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Enhanced Sub-Block Partitioning and Effective Post-Processing for the PTS Algorithm

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Keywords:
Clipping method; Mu-law method; OFDM; PAPR reduction; PTS scheme.

Highlights:

- *PAPR is a major issue of the OFDM multicarrier modulation technique during the signal transmission process.*
- *Clipping and Mu-Law companding simple distortion methods are simple approaches to reduce PAPR.*
- *Combining PTS with Mu-Law companding or clipping during post-processing achieves superior PAPR reduction.*

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Abstract: The transmitted OFDM is a multicarrier modulation technique for efficient and reliable data communication. This technique forces a major problem during the signal transmission process, which is a high peak-to-average power ratio (PAPR), leading to significant performance degradation when employing a nonlinear power amplifier. The traditional Partial Transmit Sequence (PTS) scheme is a popular PAPR reduction technique. The PTS technique involves three approaches for sub-block partitioning to mitigate PAPR: adjacent (AD), interleaved (IL), and pseudorandom (PR) partitioning. This paper presents a hybrid reduction technique that combines IL partitioning with the AD scheme, enhancing the PTS sub-block partitioning approach. The proposed technique is further improved by hybridizing it with two other simpler methods, such as Mu-Law companding or post-processing phase clipping, to enhance the reduction capability. Simulation outcomes demonstrate that this approach achieves a more substantial PAPR reduction, even surpassing the performance of PR partitioning, which is commonly considered the most efficient PAPR reduction technique.

تحسين تقسيم الكتل الفرعية والمعالجة اللاحقة الفعالة لخوارزمية التسلسل الجزئي للأرسال

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الخلاصة

الإرسال المتعدد للترددات المتعامدة هو تقنية تعديل متعدد الناقلات للاتصالات الفعالة والموثوقة للبيانات. تعاني هذه التقنية من مشكلة رئيسية في أثناء عملية الإرسال وهي ارتفاع طاقة القمة نسبة الى معدل الطاقة. هذا يقود الى تدهور كبير في الأداء عند استخدام مكبر طاقة غير خطي. نظام التسلسل الجزئي التقليدي هو إحدى التقنيات المعروفة لتقليل طاقة القمة. هذه التقنية تقسم إلى ثلاثة مقتربات لتقسيم كتل الترددات لغرض تخفيف تأثير ارتفاع طاقة القمة نسبة إلى معدل الطاقة وهي التقسيم المتجاور، والتقسيم المتداخل، والتقسيم شبه العشوائي. يقدم هذا البحث تقنية هجينة لتقليل ارتفاع طاقة القمة من خلال جمع تقنية التقسيم المتداخل وتقنية التقسيم المتجاور، مما يحسن من أداء تقنية التسلسل الجزئي التقليدي. التقنية المقترحة طورت بشكل أكبر من خلال التهجين مع طريقتين اخريين بسيطتين مثل تضغيط مو-لاو و تقليم مرحلة ما بعد المعالجة لتعزيز قدرتها على تقليل ارتفاع طاقة القمة. تظهر نتائج المحاكاة ان هذا النهج يحقق تقليلا اكبر في طاقة القمة نسبة الى معدل الطاقة بشكل يتجاوز أداء تقنية شبه العشوائي الذي تعد عادة التقنية الأكثر فعالية في تقليل طاقة القمة نسبة إلى معدل الطاقة.

الكلمات الدالة: طريقة التقليم، طريقة مو-لاو، مضاعفة تقسيم الترددات المتعامدة، ارتفاع طاقة القمة نسبة الى معدل الطاقة، تسلسل الارسال الجزئي.

