneous residual power. The error probability, due to clipping in the proposed scheme, hence, is a little higher than ACE as the tradeoff. Even so, the BER performance of our method is acceptable in comparison with the benefits gained from PAPR reduction and computational resources.

Figure 8. BER performance of the QPSK–OFDM with the SAG method compared with the ACE method.
5. Conclusions

Reducing the symbol errors caused by clipping the OFDM signals is generally more difficult through controlling the clipping error power in the time domain. In this paper, we propose a scheme of the self-adjustment gain for reducing the PAPR values without increasing the error probability. This method adjusts each clipped signal point to a new position, according to the ratios between the residual and system powers for reducing the system errors, which have the effects of controlling the status of data after feedback of the clipping signals. The self-adjustment gain adaptively takes a portion of the discrepancy between the clipped state and the original state, for updating each signal constellation. From our simulation results, we can observe that the proposed SAG can attain a significant drop in CCDF with one iteration. The PAPR reduction gains up to 2 dB, 1 dB, and 0.7 dB, compared with ACE with one, two, and three iterations, respectively, for QPSK/OFDM at CCDF $= 10^{-4}$. For 16QAM/OFDM, 1.3 dB, 0.9 dB, and 0.5 dB in the PAPR reduction gain are obtained, in comparison with ACE with one, two, and three iterations, respectively. SAG also outperforms the active constellation extension, with the projection onto convex sets (ACE-POCS) and gradient project (SGP) methods in the first two iterations. The advantage of less computational complexity in the proposed scheme means that the PAPR value can drastically change at the faster speed. Hence, the proposed method can achieve the required PAPR reduction performance within acceptable BER performance and significantly save computational time, in comparison with ACE-based methods with iterations.

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