Palm Date Leaf Clipping: A New Method to Reduce PAPR in OFDM Systems

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Abstract: Orthogonal frequency division multiplexing (OFDM) is the key technology used in high-speed communication systems. One of the major drawbacks of OFDM systems is the high peak-to-average power ratio (PAPR) of the transmitted signal. The transmitted signal with a high PAPR requires a very large linear range of the Power Amplifier (PA) on the transmitter side. In this paper, we propose and study a new clipping method named Palm Clipping (Palm date leaf) based on hyperbolic cosine. To evaluate and analyze its performance in terms of the PAPR and Bit Error Rate (BER), we performed some computer simulations by varying the Clipping Ratio (CR) and modulation schemes. The obtained results show that it is possible to achieve a gain of between 7 and 9 dB in terms of PAPR reduction depending on the type of modulation. In addition, comparison with several techniques in terms of PAPR and BER shows that our method is a strong alternative that can be adopted as a PAPR reduction technique for OFDM-based communication systems.

Keywords: OFDM; high peak-to-average power ratio (PAPR); bit error rate (BER); high power amplifier (HPA); solid-state power amplifier (SSPA); clipping; palm clipping

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is the fundamental technology employed in Wi-Fi, Worldwide Interoperability for Microwave Access (WiMAX), and 4G wireless communication systems such as Long-Term Evolution (LTE), Long-Term Evolution Advanced (LTE-A), and 5G [1–3]. However, its main deficiency is its relatively high peak-to-average power ratio (PAPR) [4,5]. Several methods have been proposed to reduce the high PAPR of OFDM systems. For example, the Selective Mapping Technique (SLM) [6] is a promising technique to reduce the PAPR. Its principle consists of generating U alternative sequences and choosing the one that has the minimum PAPR value [7,8]. Several improvements and variants of the SLM method have been proposed to reduce its complexity [8] by avoiding side information [9,10]. Another technique called Partial Transmit Sequences (PTS) was proposed in [11]. The basic idea of PTS is to divide the original OFDM signal into some sub-blocks. Each sub-block is weighted by a given value to obtain many candidate signals with a lower PAPR value [12–14]. It is known that PTS is a popular method used to reduce PAPR in OFDM systems. Several variants of PTS have been proposed, such as Hybrid Genetic Algorithm Partial Transmit Sequences (HGA-PTS) [15], Particle Swarm Optimization Partial Transmit Sequences (PSO-PTS) [16], and Genetic Algorithm Partial Transmit Sequences (GA-PTS) [17].

In [18], Tone Injection (TI) is used to reduce PAPR with the insertion of a tone. However, it requires a certain amount of computational complexity to find the right tone to inject into the signal in order to reduce its PAPR. Tone Reservation (TR), which was proposed in [19], reverses a small number of
subcarriers to create a signal that can cancel the high peaks in the original signal on the transmitter side. However, the effectiveness of this method on PAPR reduction depends on the number of reserved tones and their positions. Therefore, it requires a high computational complexity to find the reserved positions. In addition, TR requires additional information, also called side information, which reduces the data rate.

The channel coding-based technique is not only used for correcting the received errors, but also to reduce the PAPR values of OFDM systems. The main idea behind this is to select a code word that produces a good PAPR reduction [20,21]. However, this method has high computational complexity when finding the best code word to reduce PAPR values and allow the received errors to be corrected.

Companding (compressor/expander) techniques are generally used in wave domains. They are also used to reduce PAPR values by compressing the OFDM signal at the transmitter end; the receiver expands the signal. The main inconvenience of this technique is the signal degradation quality, which increases the Bit Error Rate. Mu-law and A-law are the most common companding techniques used to reduce PAPR, and often these methods are combined with other methods such as coding [22,23] or SLM [24] in order to improve signal quality.

Clipping is the most basic method used to reduce the PAPR value. The main idea is to truncate the peak of the OFDM signal below a threshold level [25]. Thanks to its simplicity, many clipping techniques are used to reduce the PAPR, including Classical Clipping (CC) [26], Smooth Clipping (SC) [27], Heavyside Clipping (HC) [28], and Deep Clipping (DC) [29].

Recently, hybrid techniques have become the most commonly used methods. They are based on a combination of two or three techniques used to obtain good results in terms of PAPR, Bit Error Rate (BER), complexity, and transmission rate [30–35].

In this paper, we present a new Palm date leaf Clipping (PC) method based on the hyperbolic cosine function to reduce the PAPR in OFDM systems. The PC method is inspired by the shape of palm date leaves on a massive stem. Their form allows them to resist both interference from other leaves and twisting that can be caused by the wind. By analogy, Palm Clipping does not trim the signal after a threshold, but reduces it, which is something that simplifies its reconstruction. We analyze its performance in terms of PAPR and BER. The proposed method can effectively enhance the PAPR reduction performance with the best BER for certain Clipping Ratios (CR). Simulation results show that the proposed algorithm significantly outperforms the conventional scheme in terms of PAPR reduction of OFDM signals.