1.INTRODUCTION

OFDM is a multicarrier multiplexing technique for wireless communications because it supports strong reliability, high data rate in frequency selective fading channels environments with high spectral efficiency and a simple receiver [1, 2]. OFDM technology is employed as the standard in numerous wireless information application systems, such as 3GPP standards, digital video broadcasting (DVB), IEEE 802.11 (WiFi), digital audio broadcasting (DAB), and IEEE 802.16 (WiMAX) [3, 4]. High PAPR is a major challenge of OFDM in the time domain at the transmitter, leading to unwanted out-of-band radiation and significant inter-modulation when the signal traverses through nonlinear components such as a high power amplifier (HPA) [5]. Various techniques have been proposed to deal with this limitation. These techniques are classified into two main categories: distortion and distortionless methods [6]. Clipping [7] and companding [8] represent the distortion techniques. The clipping technique involves trimming the peak power of signals to a specified threshold level. The companding technique expands the small-amplitude signals while suppressing the large-amplitude signals by nonlinearly scaling the time-domain signals. Distortionless technique is represented by some methods, such as systematic coding [9], selective mapping (SLM) [10], partial transmit sequence (PTS) [11], tone injection [12], tone reservation [13], and active constellation extension (ACE) [14]. A distortionless technique, known as PTS, has recently drawn more attention due to its potent PAPR reduction abilities and effectiveness. The PTS scheme generates numerous alternative signal sequences that are similar to the original signal and selects the one with the lowest PAPR [15]. The present paper studies a hybrid PTS-based approach, where the sub-block partitioning scheme of PTS is enhanced by incorporating IL into AD partitioning schemes. The technique's ability to reduce PAPR is enhanced by combining two straightforward methods, Mu-Law companding and clipping, during the post-processing stage, developing two hybrid systems: one incorporates Mu-Law companding with enhanced PTS, while the second one incorporates clipping with enhanced PTS. The paper is structured as follows: Section II presents information on the PAPR problem's definition and the fundamentals of the OFDM system, along with explanations of the PTS, clipping, and nonlinear companding technique schemes. The schemes for sub-block partitioning are illustrated in Section III. The hybrid approach is described in Section IV. The numerical outcomes from the simulations are presented in Section V. Finally, Section VI concludes the paper.

2.PAPR AND ORDINARY PAPR REDUCTION SCHEMES

2.1.PAPR in OFDM System

The OFDM signal for N sub-carriers is produced by a block of data symbols $X = \{X_k\}$, where $K = 0, 1, \ldots, N-1$. The discrete-time domain OFDM signal $x(n)$, can be written as [16]:

$$\boldsymbol{x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k\, e^{(j2\pi kn/N)}, 0 \leq n \leq N-1} \quad \textbf{(1)}$$

The ratio between the maximum instantaneous power and its average power can be defined as the PAPR of OFDM signals, as expressed in Eq. (1) [17, 18]:

$$\boldsymbol{PAPR\big(X(n)\big) = \frac{max\ |x(n)|^2}{E\{|x(n)|^2|\}}} \quad \textbf{(2)}$$

where $E\{.\}$ denotes expected value.

The Complementary Cumulative Density Function (CCDF) is utilized to show the PAPR feature and measures the reduction efficacy of the system, which could be written as in [19]:

$$\boldsymbol{CCDF(PAPR_0) = R_P(PAPR > PAPR_0)} \quad \textbf{(3)}$$

2.2. Partial Transmit Sequence Scheme

The information of a data block in the frequency domain X is divided into smaller M disjoint sub-blocks, which are represented by vectors, as shown in Fig. 1, and written as [20, 21].

$$X = \sum_{m-1}^{M} X_m \; where \; m = 0, 1, \ldots, M-1 \qquad (4)$$

By assuming that each sub-block is composed of a group of uniformly sized subcarriers, the Inverse Fast Fourier Transform (IFFT) is utilized to translate these sub-blocks to the time domain.

$$x_m = \sum_{m-1}^{M} IFFT\{X_m\} \qquad (5)$$

The PTS scheme's configuration goal is to combine the M sub-blocks in a weighted manner, and their phases are independently rotated. Hence, the transmitted signal is carefully selected to contain the smallest PAPR. After a combination, the signal is depicted as:

$$x = \sum_{m-1}^{M} b_m x_m \qquad (6)$$

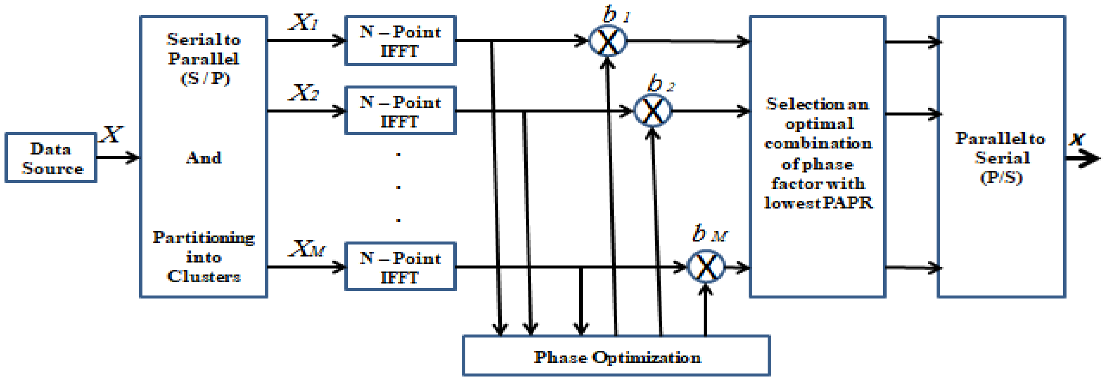

Fig. 1 PTS System Block Diagram.

