A Two-Dimensional Peak-to-Average Power Ratio Reduction Method Based on Iterative Noise Filtering for Dual-Band Power Amplifiers

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Abstract This letter proposes a new two-dimensional (2-D) PAPR reduction method to improve the peak clipping precision and the error vector magnitude (EVM) performance. On one hand, it conducts joint peak clipping for dual-band signals; on the other hand, it uses iterative noise filtering to suppress peak regeneration and spectral spread caused by hard clipping. Simulation results show that when the PAPR of OFDM dual-band signal is reduced to 6.8dB, compared with the traditional 2-D PAPR reduction algorithm, the EVM value of the signal is reduced from 10.3% to 6.9%, which reflects less signal distortion.

key words: Dual-Band, Power Amplifier, Peak-to-Average Power Ratio Reduction

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

With the continuous development of modern wireless communication technology, the spectrum resources for wireless communications have become increasingly crowded. To make full use of the scarce spectrum resources, orthogonal frequency division multiplexing (OFDM) technology has been proposed, which is a multi-carrier modulation technology and utilizes the orthogonal overlap of spectrum between sub-carriers to improve spectrum utilization. Therefore, it has become one of the core technologies for the fourth generation (4G) and the fifth generation (5G) mobile communications [1, 2, 3]. However, an OFDM signal is characterized with non-constant envelope and high peak-to-average power ratio (PAPR). When amplified by a nonlinear RF power amplifier (PA), it always generates nonlinear distortion, which will cause out-of-band spectrum leakage at the transmitter side, and bit-error-ratio (BER) increase at the receiver side [4, 5]. With 5G gradually entering the commercial stage, the problems of communication transmitters such as increasing number of base stations, larger size, and more power consumption caused by the coexistence of multi-generation wireless communication standards are becoming apparent. Therefore, it has become a trend to use a single PA in the transmitter to support multi-band concurrent signal transmission [6, 7], which also puts forward higher requirements for the linearity and efficiency performance of the PA [8, 9]. A traditional method is power back-off for the input signal to ensure the PA works within its linear range [10]. This method is simple to implement, but will significantly reduce the efficiency of the power amplifier and waste energy [11, 12]. By pre-processing the transmitted signal, the PAPR reduction technique can reduce the probability of the signal with a significant peak value, thus reducing power back-off. This technique can improve the efficiency of the PA, and has become one of the key techniques for current wireless communication systems [13, 14].

Currently, the PAPR reduction technique faces challenges in concurrent dual-band scenarios [15, 16, 17, 18, 19]. The traditional 2-D PAPR reduction method [20] considers the total amplitude of the dual-band signals in the process of peak clipping. It adopts a simple amplitude compression and filtering, leading to over-reduction and under-reduction phenomena at some sampling points. The differential 2-D PAPR reduction method [21] improves this situation. However, the introduction of difference coefficient is also prone to cause improper peak clipping [22]. Furthermore, the unequal proportional clipping process is complicated, which is not conducive to hardware implementation. In addition, both above methods adopt the structure of cascaded filtering with hard limiting, which will produce peak regeneration, resulting in the actual PAPR value of the signal after peak clipping deviates from the target value.

To address these practical problems, this letter proposes a new 2-D PAPR reduction method. Firstly, the equal proportional peak clipping method is used for joint processing of dual-band signals; then, two iterations of noise filtering are performed to effectively deal with peak regeneration and inappropriate peak clipping cases. Experimental simulation results show that this method can effectively improve the peak clipping precision, i.e., make the actual PAPR value after PAPR reduction close to the target PAPR, and has a considerable error vector amplitude (EVM) performance.

The structure of this letter is as follows. In the first section, the definition and characteristics of PAPR are introduced. In the second section, the existing and the proposed 2-D
PAPR reduction methods are described. In the third section, the algorithm simulation and result analysis are carried out. Finally, the fourth section summarizes this letter.