A comparative study was carried out between our method, PC, and other advanced methods. The obtained results confirm that the PC method has the same performance compared to the studied methods and sometimes outperforms them in terms of PAPR and BER. In addition, the PC method resists degradation of the signal compared to other conventional clipping methods that use a High-Power Amplifier (HPA) under the same conditions.

The remainder of the paper is organized as follows. An introduction to OFDM systems and the PAPR problem is presented in Section 2. Section 3 presents some classic clipping techniques designed for the purpose of PAPR reduction. Analyses and descriptions of the proposed method are presented in Section 4. The results and discussion are presented in Section 5, while our conclusions are summarized in Section 6.

2. OFDM Systems and PAPR

The principle of the OFDM system is presented in Figure 1. On the transmitter side, the input data are mapped by one of the modulation (Mod) schemes: Quadrature Amplitude Modulation (QAM), or Phase-Shift Keying (PSK). Then, the signal is converted from Serial to Parallel (S/P), and after that, an inverse of Fourier Transformation is applied using the Inverse Fast Fourier Transformation algorithm (IFFT). The obtained signal is converted from Parallel to Serial (P/S) before being transferred to the channel. On the receiver side, the received signal is converted from Serial to Parallel (S/P) and
An OFDM signal $x(t)$ is defined by the following equation:

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j \frac{2\pi k t}{T_s}} \text{ with } 0 \leq t \leq T_s$$

(1)

where $T_s$ is the period of an OFDM symbol, $N$ is the number of subcarriers, and $X_k$ is the $k$th subcarrier of the same symbol. The baseband OFDM signal is sampled by applying the Nyquist rate ($t = t s/N$). Therefore, the discrete OFDM signal in the time-domain can be expressed as

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j \frac{2\pi k n}{N}} \text{ with } 0 \leq n \leq N - 1.$$ 

(2)

The PAPR of the time domain OFDM symbol is defined as the ratio of maximal instantaneous power to the average power as

$$PAPR = \frac{\text{Max}\{|x(n)|^2\}}{E\{|x(n)|^2\}}, \quad 0 \leq n \leq N - 1,$n

(3)

where $E[.]$ represents the expectation value.

The PAPR performance is portrayed using a Complementary Cumulative Distribution Function (CCDF), which is the probability that PAPR exceeds a threshold value. The CCDF is defined by the following formula:

$$CCDF(PAPR_0) = \Pr[PAPR \geq PAPR_0],$$

(4)

where $PAPR_0$ is a threshold value and $N$ is the number of subcarriers.

3. Clipping Methods

In this section, we explore some classical clipping methods used to reduce the PAPR value. The basic idea is to trim the peak of the OFDM signal above a given threshold, which we call $A$ in this paper.

A signal $x(t)$ can be modified with polar representation by the equation below:

$$\tilde{x}(t) = f(|x(t)|) \cdot e^{j\phi(x(t))},$$

(5)

where $f$ is the amplitude function of the input signal $x(t)$, $\phi$ is the phase, and $\tilde{x}(t)$ is the clipped signal. Each method is characterized by its clipping function. Accordingly, we present the characteristic function of each clipping method.
In Classical Clipping (CC) [26], the output of the amplitude function is defined by the following equation:

\[
f(r) = \begin{cases} 
  r & \text{if } r \leq A \\
  A & \text{if } r > A
\end{cases},
\]

(6)

where \( r \) is the amplitude of the signal \( x(t) \). As depicted in Figure 2, the output amplitude of the signal is linear if the value is less than the clipping value \( A \). However, it is equal to the value \( A \) when the argument is greater than \( A \).

![Figure 2. Classical Clipping Function.](image)

In Deep Clipping (DP) proposed in [29], the clipping function is defined as

\[
f(r) = \begin{cases} 
  r & \text{if } r \leq A \\
  A - d(r - A) & \text{if } A < r \leq \frac{1+d}{d} A \\
  0 & \text{if } r > \frac{1+d}{d} A
\end{cases},
\]

(7)

where \( A \) is the threshold level and \( d \) is the clipping depth factor (see Figure 3).

![Figure 3. Deep Clipping function.](image)

Regarding the Smooth Clipping (SC) technique proposed in [27], the clipping function is represented in Figure 4 and defined as

\[
f(r) = \begin{cases} 
  r - \frac{1}{b} r^3 & \text{if } r \leq \frac{3}{2} A \\
  \frac{A}{3} & \text{if } r > \frac{3}{2} A
\end{cases} \text{ where } b = \frac{27}{4} A^2.
\]

(8)
In Heavyside Clipping (HC) used in [28], the clipping function is defined as

\[ f (r) = A, \quad \forall r \geq 0 . \]  

In this case, the amplitude function is equal to the threshold value \( A \), as portrayed in Figure 5.

