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A Hybrid Approach to Reduce the PAPR of OFDM Signals Using Clipping and Companding

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ABSTRACT Orthogonal frequency division multiplexing (OFDM) is an important technology that has been widely used in broadband wireless communications. However OFDM has some drawbacks, one of which is the high peak-to-average power ratio (PAPR) problem. Many techniques for reducing PAPR thus have been proposed in the literatures, where clipping and companding are effective techniques and have gained a lot of research interest. Based on the study of clipping and companding, this paper proposes a hybrid approach to reduce the PAPR of OFDM signals. An iterative clipping and filtering (ICF) technique and an enhanced nonlinear companding (ENC) scheme are used as the typical clipping and companding techniques in this paper. The results of the analysis show that the computational complexity of the proposed method is slightly higher than that of ENC, but much lower than that of ICF. And the simulation results show that the proposed method has better performance on PAPR reduction and bit error rate (BER) in contrast to ICF. On the other hand, compared to ENC with equal PAPR reduction, the proposed method still achieves better performance on BER.

INDEX TERMS Orthogonal frequency division multiplexing, peak-to-average power ratio, PAPR reduction, clipping, companding, hybrid approach.

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is one of the most popular technologies for broadband wireless communication and has been used in several widely used standards, such as Digital Video Broadcasting (DVB), Wireless Local Area Network (WLAN) and 4G-LTE [1]–[4]. More recently, in addition to inherit Discrete Fourier Transform-spread-OFDM (DFT-s-OFDM) as one of the uplink modulation schemes, 3GPP has decided to adopt OFDM with a cyclic prefix (CP-OFDM) for both of the uplink and downlink in the 5G new radio (5G NR) [5]. The advantages of OFDM include high spectral efficiency and tolerance of multipath fading channels. However, it also has some drawbacks with practical implementations, one of which is the problem of high peak-to-average power ratio (PAPR). Practically, high PAPR would cause nonlinear distortion of the power amplifier [6], [7]. Although power back-off can be used to reduce the nonlinear distortion, it however will reduce the power efficiency [8]. This is because of that as one of the main energy-consumer in the device, the power amplifier is usually expected to work near the saturation region [9], [10]. Therefore, as alternative technology that can be used to improve the efficiency of power amplifiers, PAPR reduction has become an attractive research [11].

Recently, numbers of PAPR-reduction techniques have been proposed in the literatures, including coding techniques, multiple signaling & probabilistic techniques, signal distortion techniques [12], [13]. Coding techniques achieve PAPR reduction by choosing appropriate codewords, but this typically results in a loss of coding rate [14]. Multiple signaling & probabilistic techniques, such as selective mapping (SLM) and partial transmit sequence (PTS), are implemented by generating multiple candidate signals and selecting the one with the lowest PAPR for transmission [15], [16]. They would result in high computational complexity and the transmission of side information. Signal distortion techniques reduce the PAPR by modifying the transmission signal, which usually cause in-band and out-of-band distortion. However, they are usually easy to be implemented and do not require transmission of side information [17], [18].

Clipping is one of the well-known signal distortion techniques for PAPR reduction. Due to that simple clipping will cause out-of-band distortion, filtering is additionally

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implemented to follow the clipping to meet the spectral radiation requirements. However, the filtering leads to the regrowth of peak and degrades the performance of PAPR reduction. Therefore, many improved methods of clipping based techniques have been proposed. [19] proposed the iterative clipping and filtering (ICF) to suppress the peak regrowth for the desired PAPR reduction. In order to reduce the computational complexity caused by iteration operations in ICF, [20] proposed a simplified clipping and filtering technique. [21] proposed an optimized iterative clipping and filtering (OICF) technique to enhance the performance of ICF, and [22] proposed a simplified approach to OICF. There are also some other methods proposed in recent years, such as the approaches in [23]–[25]. These clipping based techniques generally take clipping followed some post-clipping operations.

Apart from clipping, companding is an effective signal distortion technique to reduce the PAPR by compressing or expanding the amplitude of the OFDM signals [11], [26]. [27] proposed a companding technique using mu-law algorithm, which is originally used in speech processing. Then, a number of companding based technologies were proposed, including nonlinear companding transform, linear companding transform, exponential companding technique, raised cosine-like companding scheme and so on [28]–[32]. Recently, [33] proposed the enhanced nonlinear companding scheme (ENC) that can limit the signal to a desired power level and require no inverse operations at the receiver. This makes ENC an attractive approach to PAPR reduction.

In general, clipping and companding have many common advantages: 1) both of the two techniques focus on amplitude modifying; 2) no need of the transmission of side infomation; 3) lower computational complexity than other PAPR reduction techniques and the complexity is independent of the number of subcarriers. In fact, companding can also be seen as a special clipping technique [34]. One of the main differences between clipping and companding is that the former mainly clips large signals beyond the clipping threshold, while the latter generally compresses large signals and expands small signals simultaneously. Another difference is that clipping based techniques only take processings in the transmitter, while companding usually needs to perform the inverse companding transform in the receiver besides the companding transforms in the transmitter. However, the ENC proposed in [33] does not require any additional operations of signal recovery in the receiver, and the simulation results show that it has provided better performance on PAPR reduction and bit error rate (BER) than other companding techniques. The ENC shows that its characteristics are more similar to those of clipping based techniques. Therefore, here we consider to combine clipping and companding to propose a hybrid approach to PAPR reduction for better performance.

We firstly analyzed the characteristics of the clipping and companding techniques. Then, based on ENC, the companding function is redesigned by introducing the clipping ratio, which is generally used in the clipping based techniques. The clipping ratio is used to calculate the clipping threshold. In the traditional clipping method, the amplitude is clipped to the clipping threshold, but the peak regrowth occurs when passed through the filter, leading to the maximum amplitude of the transmitted signal higher than the clipping threshold. In the proposed method, the clipping threshold is adopted as the limit amplitude of the output signals, that is, the maximum amplitude of the transmitted signal is smaller than the clipping threshold. This results in smaller peaks for the proposed method. On the other hand, the companding function of the proposed method is designed to merely compress the large signals while keeping the small signals unchanged. This results in less distortion for the proposed method.