As previously mentioned, three types of sub-block partition can be used with the PTS OFDM technique: IL, AD, and PR [22]. Despite its increased computational complexity and design challenges, the PR partition offers the most efficient PAPR reduction response among these partitions [23]. Figure 2 shows the response of the PAPR reduction using three popular partitioning types for the standard PTS scheme. The following sections provide a detailed explanation of the mathematical underpinnings of these three schemes.

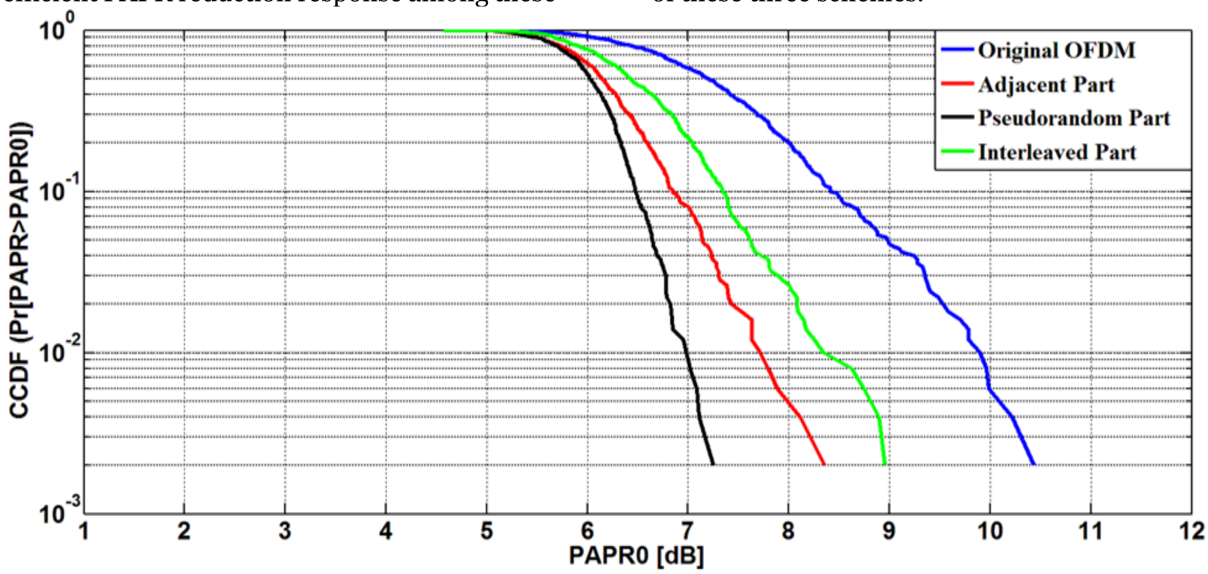

Fig. 2 Performance Comparison of Sub-Block Partitions for PAPR Reduction.

2.3. Clipping Scheme

Clipping is a straightforward yet effective method for reducing PAPR. It involves truncating the high-amplitude peaks of OFDM signals beyond an allowed range before they pass through the power amplifier. This action restricts the amplitude peaks of the input signal to a predetermined value, which, after correction, does not increase the threshold; otherwise, the clipper passes the signal without changing it. An amplitude threshold level is set, and subcarriers with amplitudes above that level are clipped or cleaned to produce a lower PAPR rate. The clipping operation is described as [24]:

$$\hat{C}(x) = \begin{cases} x, & |x| \le A \\ A, & |x| > A \end{cases} \qquad (7)$$

where $\hat{C}(x)$ is the clipped signal, x is the original signal, and A is the predetermined clipping level, which is a positive real number. An OFDM transmitter based on clipping is illustrated in Fig. 3.

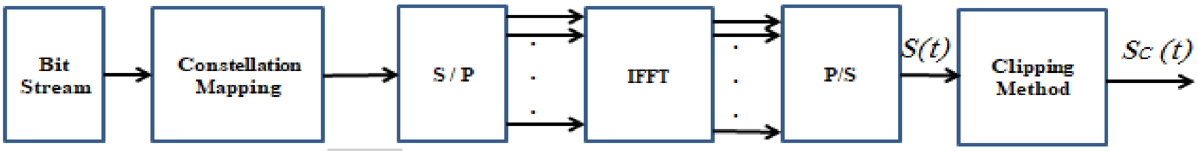

Fig. 3 OFDM Transmitter's Clipping Scheme.

2.4.Nonlinear Companding Transforms

Nonlinear companding transforms stand out as an especially appealing technique due to their superior system performance. This specialized clipping scheme, akin to the traditional clipping technique, has demonstrated even better performance than the standard clipping method [24, 25]. The Mu-law companding transform, used as the first nonlinear companding transform, is used in speech processing. This method preserves a constant average power by amplifying signals with small amplitudes and compressing those with larger amplitudes. This process results in a reduction in the PAPR. Figure 4 illustrates a Mu-Law companding-based OFDM transmitter [26].