Guel el al. [36] present a comparison between the four clipping methods described in this section. From this analysis, the CC, DC, and SC methods are very similar, whereas the HC method gives a good reduction of PAPR with a great degradation of signal performance compared to the other techniques. The authors in [37] analyzed and compared the same clipping methods under Orthogonal frequency division multiplexing/Offset Quadrature amplitude modulation (OFDM/OQAM); the obtained results confirm those obtained in [36].

Clipping is the simplest technique used to reduce the PAPR value in OFDM systems. However, it is well known that clipping destroys and degrades the quality of the signal. To this end, we propose and analyze a new clipping method, which is studied in detail in the following sections. To understand the effect of clipping methods, we use a Clipping Ratio (CR) related to both the clipping level \( A \) and the OFDM signal average power, as defined in the following equation:

\[ CR = 20 \log_{10} \frac{A}{\sqrt{P_{\text{avg}}}} \text{[dB]}, \]  

where \( P_{\text{avg}} = E\{ |x(n)|^2 \} \) represents the average power of the input signal and \( A \) is the threshold value.
4. Analysis and Description of the Proposed Palm Clipping Method

In this section, we present the Palm Clipping method and its basic principles. The Palm Clipping block is added to the OFDM System (PC-OFDM) before transmission over the channel, as shown in Figure 6. The main target of this work was to find a good compromise between PAPR values and a good value of BER.

![OFDM system transmitter side with Palm Clipping and the High-Power Amplifier (HPA).](image)

**Figure 6.** OFDM system transmitter side with Palm Clipping and the High-Power Amplifier (HPA).

**Palm Clipping Function $P^A_\beta$**

The proposed clipping function based on the cosine hyperbolic for clipping a signal $x(t)$ is defined as

$$\tilde{x}(t) = \begin{cases} 
    x(t) & , \ |x(t)| \leq A \\
    P^A_\beta(x(t))e^{i\phi(x(t))} & , \ |x(t)| > A 
\end{cases}, \ (11)$$

where $A$ is the threshold level, $\phi$ is the phase of the input signal $x(t)$, and the function $P^A_\beta(r)$ for a given amplitude $r$ is expressed by

$$P^A_\beta(r) = \frac{A}{\cosh\left(\frac{r-A}{\beta}\right)}, \ (12)$$

where $\beta$ is the smoothness factor of the curve function.

The basic idea of the proposed function $P^A_\beta$ is to attenuate the signal after a threshold value, as depicted in Figure 7. When $\beta$ tends to infinity, function $P^A_\beta$ tends to the saturation value $A$ (the same as in Classical Clipping).

![Palm clipping function $P^A_\beta(r)$ with $A = 10$ and the variable smoothness parameter $\beta$.](image)

**Figure 7.** Palm clipping function $P^A_\beta(r)$ with $A = 10$ and the variable smoothness parameter $\beta$. 


Figure 8 presents a graph of Palm Clipping as a function of $\beta$; this figure regroups the response curves when the input amplitude $r$ is equal to 10, 11, 15, 20, and 25, and the threshold value $A$ is equal to 10. From the curve presented in this figure, we observe that the response of the function is controlled by beta. When beta tends to infinity, $P^A_{\beta}$ tends to clipping value $A$, which is the same as in Classical Clipping (CC). For example, when $r = 25$, the curve of function $P^A_{\beta}$ converges slightly to the clipping value $A$. Moreover, when $r = 11$, we see a convergence toward $A$; this variation will be exploited with the variation of the constellation. We know that the amplitude increases with the constellation; therefore, the signal is very sensitive to variation. In order to validate our method, we carried out several simulations that are detailed in the following section.

![Figure 8. Palm Clipping function $P^A_{\beta}(r)$ as a function of $\beta$ with $A = 10$.](image)

5. Simulation Results

To evaluate the performance of proposed Palm Clipping technique, we considered the OFDM system shown in Figure 6 and set the parameters as listed in Table 1. Since it known that the PAPR problem becomes worse for higher-order Quadrature Amplitude Modulations (QAM), we considered 16-QAM and 64-QAM as modulation schemes, in addition to 4-QAM. The number of subcarriers $N$ was set to 64, and the number of OFDM symbols generated was 10,000. The performance of the proposed method is described by the CCDF curves of PAPR and BER degradation. The two principal parameters are also considered, namely CR and the smoothness parameter $\beta$.

| Parameter                        | Value                                      |
|----------------------------------|--------------------------------------------|
| Modulation type                  | 4-QAM, 16-QAM, and 64-QAM                  |
| Number of symbols                | 10,000                                     |
| Number of subcarriers $N$        | 64                                         |
| Channel Model                    | AWGN                                       |
| Clipping Ratios (CR) in dB       | 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10       |
| Smooth $\beta$                   | 0.5 and 5                                  |
| HPA type                         | SSPA                                       |
| HPA parameter $p$                | 2                                          |

Table 1. Simulation parameters. QAM: Quadrature Amplitude Modulation.
To validate our method, we firstly studied the PAPR reduction performances by varying the modulation type (4-QAM, 16-QAM, and 64-QAM), CR, and smoothness parameters, as mentioned in Table 1. Secondly, we analyzed the BER with the same conditions, with and without HPA, in order to evaluate to the output back-off of the power amplifier. Finally, we compared our method with other PAPR reduction methods.