Under such deployment, the proposed method will have features of both clipping and companding simultaneously. That is, compressing the peaks beyond the clipping threshold in the transmmiter, without any additional operations in the receiver, and no transsmition of side information is needed. Compared to ENC, the proposed method introduces the clipping ratio and calculates the clipping threshold according to the average power of the OFDM symbol, which makes the control of the input signal amplitude more accurate. Compared to ICF, the proposed method does not require post-clipping operation or additional fast Fourier transforms between the frequency domain and the time domain. Thus, although the computational complexity of the proposed method is slightly higher than ENC, the complexity however is much lower than that of ICF. Finally, we carried out simulations and compare the proposed method to ICF and ENC. The numerical results show that the proposed method has better performance on PAPR reduction and BER than ICF. And with equal PAPR reduction, the proposed method achieves better performance on BER than that of ENC.

The remainder of the paper is organized as follows. In Section II we introduce the background, including the system model and the related previous studies. In Section III we demonstrate and analyze the proposed hybrid method. In Section IV we provide the simulation results and related analysis. Finally, the conclusion will be provided in Section V.

II. BACKGROUND

In this section, we firstly introduce the system model of OFDM and the problem of high PAPR. Then, we demonstrate two existing works related to our work, i.e., ICF and ENC.

A. SYSTEM MODEL

In the OFDM system, to obtain the high data rate and the tolerace of delay spread simultaneously, the wideband signal is converted into several parallel narrowband signals for transmission. The data to be transmitted should be modulated onto the subcarriers of the OFDM system after the serial-to-parallel conversion. And the subcarriers are orthogonal to each other, so as to achieve high spectral efficiency and robust against intersymbol interference. In modern communications, fast Fourier transform (FFT) is widely used to ensure orthogonality between subcarriers of the OFDM systems.

Therefore, an OFDM signal can be expressed as

$$d(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} D(k) e^{j\frac{2\pi nk}{N}}, \tag{1}$$

where N is the number of subcarriers, and D is a complex vector containing N components as subcarriers modulated by phase shift keying (PSK) or quadrature amplitude modulation (QAM). $d(n)$ is the time-domain signal to be transmitted, then $D(k)$ can be regarded as a frequency-domain signal.

In order to better approximate the continuous signal, we usually need to oversample the time domain OFDM signal by L (typically $L \geq 4$) [34]. This process can be achieved by zero padding in the frequency domain. The extended frequency-domain OFDM symbol can be expressed as

$$\begin{aligned} X &= [X(0), X(1), \ldots, X(LN-1)] \\ &= [D(0), D(1), \ldots, D(N-1), \underbrace{0, 0, \ldots, 0}_{(L-1)N}]. \end{aligned} \tag{2}$$

Then, the time-domain OFDM signal $x(n)$ can be expressed as

$$x(n) = \frac{1}{\sqrt{LN}} \sum_{k=0}^{LN-1} X(k) e^{j\frac{2\pi nk}{LN}}. \tag{3}$$

Since D is a complex vector whose components are signals after constellation mapping, OFDM symbols are complex and can be described as

$$x(n) = a(n) + jb(n), \quad n = 0, 1, \ldots, LN-1, \tag{4}$$

where $a(n)$ and $b(n)$ are respectively the real and imaginary parts of the OFDM symbol.

In order to further improve the spectral efficiency and tolerance of multipath fading, OFDM systems in wireless communication have a tendency to support more subcarriers and higher order modulations. When the number of subcarriers N is sufficiently large (typically $N \geq 64$), $a(n)$ and $b(n)$ are independent and identical Gaussian distributed variables according to the central limit theorem. Therefore, the amplitude $|x(n)| = \sqrt{a(n)^2 + b(n)^2}$ follows the Rayleigh distribution [35]. And the probability density functions (PDFs) can be described as

$$f_{|x(n)|}(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \tag{5}$$

where σ^2 is the variance, and r is the amplitude of $x(n)$.

According to the characteristics of the Rayleigh distribution, the peak power of the OFDM symbol is much larger than the average power. To describe this feature, PAPR thus can be proposed and defined as

$$\mathrm{PAPR}[x(n)] = \frac{\max\limits_{0 \leq n \leq LN-1} [|x(n)|^2]}{\frac{1}{LN} \sum\limits_{n=0}^{LN-1} (|x(n)|^2)}. \tag{6}$$

One of the important concerns in the implementation of OFDM is the problem of PAPR reduction. The performance of PAPR reduction is usually evaluated using complementary cumulative distribution function (CCDF), which is defined as

$$\mathrm{CCDF}[\mathrm{PAPR}(x(n))] = \mathrm{prob}[\mathrm{PAPR}(x(n)) > \mathrm{PAPR}_0], \tag{7}$$

where prob[$\cdot$] is the probability operator and PAPR_0 is the reference threshold.

B. ITERATIVE CLIPPING AND FILTERING (ICF)

Traditional clipping based techniques typically put a hard limiter on the OFDM symbols. The process can be described as

$$\bar{x}(n) = \begin{cases} x(n), & |x(n)| \leq T \\ Te^{j\phi(n)}, & |x(n)| > T, \end{cases} \tag{8}$$

where $\phi(n)$ is the phase of $x(n)$, and T is the amplitude threshold which is calculated as

$$T = \gamma \sqrt{P_{av}}, \tag{9}$$

where P_{av} is the average power of the OFDM symbols, and γ is the clipping ratio.

According to (8), the large signal is limited to the threshold while the small one keeps unchanged. Due to out-of-band radiation caused by the hard limiter, it therefore is expected that filtering shuould be applied. A typical filter is designed as

$$H(k) = \begin{cases} 1, & 0 \leq k \leq N-1 \\ 0, & N \leq k \leq LN-1. \end{cases} \tag{10}$$

As the filter will lead to a peak regrowth of the OFDM symbol, ICF is proposed to achieve the desired PAPR reduction by repeated clipping and filtering.