2. Definition and characteristics of signal PAPR

OFDM signal is superimposed by multiple independent modulated subcarriers. When these subcarriers have the same phase or close phase, their peaks will also be superimposed, so that the peak power of the signal is much greater than the average power, resulting in the OFDM signal having a high PAPR [23]. The definition of PAPR can be expressed as:

$$ PAPR = 10 \log_{10} \left( \frac{\max_{0 \leq n \leq N-1} (|x(n)|^2)}{E(|x(n)|^2)} \right) $$

where $\max (\cdot)$ represents the operator to seek the maximum, $E (\cdot)$ denotes the expectation operator, $|x(n)|^2$ represents the signal’s instantaneous power, $\cdot$ denotes the absolute value operator, and $N$ is the number of sample points. Since the probability of the occurrence of the maximum power signal point is very low, the complementary cumulative distribution function (CCDF) is usually used to characterize the probability distribution of PAPR. Using the curve of CCDF, the probability of signal PAPR exceeding a set value can be seen more intuitively and quickly [24, 25]. In practice, the dB value at the point where the probability is one in ten thousand is often used to indicate the PAPR value of the signal.

In the PAPR reduction technique, error vector magnitude (EVM) indicates signal error before and after PAPR reduction [26]. For a complex signal, it can be defined as

$$ EVM = \left[ \frac{1}{N} \sum_{i=1}^{N} \left( (I(i) - I_r(i))^2 + (Q(i) - Q_r(i))^2 \right) \right]^{\frac{1}{2}} \times 100\% $$

where $I(i)$ and $Q(i)$ respectively represent the real and imaginary parts of the $i$-th actual complex signal, $I_r(i)$ and $Q_r(i)$ respectively represent the real and imaginary parts of the ideal complex signal. The smaller EVM value means the better actual signal quality, i.e., the smaller signal distortion caused by the PAPR reduction algorithm.

3. 2-D PAPR Reduction Methods

3.1 Traditional 2-D PAPR reduction method

2-D PAPR reduction methods [20, 27, 28, 29] are designed for the application scenario of dual-band amplifiers. Compared with the dual-band one-dimensional PAPR reduction method, the traditional 2-D PAPR reduction method considers the signal amplitude of the upper and lower bands simultaneously, mainly in the peak detection module. The schematic block diagram of the method is shown in Fig. 1 [20].

When the lower and upper band signals $x_1(n)$ and $x_2(n)$ enter the peak detection module, powers of both bands are added to get the combined power $P_{sum}(n)$, which is defined as

$$ P_{sum}(n) = |x_1(n)|^2 + |x_2(n)|^2 $$

then $P_{sum}(n)$ is compared with the given power threshold value $T_{2D}$. When $P_{sum}(n) \geq T_{2D}$, the input combined power is small enough, so both $x_1(n)$ and $x_2(n)$ remain unchanged. When $P_{sum}(n) > T_{2D}$, equal proportion peak clipping processing is carried out for both signals, $x_1(n)$ and $x_2(n)$ are simultaneously multiplied by a factor $K = \sqrt{\frac{T_{2D}}{P_{sum}(n)}}$, and the ultimate equation can be described as

$$ (x_{1\_clip}(n), x_{2\_clip}(n)) = \begin{cases} (x_1(n), x_2(n)), & P_{sum}(n) \leq T_{2D} \\ (K \cdot x_1(n), K \cdot x_2(n)), & P_{sum}(n) > T_{2D} \end{cases} $$

3.2 Differential 2-D PAPR reduction method

Reference [21] proposed a differential 2-D PAPR reduction method. Different with the traditional 2-D PAPR reduction method, the method adds a comparison of the instantaneous amplitudes of both signals, and modifies the peak detection module. The block diagram of the implementation is shown in Fig. 2.

In this method, $A$ is set as the peak threshold. When $|x_1(n)| + |x_2(n)| \leq A$, the signals of both bands keep unchanged, and the output $x_{i\_clip}(n)$ is equal to the input signal $x_i(n), i \in [1, 2]$.

When $|x_1(n)| + |x_2(n)| > A$, a parameter $d$ is introduced to compare the difference between $x_1(n)$ and $x_2(n)$, and its value is generally close to or equal to $A$.