5.1. PAPR Performances

In this subsection, we present the PAPR performances for Palm Clipping with the CCDF. In the first stage, we analyzed the performance of PAPR by varying the smoothness parameter $\beta$. In the second stage, we fixed the smoothness parameter and analyzed the performance of PAPR for the variable CR. The obtained results are described in the next subsection and are considered in terms of the CCDF function.

5.1.1. PC-OFDM PAPR with Variable Smoothness Parameter

Firstly, we studied the influence of the smoothness parameter $\beta$ with the variable modulation scheme. The results are presented by the gain in dB at CCDF equal to $10^{-4}$ dB.

The obtained results for the 4-QAM modulation with variable CRs are presented in Figure 9. As we can see in this figure, the gain varied between 6 and 9.4 dB and was in a range between 0.4 and 1 for $\beta$. When $\beta$ was higher, the gain was invariable.

Figure 9. Palm Clipping (PC)-OFDM 4-QAM with variable Clipping Ratio (CR) and smoothness.

Figure 10 presents the gain in term of PAPR at CCDF = $10^{-4}$ for the 16-QAM modulation. The obtained gain was between 2 and 9 dB. The best results were obtained when $\beta$ was between 0.5 and 1 for all CR values. An unvarying gain was obtained when $\beta$ was higher.

Figure 11 regroups the obtained gain in PAPR at CCDF = $10^{-4}$ with PC-OFDM and the 64-QAM modulation. In this case, the maximum gain was less than 9 dB with a minimum equal to 1.98 dB for different CRs. The gain increased with the value of $\beta$ until it reached a maximum value when $\beta$ was between 0.4 and 1. After this, the gain decreased while $\beta$ increased before becoming stable.
In this subsection, we present some simulations related to the PAPR in order to study the effect of the parameter CR for each modulation type. The obtained results presented by the CCDF are depicted in the 4-QAM modulation (Figure 12), the 16-QAM modulation (Figure 13), and the 64-QAM modulation (Figure 14).

From this study and previous results of the variable smoothness parameter \( \beta \) with different modulation types and CR, we can deduce that the maximum gain in terms of PAPR is given when \( \beta \) is between 0.4 and 1, which is almost the same for the higher values of \( \beta \). Furthermore, increasing the constellation, our method makes it possible to reduce the values of PAPR as we reduce the CR value. In the rest of the study, we set the value of \( \beta \) at 0.5 and 5 and study the variation of CR.

5.1.2. PAPR Performance with Variable CR

In this subsection, we present some simulations related to the PAPR in order to study the effect of the parameter CR for each modulation type. The obtained results presented by the CCDF are depicted in the 4-QAM modulation (Figure 12), the 16-QAM modulation (Figure 13), and the 64-QAM modulation (Figure 14).
Figure 11. PC-OFDM 64-QAM with variable CRs and smoothness.

From this study and previous results of the variable smoothness parameter $\beta$, we can deduce that the maximum gain in terms of PAPR is given when $\beta$ is between 0.4 and 1, which is almost the same for the higher values of $\beta$. Furthermore, increasing the constellation, our method makes it possible to reduce the values of PAPR as we reduce the CR value. In the rest of the study, we set the value of $\beta$ at 0.5 and study the variation of CR.

5.1.2. PAPR Performance with Variable CR

In this subsection, we present some simulations related to the PAPR in order to study the effect of the parameter CR for each modulation type. The obtained results presented by the CCDF are depicted in Figure 12 for the 4-QAM modulation, Figure 13 for the 16-QAM modulation, and Figure 14 for the 64-QAM modulation.

According to the results of this study, we notice that the value of PAPR degraded when the CR decreased for all modulation schemes, with small differences for a given CR. However, the performance in terms of PAPR reduction was good, and we were able to achieve 2.25 dB at CCDF equal to $10^{-4}$ when CR = 1 dB.

Figure 15 depicts the gain in dB compared to normal OFDM; it can be seen that the variations of parameter $\beta$ do not have a significant influence on PAPR when the CR is greater than 5 dB, and the PAPR decreases when CR decreases. As shown in this figure, we can have a gain of between 1.91 dB (64-QAM) and 2 dB (QAM) when CR = 10 dB. Therefore, it is important to study the impact of $\beta$ on PAPR.
According to the results of this study, we notice that the value of PAPR degraded when the CR decreased for all modulation schemes, with small differences for a given CR. However, the performance in terms of PAPR reduction was good, and we were able to achieve 2.25 dB at CCDF equal to $10^{-4}$ when CR = 1 dB.