Therefore, the steps to carry out ICF can be described as follows.

1) Calculate the average power of the OFDM symbol and the clipping threshold according to (9);
2) clip the signal to the clipping threshold according to (8);
3) filter the signal according to (10);
4) repeat the step 1) to 3) $(K-1)$ times, where K is the preset number of iterations.

As a typical clipping based technique, ICF is used for comparative evaluation in our research [24], [25].

C. ENHANCED NONLINEAR COMPANDING (ENC)

Companding and clipping are both effective techniques for PAPR reduction and have obvious advantages in practical implementations. The clipping-based methods usually require signal processing only before the input of amplifier in the transmitter, while the companding-based methods typically require not only companding in the transmitter but also corresponding operations of decompanding in the receiver.

However, the ENC method proposed in [33] does not require decompanding in the receiver, and greatly reduces the complexity of the system. This allows the method to exhibit some of the characteristics of clipping and companding at the

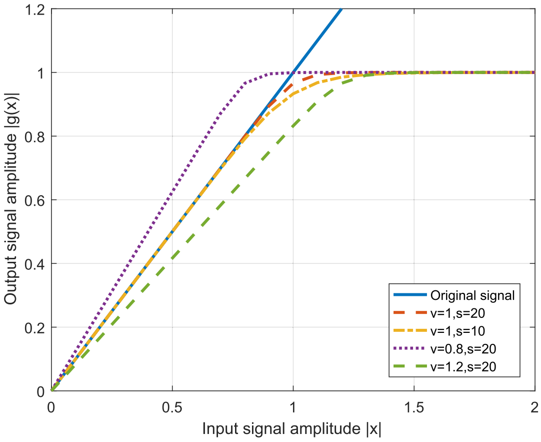


FIGURE 1. The characteristics of the companding function of ENC.

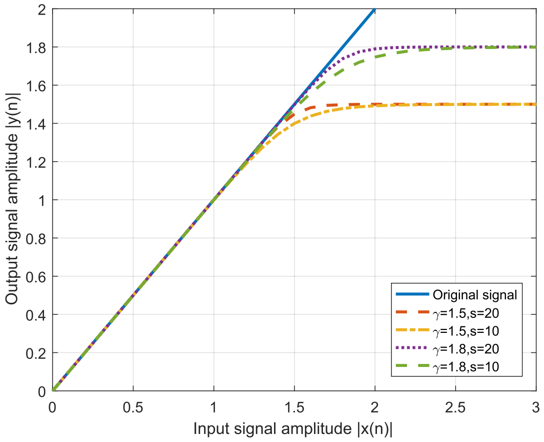


FIGURE 2. The characteristics of the proposed companding function.

same time. Therefore, we consider combining clipping and companding in this paper based on the ENC method.

The companding function in the ENC method is defined as

$$g(x) = M(1 + (\frac{v}{|x|})^{\frac{1}{\alpha}})^{-\alpha}\text{sgn}(x). \tag{11}$$

In (11), v can be regarded as a normalization factor, which indicates the amplitude of x to be compressed or expanded. The parameter α controls the shape of the companding curve, and is defined as $\alpha = 1/s$ with s being the shape factor. And $\text{sgn}(\cdot)$ is the sign function that obtains the phase of complex signal. Due to $(1 + (\frac{v}{|x|})^{\frac{1}{\alpha}}) > 1$, there is $((1 + (\frac{v}{|x|})^{\frac{1}{\alpha}})^{-\alpha}\text{sgn}(x)) < 1$, and the limit of the term $((1 + (\frac{v}{|x|})^{\frac{1}{\alpha}})^{-\alpha}\text{sgn}(x))$ equals to 1. Therefore, the parameter M can be regarded as a linear scaling factor that denotes the maximum amplitude of the output signal.

Therefore, the features of the function are mainly determined by v and s. Based on these, Fig.1 shows the characteristics of the function with different values of v and s when $M = 1$.

As can be seen from Fig.1, the parameter s controls the shape of the companding curve. That is, the smaller the s, the smoother the curve rises, vice versa. The parameter v determines the input amplitude expanded or compressed. Specifically, smaller signal is expanded when $v < 1$, and compressed when $v > 1$. This means that for signals with different input amplitudes, v and s need to be carefully chosen to meet the trade-off between the performance of BER and PAPR reduction [33].

The steps of ENC are relatively simple. The time-domain signal after inverse FFT (IFFT) is directly companded according to (11) to obtain the transmitted signal. Furthermore, ENC does not require additional operations of signal recovery in the receiver. And the simulation results in [33] show that ENC outperforms other considered companding techniques on BER performance. To this end, ENC is leveraged in our simulations as a typical companding based technique.

III. THE PROPOSED METHOD AND ANALYSIS

In this section, we propose a hybrid approach to reduce PAPR using clipping and companding. Then, the analyses of the proposed method on performance and computational complexity are demonstrated.

A. THE PROPOSED METHOD

As verified in [33], the ENC method can achieve high performance by choosing the parameters v and s. In fact, the modulations or the number of subcarriers may be variable to support better transmission, even in the single OFDM system. Then the characteristics of the amplitude of the OFDM signals may change accordingly. In this case, the values of v and s need to be re-calibrated to validate the robust performance of the system.

To this end, we expect that the system could work stablely given the input power of the OFDM symbol fluctuates. In addition, we found that the companding curve is similar to that of clipping, where the amplitude of the large signal is limited to a certain threshold. The difference is that the small signals may be expanded or compressed when ENC is used, while they remain almost unchanged when the clipping method used. In order to maintain the characteristics of both companding and clipping, the large signals are expected to be compressed while the small signals keep unchanged.

According to the above analysis, we propose the new companding function as

$$y(n) = \begin{cases} \dfrac{Te^{j\phi(n)}}{(1 + (\dfrac{T}{|x(n)|})^{1/\alpha})^{\alpha}}, & |x(n)| > 0 \\ 0, & |x(n)| = 0, \end{cases} \tag{12}$$

where $\phi(n)$ is the phase of $x(n)$; α is defined as $\alpha = 1/s$ as the same as in (11), and T is the clipping threshold, which is calculated according to (9), i.e., $T = \gamma\sqrt{P_{av}}$.