When $|x_1(n)| + |x_2(n)| > A$, and $|x_1(n) - x_2(n)| \leq d$, the amplitude difference between $x_1(n)$ and $x_2(n)$ is small, therefore the equal proportional peak clipping is operated as:
This letter proposes a new 2-D PAPR reduction method, where peak clipping or bypass is performed, and the smaller amplitude keeps unchanged. Assumed $|x_i(n)| < |x_j(n)|$, $i, j \in \{1, 2\}$, the expressions of the output signals are obtained as follows:

$$\left\{ \begin{array}{l}
|x_{1,clip}(n)| = |x_2(n)| \\
|x_{2,clip}(n)| = A - |x_j(n)|
\end{array} \right.$$  \hspace{1cm} (6)

3.3 PAPR reduction method based on 2-D iterative noise filtering

By introducing a difference coefficient, the differential PAPR reduction method prevents excessive peak clipping of small signal points to a certain extent. However, it may lead to improper peak clipping [22]. Moreover, the peak clipping is a nonlinear signal processing, which inevitably brings spectrum expansion. Band-limited filtering is required in the above two methods to solve the problem, leading to peak regeneration, so the actual PAPR cannot reach the set target value.

This letter proposes a new 2-D PAPR reduction method, which adopts a simplified combined peak clipping module, cutting off most of the signals beyond the threshold. Then, to reduce peak regeneration in a good manner, a following noise filtering module is added and two iterations are carried out. The specific implementation process of the proposed method is shown in Fig. 3.

The specific implementation process of the algorithm is as follows.

First, the peak detection module is performed. When $|x_1(n)|+|x_2(n)| > B$, the signals of both bands are directly subjected to equal proportional peak clipping processing:

$$\left\{ \begin{array}{l}
x_{1,clip1}(n) = \frac{B}{|x_1(n)|+|x_2(n)|} x_1(n) \\
x_{2,clip1}(n) = \frac{B}{|x_1(n)|+|x_2(n)|} x_2(n)
\end{array} \right.$$  \hspace{1cm} (7)

where $x_{1,clip1}(n)$ and $x_{2,clip1}(n)$ are the signals of both bands after the first peak clipping respectively; $B$ is peak threshold which is expressed as:

$$B = sqrt(10^{\text{clip}_d\text{dB} \cdot \text{var}(x_1(n)+x_2(n)))}$$  \hspace{1cm} (8)

where clip\_dB is the target PAPR value and var$(x_1(n)+x_2(n))$ is the variance of the dual-band signal, approximately equal to its average power. When $|x_1(n)|+|x_2(n)| > B$, peak clipping is not performed, and the signals remain unchanged:

$$\left\{ \begin{array}{l}
x_{1,clip1}(n) = x_1(n) \\
x_{2,clip1}(n) = x_2(n)
\end{array} \right.$$  \hspace{1cm} (9)

Second, a following noise filtering module is added to suppress the spectrum expansion. Noise signals $I_{\text{noise1}}(n)$ and $I_{\text{noise2}}(n)$ of the two bands are calculated respectively:

$$\left\{ \begin{array}{l}
I_{\text{noise1}}(n) = x_1(n) - x_{1,clip1}(n) \\
I_{\text{noise2}}(n) = x_2(n) - x_{2,clip1}(n)
\end{array} \right.$$  \hspace{1cm} (10)

Noise filters are used to filter out noise components outside the signal bandwidths. Then filtered noise signals $I'_{\text{noise1}}(n)$ and $I'_{\text{noise2}}(n)$ are subtracted from the original signals after delay alignment, and the first PAPR reduction iteration is completed and, $x'_{1,clip1}(n)$ and $x'_{2,clip1}(n)$ of the first iteration are obtained as:

$$\left\{ \begin{array}{l}
x'_{1,clip1}(n) = x_1(n) - I'_{\text{noise1}}(n) \\
x'_{2,clip1}(n) = x_2(n) - I'_{\text{noise2}}(n)
\end{array} \right.$$  \hspace{1cm} (11)

Finally, because the noise spectrum of each band is limited to the signal bandwidth by filtering, which may cause peak regeneration, the second iteration is performed to solve the problem. In the second iterative process, the peak clipping threshold $B$ remains unchanged. The signals $x'_{1,clip1}(n)$ and $x'_{2,clip1}(n)$ enter the peak detection module again as input signals for iterative processing. Like the first iterative process, if $|x'_{1,clip1}(n)|+|x'_{2,clip1}(n)| > B$, it is treated according to equation (7); else if $|x'_{1,clip1}(n)|+|x'_{2,clip1}(n)| \leq B$, it is processed according to Eq. (9). Ultimately, the PAPR reduction signals $x''_{1,clip1}(n)$ and $x''_{2,clip1}(n)$ are generated after the second iteration.

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Fig. 2. Schematic diagram of differential 2-D PAPR method.