Figure 15 depicts the gain in dB compared to normal OFDM; it can be seen that the variations of parameter $\beta$ do not have a significant influence on PAPR when the CR is greater than 5 dB, and the PAPR decreases when CR decreases. As shown in this figure, we can have a gain of between 1.91 dB (64-QAM) and 2 dB (QAM) when CR = 10 dB. Therefore, it is important to study the impact of $\beta$ on the signal performance. The obtained value of CCDF at $10^{-4}$ for variable CR and the modulation scheme with two values of $\beta$ (0.5 and 5) of the proposed method are summarized in Table 2.
Table 2. CCDF $= 10^{-4}$ for the proposed method for $\beta = 0.5$ and $\beta = 5$ with variable modulation and CRs.

| Modulation | 4-QAM | 16-QAM | 64-QAM |
|------------|-------|--------|--------|
| CR [dB]    | $\beta = 0.5$ | $\beta = 5$ | $\beta = 0.5$ | $\beta = 5$ | $\beta = 0.5$ | $\beta = 5$ |
| 0          | 2.25  | 2.33   | 2.34   | 2.81   | 2.67   | 4.18   |
| 1          | 2.63  | 2.69   | 2.67   | 3.13   | 3.17   | 4.48   |
| 2          | 3.04  | 3.09   | 3.18   | 3.54   | 3.72   | 4.85   |
| 3          | 3.57  | 3.58   | 3.68   | 4.04   | 4.41   | 5.22   |
| 4          | 4.17  | 4.15   | 4.26   | 4.60   | 5.04   | 5.67   |
| 5          | 4.83  | 4.78   | 4.94   | 5.14   | 5.70   | 6.16   |
| 6          | 5.57  | 5.52   | 5.67   | 5.87   | 6.37   | 6.54   |
| 7          | 6.41  | 6.34   | 6.49   | 6.59   | 7.03   | 7.11   |
| 8          | 7.27  | 7.21   | 7.31   | 7.35   | 7.69   | 7.73   |
| 9          | 8.15  | 8.15   | 8.19   | 8.18   | 8.34   | 8.37   |
| 10         | 9.03  | 9.01   | 9.03   | 9.03   | 9.04   | 9.08   |

The obtained results from Figure 15 and Table 2 are very interesting and confirm that our proposed Palm Clipping method achieves good PAPR reduction values when CR = 0 dB and $\beta = 0.5$. It is well demonstrated that it is possible to achieve a gain of between 7 and 9 dB depending on the type of modulation scheme and CR. Since we know that all the clipping techniques deform the transmitted signal, it is very important to analyze the BER performances of the proposed method to find the best compromise between PAPR and BER.

5.2. BER Performances

In this subsection, we present the BER performances analysis of the proposed method. Firstly, we set the smoothness parameter value to 0.5 and then to 5, with variable CR and modulation types. The results depicted in Figure 16 (4-QAM), Figure 17 (16-QAM), and Figure 18 (64-QAM) were achieved by varying the Signal-to-Noise Ratio (SNR).

![Figure 16. Bit Error Rate (BER) performance of the PC method with variable CR, N = 64, and the 4-QAM modulation over the Additive White Gaussian Noise (AWGN) channel.](image-url)
Regarding signal degradation, it starts at CR rates below 6 dB. In addition, the BER performance with CR values greater than 4 dB, the signal degradation in terms of BER becomes more and more significant. On the other hand, for CR values lower than 4 dB, the signal degradation for each modulation type by varying the Signal to Noise Ratio (SNR).

As shown in this figure, the signal degradation in terms of BER becomes more and more significant. In addition, the BER performance with β = 5 is better than that recorded with β = 0.5. We observe in Figure 17 that the BER performance with β = 5 is better than that recorded with β = 0.5 for all CR rates. Regarding signal degradation, it starts at CR rates below 6 dB.

**Figure 17.** BER performance of the PC method with variable CR, N = 64, and the 16-QAM modulation over the AWGN channel.

**Figure 18.** BER performance of the PC method with variable CR, N = 64, and the 64-QAM modulation over the AWGN channel.