The proposed companding function is derived from (11). The main difference is that, in (11), the normalization factor v and the output scaling factor M are fixed values that are preset

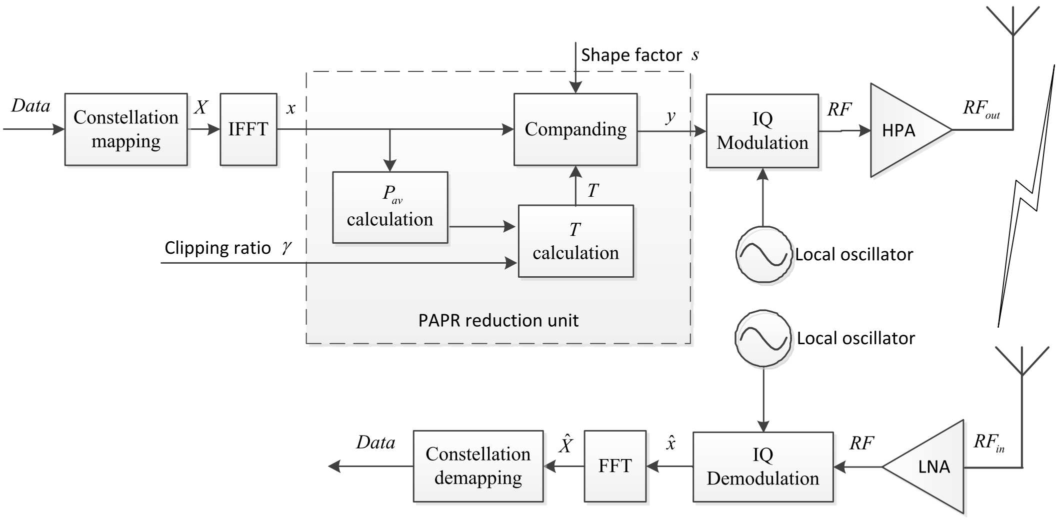


FIGURE 3. **The simplified block diagram of the OFDM system with the proposed method.**

respectively, on the other hand, in (12) these two factors are replaced by the same parameter T, which varies according to the average power of the OFDM symbol.

Due to that the same parameter, i.e., the clipping threshold T is adopted as the normalization factor and the output scaling factor simultaneously, the proposed function exhibits the characteristics of 1) the signals with amplitude far smaller than T keep unchanged; 2) the signals with amplitude close to T are nonlinearly compressed; and 3) the signals with amplitude far larger than T are limited to T. In addition, since T varies with the average power of the OFDM symbol, the proposed function will lead to more approximate to the desired PAPR and less distortion.

The characteristics of the proposed companding function are shown in Fig.2. Since the proposed method introduces the parameter of clipping ratio, the amplitudes of small signals can be kept substantially unchanged when different clipping ratio or shape factor are used. This is consistent with the characteristics of the clipping based methods. On the other hand, the proposed method limits the large signal to the clipping threshold, which is also a feature of the clipping based methods. Therefore, the proposed method can be regarded as a hybrid approach of companding and clipping.

In summary, the simplified block diagram of the OFDM system with the proposed method is shown in Fig.3. According to the figure, the PAPR reduction unit is inserted after the IFFT block in the transmitter. This shows that the proposed method does not change the original protocol, so it can be used for various communication standards. In addition, the proposed method does not require any additional operation in the receiver. This indicates that the proposed method is relatively easy to be implemented and has the potential to communicate with devices that do not use the same technique of PAPR reduction.

The steps of the proposed method are described as follows.

1) Calculate the average power of the OFDM symbol;
2) calculate the clipping threshold according to (9);

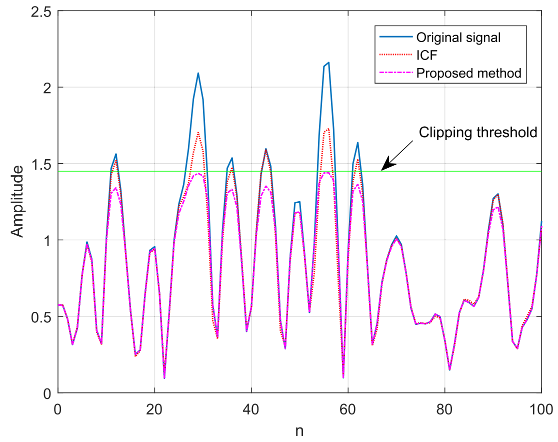


FIGURE 4. **The comparison of signals obtained by ICF and the proposed method.**

3) compand the OFDM signals according to (12) to obtain the transmitted signals.

B. ANALYSIS OF THE PROPOSED METHOD

The proposed method is based on a companding function to obtain the features of clipping such that the peak amplitude of the OFDM symbol is less than the clipping threshold. In the clipping based methods, additional operations are usually required following clipping, which usually produces a peak regrowth that causes the peak amplitude to exceed the clipping threshold.

The amplitude comparison of signals obtained by using ICF and the proposed method is shown in Fig.4, where the time-domain samples are from a segment of an OFDM signal with 64 subcarriers and 4 times oversampled.

We can see in Fig.4 that the amplitudes of several signal peaks of ICF exceed the clipping threshold, while the max amplitude of the proposed method is less than the clipping threshold. Moreover, according to the characteristics of the Rayleigh distribution that the amplitude of the OFDM signals

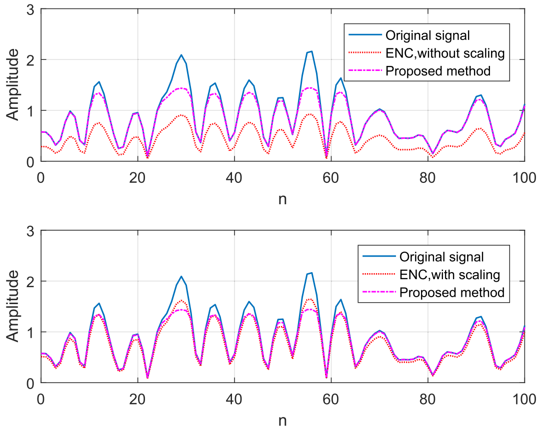


FIGURE 5. The comparison of signals obtained by ENC and the proposed method.

following, the proportion of the clipped peaks is relatively small, so the average power of the signal obtained using the proposed method or clipping is almost the same. Therefore, according to (6), the proposed method should have better PAPR-reduction performance than the clipping method with the same clipping ratio.