Fig. 3. Block diagram of the propose method.
4. Simulation results and analysis

This section discusses the effectiveness of the PAPR reduction method proposed in this letter through experimental simulation. The simulation signal used is a dual-band OFDM signal with 64QAM modulation mode. The upper and the lower band signal are apart from 70MHz, each with 10MHz bandwidth, the sampling frequency is 122.88MHz, and the PAPR value of the signal is 9.7dB.

The key of the proposed algorithm proposed is the design of the noise filter. In order to obtain a steeper filter transition band with lower filter order, two-stage cascade structures are adopted, the first stage is an interpolation prototype filter, and the second stage is a mirror filter. The main parameters are set as follows: the pass-band cut-off frequency of the cascaded filter 3.84MHz, the initial frequency of stop-band 5.21MHz, the pass-band fluctuation 0.5dB, and the stop-band attenuation 50dB. Fig. 4 and Fig. 5 are the amplitude-frequency characteristic curve of the filters, where the order of the interpolation prototype filter is 22, the interpolation multiples are 6, and the order of the mirror filter is 25.

![Fig. 4. Amplitude frequency characteristics of interpolation prototype filter and mirror filter.](image)

Fig. 4 compares the time domain waveform of the signal in the case of one iteration and two iterations when the target PAPR is 6.6dB. After the first iteration, the signal amplitudes at many sampling points are still significantly higher than the threshold; After the second iteration, the signal amplitudes are mainly below the threshold. It shows that the addition of the second iteration has effectively improved the PAPR performance, so there is no need to design the third iteration process.

Next, we set target PAPR values to be 9dB, 8dB, 7dB, and 6.6dB, respectively for simulation, and the obtained CCDF curves are shown in Fig. 7, and the actual PAPR values are 9dB, 8dB, 7.2dB, and 6.8dB correspondingly. This figure shows that the output PAPR are almost consistent with the target PAPR, which proves that this method can effectively reduce the PAPR of a dual-band OFDM signal.

![Fig. 5. Amplitude frequency characteristics of cascaded filter.](image)

![Fig. 6. Time domain comparison of iteration times.](image)

![Fig. 7. CCDF curve of the proposed 2-D PAPR reduction method.](image)

The comparison of the actual PAPR performance of the three 2-D PAPR reduction methods mentioned above is shown in Fig. 8. The target PAPR is set to be 6.6dB, and the actual PAPR of the traditional 2-D method, the differential 2-D method, and the proposed method is 8.1dB, 7.4dB, and 6.8dB, respectively. Compared with the other two methods, the actual PAPR of the proposed method is the closest to the target PAPR, and has the highest PAPR reduction precision for the sake that it suppresses the peak regeneration greatly.
with the iterative noise filtering processing.

Fig. 9 compares EVM values corresponding to the actual PAPR obtained under different 2-D PAPR reduction methods. The abscissa is the actual PAPR value of the dual-band signal after PAPR reduction, and the ordinate is the EVM value. When the PAPR value of the dual-band signal is reduced to 8dB, the EVM values of the traditional method, the differential method, and the proposed method are 3.9%, 3.3%, and 3.0%, respectively. When the PAPR value of the dual-band signal is further reduced to 6.8dB, the EVM values of the traditional method, the differential method, and the proposed method are 10.3%, 8.9%, and 6.9%, respectively. The proposed method’s EVM performance outperforms the other two methods, which means the smallest signal distortion. The modulation mode of the signal used in the experiment is 64QAM, and its maximum allowable EVM is 8% [30]. Therefore, the EVM performance of the algorithm proposed in this letter has apparent advantages, which can obtain a lower PAPR value on the premise of ensuring the EVM performance to reduce the power back-off and enhance the efficiency of PA.

5. Conclusion

PAPR reduction is one of the important techniques to be addressed in developing multi-band signal transmission systems. In this letter, the traditional 2-D PAPR reduction method and the differential 2-D PAPR reduction method are analyzed and a new 2-D PAPR reduction method is proposed. Based on jointed equal proportional peak clipping and iterative noise filtering, the proposed method is simple to implement and can improve the PAPR reduction performance of dual-band systems. The proposed method is applied to a dual-band OFDM signal with 64QAM modulation mode. Simulation results demonstrates that it can obtain the lowest PAPR value on the premise of ensuring the allowable EVM when compared with the other two methods.

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