Figure 16 shows that the BER performances of our method are similar compared to the normal OFDM BER curve, especially for CR values greater than 4. On the other hand, for CR values lower than 4 dB, the signal degradation in terms of BER becomes more and more significant. In addition, those large CR values (i.e., higher than 4 dB) offer good performances in terms of PAPR reduction (see Table 3) without degradation of the BER performance, as was previously mentioned. We observe in Figure 17 that the BER performance with β = 5 is better than that recorded with β = 0.5 for all CR rates. Regarding signal degradation, it starts at CR rates below 6 dB.
Table 3. Gain in PAPR at CCDF $= 10^{-4}$ and BER loss at $= 10^{-3}$ when $\beta = 5$ with variable CR and modulation type.

| Modulation | 4-QAM | 16-QAM | 64-QAM |
|------------|-------|--------|--------|
| CR [dB]    | PAPR Gain | BER Loss | PAPR Gain | BER Loss | PAPR Gain | BER Loss |
| 1          | 8.29   | 3.99   | 7.87 | >4 | 6.50 | >5 |
| 2          | 7.89   | 2.584  | 7.46 | >4 | 6.52 | >5 |
| 3          | 7.40   | 1.52   | 6.96 | >4 | 6.15 | >5 |
| 4          | 6.83   | 0.892  | 6.40 | >3.9 | 5.78 | >5 |
| 5          | 6.2    | 0.454  | 5.86 | 3.84 | 5.33 | >5 |
| 6          | 5.46   | 0.22   | 5.13 | 1.33 | 4.84 | >5 |
| 7          | 4.64   | 0.09   | 4.41 | 0.48 | 4.46 | 4.72 |
| 8          | 3.77   | 0.03   | 3.65 | 0.05 | 3.89 | 0.94 |
| 9          | 2.83   | 0.029  | 2.82 | 0.01 | 3.27 | 0.18 |
| 10         | 1.97   | 0      | 1.97 | 0 | 2.63 | 0 |

Figure 18 presents the performance curves in terms of BER in the case of the 64-QAM modulation. As shown in this figure, the signal degradation starts a CR value of 7 dB, and it becomes worse and worse from 6 dB and lower.

We conclude that for the three considered modulations, namely 4-QAM, 16-QAM, and 64-QAM, the performance of the proposed method is better as long as the CR increases. In addition, it is shown that the BER degradation is reduced when the smoothness parameter beta is equal to 5 for all the modulation types. Table 3 summarizes the obtained gain in terms of the PAPR at CCDF $= 10^{-4}$ and BER loss at $= 10^{-3}$ for each modulation type by varying the Clipping Ratio when $\beta$ is equal to 5.

5.3. Comparative Study

In this subsection, we present a comparative study of the proposed method and some of the state-of-the-art methods. We begin with a comparison of the PAPR with different variants of PTS. Secondly, we compare the proposed method with SLM and its variants in terms of PAPR and BER. Finally, we compare the proposed method with other clipping techniques by integrating the High-Power Amplifier (HPA). The number of subcarriers was set to 64 and the modulation was set to 16-QAM over the AWGN channel.

5.3.1. PAPR Comparison with PTS Variants

In this subsection, we compare the proposed method with PTS and some of its variants: Hybrid Genetic Algorithm PTS (HGA-PTS) [15], Genetic Algorithm PTS (GA-PTS) [34], Random Search PTS (RS) [38], Iterative flipping PTS (IPTS) [38], FSO-PTS [16], and Optimal PTS (OPTS) with an exhaustive search [15]. The parameters of PTS are as follows:

- $w = 4$ (Phase rotation factors $\{+1, -1, -j, +j\}$);
- $V = 8$ (Sub-blocks number);
- $P = 30$ (Genetic algorithm: population size);
- $I = 40$ (Genetic algorithms: number of generations or iterations).

The performance in terms of the PAPR is depicted in Figure 19. Table 4 summarizes the CCDF values and the gain in terms of the PAPR at CCDF $= 10^{-3}$ of the proposed Palm Clipping method compared with PTS and its variants.
In this subsection, we compare our proposal method with SLM and its variants. In [8], the author proposes a new SLM based on the Genetic Algorithm SLM (GA-SLM); this method is compared with PTS and its variants with

HGA-PTS: Hybrid Genetic Algorithm PTS, OPTS: Optimal PTS.

In this subsection, we compare the proposed method with SLM and its variants in terms of PAPR and BER. According to the result depicted in Figure 19, we compare the proposed method with SLM and its variants in terms of PAPR and BER. In addition, we note that the PC method gives the best results compared with IPTS, PSO-PTS, and GA-PTS when CR = 7 dB. Hybrid HGA-PTS is better than the PC method when CR = 7 dB. When CR = 6 dB, the proposed PC method presents about 0.3 dB less than the HGA-PTS. In addition, we note that the PC method achieves a good PAPR reduction of about 5.67 dB when CR = 5 dB, which is the same value as when HGA-PTS is run with $V = 32$. The obtained value is greater than an exhaustive search OPTS. From this study, we conclude that the Palm Clipping method is not complex (without iterations) and does not require side information compared with PTS and their variants.