The shape factor s of the companding function in the proposed method is defined the same as in ENC. The proposed method replaces M and v in ENC with the clipping threshold T. According to (9), the value of T depends on the clipping ratio γ and the average power of the OFDM symbol. And since the input data of the system can be treat as random variables, the average power of the OFDM symbol usually does not remain constant. This causes T to vary as the average power varies. As the PAPR is also calculated according to the symbol average power, which makes the proposed method have better PAPR reduction than ENC, due to T controlling the input amplitudes more accurately than v in ENC.

Fig.5 shows the amplitude comparison of the signals obtained using ENC and the proposed method. The clipping ratio in the proposed method is set to $\gamma = 1.5$, and the parameters in ENC are set to $v = 1$ and $M = 1$. As can be seen from the upper sub-figure of Fig.5, the output amplitude of signal of ENC does not exceed 1, and the most samples are compressed. For a more direct comparison, we linearly scale the original signal of ENC in the upper sub-figure to get the equal average power as the proposed method, as shown in the lower sub-figure of Fig.5. As can be seen from the figure, the amplitudes of several peaks of the ENC signal are higher than the peaks obtained by the proposed method. This makes PAPR-reduction performance of ENC worse than the proposed method. Of course, we can also carefully adjust the parameters in equation (11) so as to ensure ENC and the proposed method have the same PAPR reduction. However, this will be achieved at the expense of BER performance. The conclusion will be evaluated by simulations in the next section.

TABLE 1. Computational complexity comparison.

	ICF	ENC	The proposed
MULTs	$LNK\log_2(LN) + 2LNK$	$2LN$	$4LN$
ADDs	$2LNK\log_2(LN) + LNK$	LN	$2LN$
LOGs	$--$	$2LN$	$3LN$

C. COMPUTATIONAL COMPLEXITY

In this subsection, we carried out comparative analyses of the computational complexity for ICF, ENC and the proposed method.

In the ICF method, it is assumed that an LN-points FFT operation requires $1/2LN\log_2(LN)$ multiplications and $LN\log_2(LN)$ additions. Then, for an ICF scheme with K iterations, it needs $LNK\log_2(LN)$ multiplications and $2LNK\log_2(LN)$ additions for FFT/IFFT operations, as each iteration requires a pair of FFT/IFFT. In addition, it needs $2LN$ multiplications and LN additions for clipping operations in each iteration, leading to a computational complexity of $2LNK$ multiplications and LNK additions for clipping operations in K iterations. Therefore, the ICF method totally requires $LNK\log_2(LN) + 2LNK$ multiplications and $2LNK\log_2(LN) + LNK$ additions.

For the ENC method, neither clipping operations nor iterative operations are required. And, the OFDM signal is directly companded by the companding function in the time domain to obtain a transmitted signal, so there is no additional FFT/IFFT operation required. Therefore, the computational complexity of ENC is only determined by the companding function, and requires $2LN$ multiplications, LN additions, and $2LN$ logarithmic operations.

In the proposed method, there is also no need for clipping operations, iterative operations, and additional FFT/IFFT operations, as in the ENC. However, the proposed method needs to carry out calculations to determine the clipping threshold T. Since T is the product of the clipping ratio and the root of the average power, the proposed method requires an additional $2LN$ multiplications, LN additions, and LN logarithmic operations. Therefore, adding the computational complexity of the companding function (12), the proposed method totally requires $4LN$ multiplications, $2LN$ additions, and $3LN$ logarithmic operations.

The computational complexities of the evaluated methods are shown in Table.1.

As denoted in Table.1, although ICF dose not require logarithmic operation, it still has significant numbers of multiplications and additions caused by fast Fourier transforms. Since the OFDM systems with $N \geq 64$ are adopt in most cases, even with one iteration, the complexity of multiplication and addition in ICF will far exceed the one that in ENC or the proposed method. Therefore, it can be concluded that the proposed method has higher computational complexity than ENC, while lower than ICF.

In order to more clearly exhibit the computational complexities of the evaluated methods, we adopt a typical OFDM

TABLE 2. An example of complexity calculations for an OFDM system.

	ICF	ENC	The proposed
MULTs	36864	2048	4096
ADDs	64512	1024	2048
LOGs	0	2048	3072

system as an example. The numerical calculations are shown in Table.2.

The parameters of the OFDM system used in Table.2 are chosen as $N = 256$, $L = 4$ and $K = 3$. According to Table.2, the proposed method has slightly higher computational complexity caused by multiplications and additions than ENC, and much lower than ICF.

IV. SIMULATION RESULTS AND DISCUSSION

In this section simulations were taken to evaluate the performance of the proposed method by comparison with the typical clipping and companding based methods. The oversamle factor is set to $L = 4$. ICF with 3 iterations is taken as the typical clipping based technique, and ENC is taken as the companding based technique for conparison.