5.3.2. PAPR and BER Comparison with SLM Variants

In this subsection, we compare our proposal method with SLM and its variants. In [8], the author proposes a new SLM based on the Genetic Algorithm SLM (GA-SLM); this method is compared with the SLM technique based on conversion matrices (CM) and a genetic algorithm (CMSLM) in terms of

![Figure 19. CCDF at $10^{-3}$ of the PC method with a CR of 5, 6, and 7 dB compared with Partial Transmit Sequences (PTS) and its variants, where $w = 4$ and $v = 8$, $N = 64$, with the 16-QAM modulation.](image-url)

| Method                                      | PAPR Value | PAPR Gain |
|---------------------------------------------|------------|-----------|
| Normal OFDM                                 | 10.67      | -         |
| RS (Random Search) [15]                     | 7.98       | 2.69      |
| IPTS [15]                                   | 7.22       | 3.45      |
| PSO-PTS [16]                                | 7.08       | 3.59      |
| GA-PTS [17]                                 | 6.65       | 4.02      |
| Palm Clipping (CR = 7 dB)                   | 6.40       | 4.54      |
| HGA-PTS [15]                                | 6.13       | 4.85      |
| Palm Clipping (CR = 6 dB)                   | 5.83       | 4.27      |
| OPTS (Exhaustive search) [15]               | 5.82       | 4.84      |
| Palm Clipping (CR = 5 dB)                   | 5.00       | 5.67      |

According to the result depicted in Figure 19 and the gain presented in Table 4, we note that the PC method gives the best results compared with IPTS, PSO-PTS, and GA-PTS when CR = 7 dB. Hybrid HGA-PTS is better than the PC method when CR = 7 dB. When CR = 6 dB, the proposed PC method presents about 0.3 dB less than the HGA-PTS. In addition, we note that the PC method achieves a good PAPR reduction of about 5.67 dB when CR = 5 dB, which is the same value as when HGA-PTS is run with $V = 32$. The obtained value is greater than an exhaustive search OPTS. From this study, we conclude that the Palm Clipping method is not complex (without iterations) and does not require side information compared with PTS and their variants.
the PAPR and BER. Figures 20 and 21 present the CCDF and BER, respectively, of the proposed method compared with the new GA-SLM, CMSLM, and the classical SLM. The following parameters apply:

- \( w = 4 \) (Phase rotation factors \(+1, -1, -j, +j\));
- \( M = 32 \) (Sub-blocks number);
- \( D = 32 \) (Genetic algorithms: population size);
- \( I = 30 \) (Genetic algorithms: number of generations or iterations).

![Figure 20. CCDF of the proposed method compared with the Selective Mapping Technique (SLM) and its variants.](image1)

**Figure 20.** CCDF of the proposed method compared with the Selective Mapping Technique (SLM) and its variants.

![Figure 21. BER performance of the proposed method compared with SLM and its variants with \( N = 64 \), and the modulation 16-QAM over the AWGN channel.](image2)

**Figure 21.** BER performance of the proposed method compared with SLM and its variants with \( N = 64 \), and the modulation 16-QAM over the AWGN channel.

Figure 20 presents the CCDF of our method with the obtained result in [8]. As shown in this figure, the proposed PC method has the same result as the GA-SLM: when CR is equal to 6 dB, we
achieve a reduction of 6 dB. On the other hand, the BER performance presented in Figure 21 shows that the proposed method has the same performance in terms of BER. In the case CR = 5 dB, we can achieve a good reduction with a loss of 1 dB in BER. According to the results in the figure, our method has the same result in terms of PAPR at CCDF = 10^{-3}, and it also has the same result in terms of BER. Therefore, in the case of CR = 5 dB, we have the best gain with a loss of about 1 dB in terms of the BER.

According to the simulation results and summarized results in Table 5, we notice that our method, when CR is less than 5 dB, has the best reduction in terms of the PAPR with a degradation in BER. Therefore, the Palm Clipping method has the same performance when CR = 6 dB. We recommend choosing a value between 6 and 7 dB in order to achieve the same result as compared with other SLM methods in terms of the PAPR and BER.

Table 5. Comparative peak-to-average power ratio (PAPR) gain at CCDF = 10^{-3} and BER loss at 10^{-3} with the PC method and Selective Mapping Technique (SLM) variants. CMSLM: conversion matrices Selective Mapping Technique, GA-SLM: Genetic Algorithm Selective Mapping Technique.

| Method      | PAPR Value [dB] | PAPR Gain [dB] | BER Loss [dB] |
|-------------|-----------------|----------------|---------------|
| CMSLM [8]   | 6.90            | 3.77           | 2.50          |
| SLM [8]     | 6.60            | 4.07           | 0             |
| GA-SLM [8]  | 6.50            | 4.17           | 2.5           |
| PC (CR = 7 dB) | 6.40      | 4.27           | 0.48          |
| PC (CR = 6 dB) | 5.83      | 4.84           | 1.33          |
| PC (CR = 5 dB) | 5          | 5.67           | 3.48          |

The Palm Clipping method achieves good results for some Clipping Ratios with the best performance in terms of BER. From this point of view, we conclude that our method is not complex (no iteration required to find the minimum PAPR) and does not need side information.