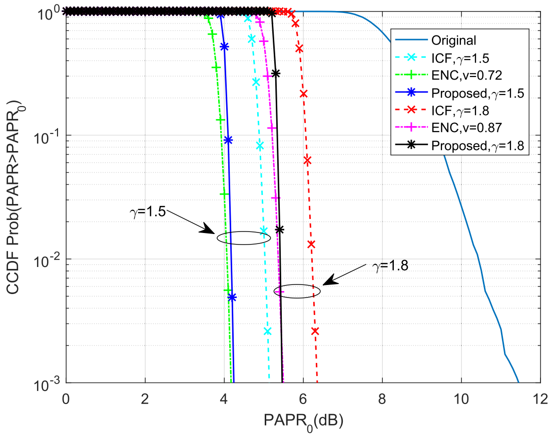
A. SIMULATION RESULTS FOR SIGNALS WITH VARIED SHAPE FACTORS

In this subsection, the OFDM system with 256 subcarriers and 16QAM modulated is adopted in the simulations. Firstly we set the clipping ratio $\gamma = \gamma_0$ for ICF and the shape factor $s = s_0$ for ENC. And both γ_0 and s_0 are adopted by the proposed method for simulations. Then the comparison of ICF and the proposed method can be evaluated with the same clipping ratio. At the same time, we carefully choose the value of v for ENC so that it achieves equal PAPR reduction with the proposed method. And, the modified signals are passed through the additive white gaussian noise (AWGN) channel. Then, the BER comparison of ENC and the proposed method can be evaluated with the same shape factor and PAPR reduction.

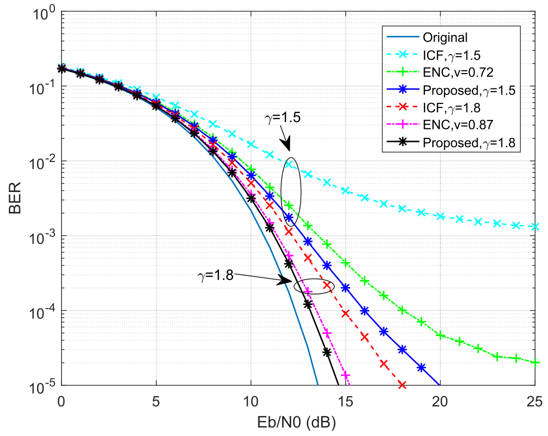
Fig.6 shows the comparison of the performance of the evaluated methods when the shape factor is set to $s = 60$, which is the same parameter setting as [33]. It can be seen from Fig.6(a) that the PAPR reduction of the proposed method has about 1dB better than ICF at a probability of 10^{-3}, when γ is set to $\gamma = 1.5$, as well as $\gamma = 1.8$. Meanwhile, the BER performance of the proposed method is also better than ICF according to Fig.6(b).

As shown in Fig.6, the value of the parameter v is carefully chosen for ENC, specifically, $v = 0.72$ when $\gamma = 1.5$, and $v = 0.87$ when $\gamma = 1.8$, so that it achieves the same PAPR reduction as the proposed method. However, according to Fig.6(b) the proposed method requires 0.6dB lower SNR than ENC at the BER of 10^{-5} when $\gamma = 1.5$. And, the BER performance of the proposed method is observably better than ENC at the BER of 10^{-5} when $\gamma = 1.8$.

In order to evaluate the effect of the shape factor s on the proposed method and ENC, we also took simulations with $s = 6$, as shown in Fig.7. As the s decreases, the PAPR reduction of the proposed method also slightly decreases, but still better than that of ICF according to Fig.7(a). According to Fig.7(b), the proposed method still has the best BER performance within the evaluated methods.



(a) The PAPR reduction comparison, $s = 60$.



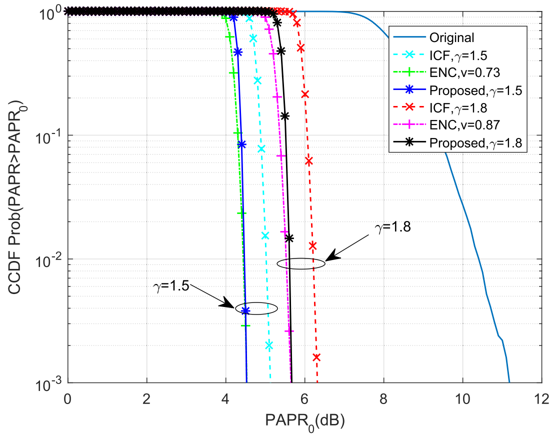
(b) The BER performance comparison, $s = 60$.

FIGURE 6. The CCDF and BER curves of the evaluated signals with $s = 60$.

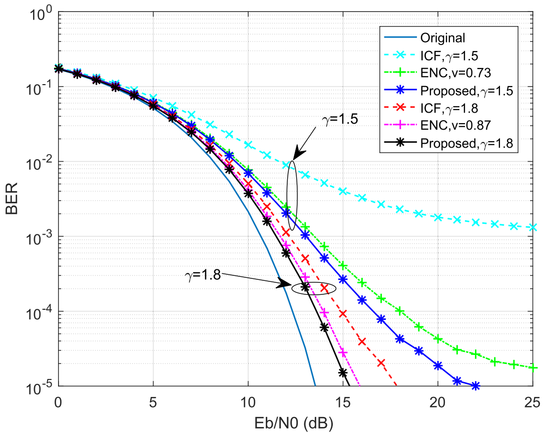
B. SIMULATION RESULTS FOR SIGNALS WITH VARIED NUMBER OF SUBCARRIERS AND MODULATION ORDERS

Due to the growing demand for wireless communications and the enhancement of signal processing techniques, broadband communications are tending to use OFDM with more subcarriers and higher modulation orders. The same is true for 5G NR. Therefore, in this subsection we carried out simulations using OFDM signals based on 5G NR to evaluate the proposed method.

According to 3GPP TS 38.211, unlike 4G-LTE, which uses the 2048-points FFT, the 5G NR adopts more flexible numerology schemes in order to support services in various scenarios. The standard specifies that physical layer resources are allocated according to resource blocks (RBs). one RB is composed of 12 consecutive subcarriers in the frequency domain, and one OFDM symbol can support up to

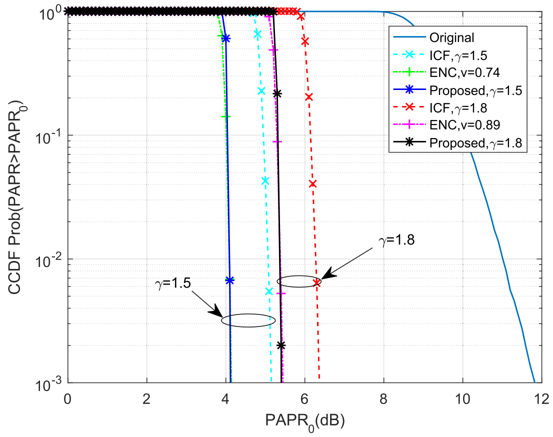


(a) The PAPR reduction comparison, $s = 6$.

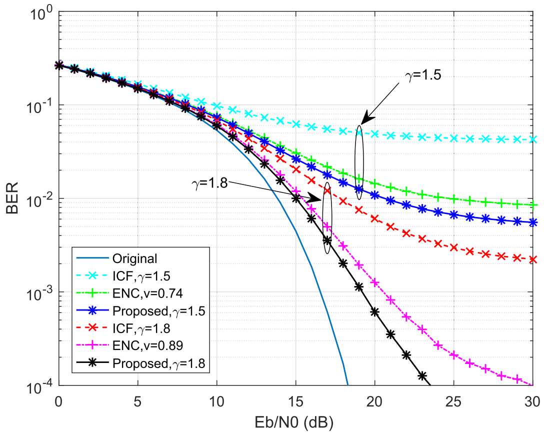


(b) The BER performance comparison, $s = 6$.

FIGURE 7. The CCDF and BER curves of the evaluated signals with *s* = 6.



(a) The PAPR reduction comparison, with 1656 subcarriers and 64QAM.



(b) The BER performance comparison, with 1656 subcarriers and 64QAM.

FIGURE 8. The CCDF and BER curves of the evaluated signals with 1656 subcarriers and 64QAM.

275 RBs [36]. That is, up to 3300 subcarriers are supported, which requires up to 4096-points FFT. Moreover, higher order modulation such as 256QAM is supported. Therefore, we carried out simulations using OFDM signals with 1656 subcarriers (138 RBs, 2048-points FFT) and 64QAM, as well as ones with 3300 subcarriers (275 RBs, 4096-points FFT) and 256QAM, to evaluate the proposed method. In addition, the shape factor s is set to 60, and the setup and steps of the simulation are the same as in the previous subsection.

Fig.8 shows the comparison of the performance of the evaluated methods using the signals with 1656 subcarriers and 64QAM modulations. According to Fig.8(a), the CCDF curve indicates that the proposed method has about 1dB better performance on PAPR reduction than ICF at a probability of 10^{-3}, when γ is set to $\gamma = 1.5$, as well as $\gamma = 1.8$. And through parameter adjusting, the ENC method can achieve the same level of PAPR reduction as that of the proposed method. In such case, we compared the BER performance of the evaluated methods.

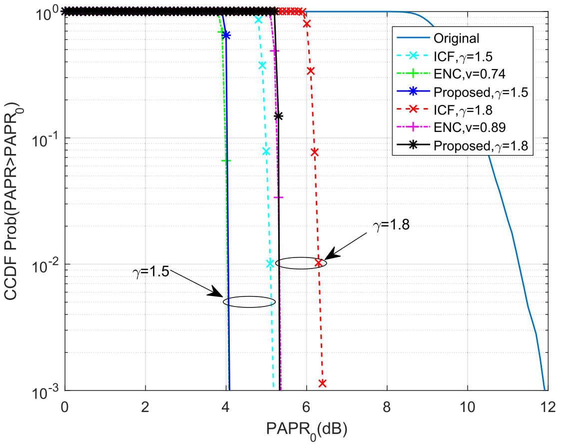
According to Fig.8(b), when γ is set to $\gamma = 1.5$, both the proposed method and the ENC method exhibit much better performance on BER than ICF. Moreover, the BER performance of the proposed method is better than that of ENC. When γ is set to $\gamma = 1.8$, the proposed method also has the best BER performance, and specifically requires about 6dB lower SNR than ENC at a BER of 10^{-4}.

In order to evaluate the application of the proposed method to signals with more subcarriers and higher modulation orders, we also considered the scheme with the highest number of subcarriers and the highest modulation order in 5G NR so far, that is, 3300 subcarriers and 256QAM modulation. The simulation results are shown as Fig.9.

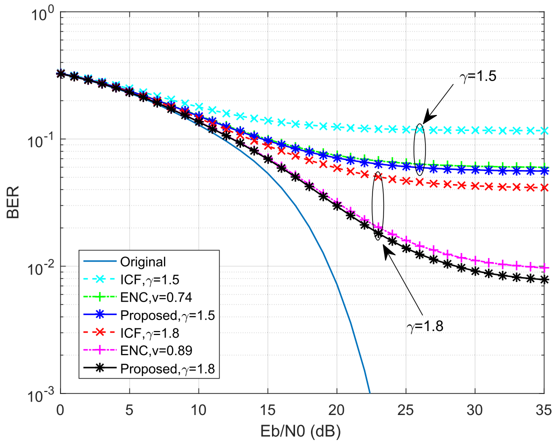
Fig.9(a) shows that the proposed method has about 1dB better performance on PAPR reduction than ICF at a probability of 10^{-3}, when $\gamma = 1.5$ and $\gamma = 1.8$. And the ENC method achieves equal level of PAPR reduction to that of the proposed method. Fig.9(b) shows that the proposed method has better BER performance than the other two methods, regardless of $\gamma = 1.5$ or $\gamma = 1.8$.

C. SIMULATION RESULTS OF THE OUT-OF-BAND RADIATION

In addition, to evaluate the out-of-band radiation performance of the proposed method, we have taken a model of solid-state



(a) The PAPR reduction comparison, with 3300 subcarriers and 256QAM.



(b) The BER performance comparison, with 3300 subcarriers and 256QAM.