5.3.3. Comparison with other Clipping Techniques Using HPA

In order to simulate the near real case, we adopt the nonlinear Solid-State Power Amplifier (SSPA) as a High-Power Amplifier (HPA) model. The BER performances of the proposed method are compared to the other clipping techniques presented in [36] with the same conditions. The output signal is mobilized in SSPA amplifier by

$$g[r(t)] = \frac{r(t)}{1 + \left(\frac{r(t)}{r_{sat}}\right)^{2p}} \phi(r) = 0 \text{ no change in phase},$$  \hspace{1cm} (13)

where the nonlinear gain $g[r(t)]$ refers to the input amplitude/output amplitude (AM/AM) conversion characteristics, $r(t)$ is the amplitude of the input signal, $r_{sat}$ is the maximum output amplitude, and the parameter $p$ controls the smoothness of the transition from the linear region to the saturation region. The saturation region of an amplifier depending on the nonlinear distortion of the signal by SSPA is measured using the Input Back-Off (IBO), which is defined as follows:

$$IBO = 10\log_{10}\frac{r_{sat}^2}{P_{avg,input}},$$  \hspace{1cm} (14)

where $r_{sat}^2$ is the input saturation and $P_{avg,input}$ is the average power of the input signal.

It is assumed that the PC-OFDM signal is passed through the SSPA amplifier and then through a channel corrupted by Additive White Gaussian Noise (AWGN). The BER performances of the proposed method with other clipping methods are depicted in Figure 22. For all the simulations carried out, $p$ was set to 2, IBO was set to 5 dB, and CR = 10 dB.
5.3.4. Comparison with other Methods

From this comparison, we refer to the work of Guel el al. [36] in which they drew the curves of BER versus SNR for a value of CR equal to 10 dB and IBO = 5 dB. The first remark to draw our attention states that that the CR rate equal to 10 dB brings no gain in terms of PAPR; see Figure 4 in [36]. As a comparison with the results shown in this paper, we present the curves of the BER with the same parameters (i.e., IBO = 5 dB, CR = 10 dB, with the 16-QAM modulation over the AWGN channel). According to the results depicted in Figure 22, our method presents a good performance compared with the four clipping methods.

5.3.4. Comparison with other Methods

From the obtained result in this subsection, we performed a comparison of the PC method with other methods. Taking into account the following features:

- Destruction (degradation): measures the effect of the method to degrade the BER performance;
- Side information: the additional information needed to ensure the recovery of the signal;
- Iteration: the number of iterations needed to achieve the best PAPR;
- Probabilistic: degree of belief for the method to find its best value to reduce the PARP.

According to the results presented in Table 6, we observe that the Palm Clipping method is not complex (no iteration required) and does not require side information to reduce the PAPR. However, it destroys some of the performance of the signal, which must be improved later by the integration of channel coding for some clipping ratios less than 5 dB and $\beta = 5$. 

![Figure 22. BER performance of PC-OFDM with a High-Power Amplifier (HPA) compared with classical clipping, 16-QAM, Input Back-Off (IBO) = 5 dB, and CR = 10 dB.](image-url)
Table 6. Comparative study of the PAPR reduction methods with the proposed method. TI: Tone Injection, TR: Tone Reservation.

| Method                  | Destruction | Side Information | Iteration | Probabilistic |
|-------------------------|-------------|------------------|-----------|---------------|
| PTS                     | No          | Yes              | Yes       | Yes           |
| SLM                     | No          | Yes              | Yes       | Yes           |
| TI                      | No          | Yes              | Yes       | Yes           |
| TR                      | No          | Yes              | Yes       | Yes           |
| Companding              | Yes         | No               | No        | No            |
| Coding                  | Yes         | No               | No        | Yes           |
| Palm Clipping           | Yes         | No               | No        | No            |
| Other clipping methods  | Yes         | No               | No        | No            |

6. Conclusions

In this paper, we proposed the Palm Clipping method, based on hyperbolic cosine, to reduce the PAPR in OFDM systems. We evaluated the performance of the proposed clipping technique in terms of PAPR and BER for different Clipping Ratios and modulation types. By implementing this method, we achieved a gain in terms of PAPR of between 7 and 9 dB depending on the type of modulation scheme, with good results in terms of BER for some CRs. The obtained results are very interesting and generate some areas of future study, which include defining the best criterion for evaluation to give the best performance in terms of PAPR and BER degradation.

The proposed method was compared with recent methods in terms of PAPR and BER loss; this comparative study confirms that the PC method can achieve a good reduction in terms of PAPR with a good BER performance for some Clipping Ratios. Furthermore, the PC method is not complex and does not require side information to reduce the PAPR values. The PC method is robust against signal degradation even when applying a power amplifier as compared with other clipping methods. Therefore, the Palm Clipping method can be used for high constellations, which encourages us to apply this method in a 5G environment with the addition of polar codes as channel coding.

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