FIGURE 9. **The CCDF and BER curves of the evaluated signals with 3300 subcarriers and 256QAM.**

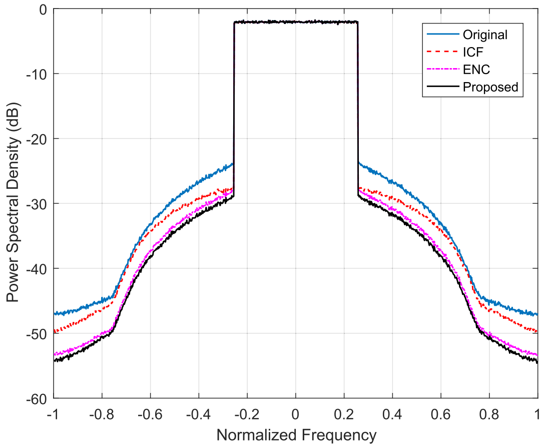


FIGURE 10. **Power spectral density comparisons of the evaluated methods.**

power amplifier (SSPA) into the simulations. The commonly used AM/AM model can be described as

$$x_o = \frac{|x_i|}{(1+(\frac{|x_i|}{q})^{2p})^{1/2p}}\mathrm{sgn}(x_i), \tag{13}$$

where x_i and x_o are respectively the input and output signals of the power amplifier [21]. The parameters $p = 3$ and $q = 1.4$ are chosen in the simulations.

Fig.10 shows the power spectral density of the signals obtained using the evaluated methods. We can see that the proposed method has better out-of-band radiation performance than ICF and ENC.

D. DISCUSSION

It can be seen from Fig.6(a) that the proposed method has better PAPR reduction than ICF, in case of either $\gamma = 1.5$ or $\gamma = 1.8$. This is due to the companding characteristics of the proposed method, i.e., the peak of the compressed signal does not exceed the clipping threshold. While the maximum amplitude of the signal in ICF is larger due to the peak regrowth caused by filtering.

It can be seen from Fig.6(b) that with equal clipping ratio, the BER performance of the proposed method is much better than ICF. In addition, at BER of 10^{-4}, the SNR reqiured by the proposed method is about 0.3dB and 2dB lower than ENC, when $\gamma = 1.8$ and 1.5, respectively. In Fig.7(b), similarly the proposed method achieves the best BER performance with equal clipping ratio. Specifically, the SNR reqiured by the proposed method is about 0.3 dB and 1.4 dB lower than ENC, when gamma = 1.8 and 1.5, respectively. This shows that with a given clipping ratio, the proposed method always has an advantage of BER performance, and the lower the clipping ratio, the greater the advantage.

According to Fig.6(a) and Fig.7(a), when the shape factor is changed from $s = 60$ to $s = 6$, the PAPR reduction of the proposed method is mildly degrade, but still significantly better than ICF. And the ENC has almost the same PAPR reduction as the proposed method. As both parameters v and s in the ENC are adjustable, we adjust the value of v while keeping the value of s equal to the proposed method for comparison evaluation.

According to Fig.7(b) and Fig.6(b), the BER performances of both the proposed method and ENC slightly improved when s changes from 6 to 60. Moreover, the former is more improved than the latter. For instance, when $\gamma = 1.8$, the difference of the SNR required by the proposed method and ENC is increased from 1.4 dB to 2 dB at a BER of 10^{-4}. This shows that the advantage of the proposed method is more obvious when the shape factor s is larger.

According to Fig.6(a), Fig.8(a) and Fig.9(a), it can be seen that the proposed method can effectively work in different OFDM systems with various amount of subcarrier. Particularly, when the amount of subcarriers increases, the CCDF curve of the proposed method drops dramatically. This is because, there are more samples within a symbol with more subcarriers, so the amplitude distribution of the OFDM symbol is more close to the standard Rayleigh distribution.

And this results in a similar level of companding of each symbol, leading to a steeper CCDF curve.

Based on Fig.6(b), Fig.8(b) and Fig.9(b), we can see that, with an increment of the modulation order, the BER performances of all the evaluated methods generally decrease. However, with the same scheme of subcarrier modulation, the proposed method has a BER performance advantage compared to the other two methods. This is because with the higher-order-modulated subcarriers, the Euclidean distance between the points in the constellation mapping will be shorter, which makes the system less tolerant to interferences. That is to say, higher order modulated signals are more sensitive to distortion. According to the analyses in Section III, the proposed method has less distortion than the other two methods at the same level of PAPR reduction. Therefore, in higher order modulated systems, the proposed method still outperforms with regard to BER performance.

In summary, we can conclude that the proposed method has better performance on PAPR reduction and BER than ICF with a given clipping ratio. And with the same level of PAPR reduction, the proposed method has better BER performance than ENC.

V. CONCLUSION

In this paper, based on the characteristics of clipping and companding, we proposed a hybrid approach to improve the performance of PAPR reduction of OFDM signals. In the proposed method, the clipping threshold is introduced for the companding function. Specifically, both the normalization factor and the output scaling factor of the companding function defined in the proposed method employ the same parameter, i.e., the clipping threshold, which varies with the average power of the OFDM symbol. This results in that the signals with smaller amplitude keep unchanged, while the ones with larger amplitude are nonlinearly compressed and the maximum peaks are limited to the clipping threshold. For this reason, the proposed method can achieve more approximate to the expected PAPR reduction while reducing signal distortion. Moreover, the proposed method does not require any post-clipping or iteration operation. Therefore, although its computational complexity is slightly higher than ENC, the complexity of our proposed method is much lower than ICF.

In the simulations, different values of the parameters, as well as OFDM signals with various number of subcarriers and modulation orders, are considered to evaluate the performance of the proposed method. The simulation results show that the proposed method has better performance on PAPR reduction and BER than ICF. Although ENC can achieve the same level of PAPR reduction as the proposed method by adjusting the values of parameters in the companding function, the proposed method however gives better BER performance than ENC.

In future work, we will try to introduce some distortionless based techniques in the research to reduce the PAPR of OFDM signals. Due to the increasingly pursuing of spectral efficiency, the modulation order of subcarrier in the OFDM system is getting higher. And higher-order modulation is more sensitive to distortion, while distortionless based techniques are expected to help to alleviate this problem. Moreover, since the physical layer of 5G signals is designed with more complicacy, we foresee that one of the promising researches is to reduce the PAPR for different waveforms of 5G signals.

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