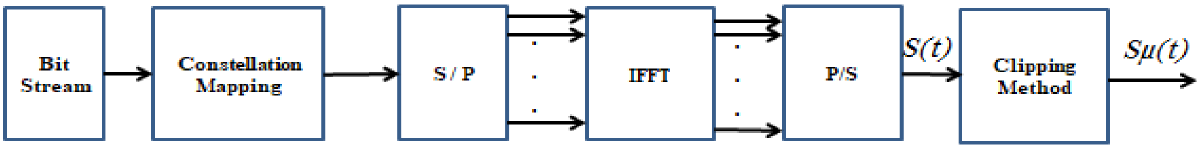

Fig. 4 OFDM's Mu-Law Companding Scheme.

The signal characteristic formula of Mu-law is expressed as in [26, 27]:

$$S_{\mu}(t) = \frac{\ln[1+F]}{\ln(1+\mu)}\,\Gamma \qquad \textbf{(8a)}$$

$$F = \mu\frac{|S(t)|}{S_{max}(t)} \qquad \textbf{(8b)}$$

$$\Gamma = S_{Max}(t).Sgn\big(S(t)\big) \qquad \textbf{(9)}$$

The instantaneous amplitude of the input is represented by $S(t)$, the peak amplitude is represented by $S_{Max}(t)$, the Sgn is a Sign function, and μ is the Mu-Law compand parameter.

3.SUB-BLOCK PARTITIONING FOR PTS SCHEMES

As previously mentioned, the PTS technique is used to simulate the partitioning of disjoint sub-blocks. Three popular partitioning methods are considered in this simulation and are explained in the following sections. These three different schemes' mathematical foundations are described by [27 – 30].

3.1.Adjacent Partitioning (AD)

Adjacent Partitioning (AD) is extensively employed due to its superior performance in reducing PAPR compared to the IL partitioning technique, albeit being less efficient than PR partitioning. In its context, it exhibits lower computational complexity than the PR technique [31, 32]. This technique involves dividing a subcarrier block into $L = N/M$ disjoint successive groups of subblocks with equal lengths, sequentially. Equations (10) - (11c) are used to represent the partitions:

$$X = [S_0 \ S_1 \ S_2 \ldots\ldots.. S_{L-1}] \qquad \textbf{(10)}$$

$$G_0 = [S_0 \quad ,0000,\ 00000, \quad \ldots\ ..0] \qquad \textbf{(11a)}$$

$$G_1 = [0000, \quad S_1 \quad ,\ 00000,\ldots \quad \ldots 0] \qquad \textbf{(11b)}$$

$$G_{L-1} = [0000, 0000, 00000, \ldots\ S_{L-1}] \qquad \textbf{(11c)}$$

where G_i represents the OFDM subset, and S_i represents the partitioning subblock.

3.2.Interleaved Partitioning (IL)

Interleaved Partitioning (IL) is the simplest technique that intends to create L subcarrier groups separated by a fixed distance interval equal to M. The groups of subcarriers are interleaved by separating them from each other by a zero or a space. By comparing with the other partitioning techniques, the IL technique has the lowest computational complexity; however, it has less efficient PAPR reduction [33]. Equations (12a) – (12c) represent these partitions:

$$G_0 = [S_0^1, 0000, S_0^2, 0000, .., S_0^M, 0..000.0] \qquad \textbf{(12a)}$$

$$G_1 = [0000, S_1^1, 0000, S_1^2, 0000, \quad \ldots, S_1^M, .0] \qquad \textbf{(12b)}$$

$$G_L = [0000, ..00.., S_L^1, 0000, S_L^2, 0000, S_L^M] \qquad \textbf{(12c)}$$

3.3. Pseudorandom Partitioning (PR)

The process of Pseudorandom Partitioning (PR) is crafted to produce a subblock by randomly selecting a subcarrier. The utilization of randomness is aimed at choosing the optimal subcarrier combination for generating an OFDM signal with a low PAPR. Despite posing a design challenge, this method outperforms others in effectively reducing PAPR [29, 33]. Equations (13a) – (13c) represent the partitions:

$$G_0 = \left[0\ S_0^1, 0000, S_0^M, 0000, .., S_0^3, 0..S_0^2\ 000.0\right] \quad (13a)$$

$$G_1 = \left[S_1^M, 0000, S_1^3, 0000, 00.., S_1^2, 0..000\ S_1^1\right] \quad (13b)$$

$$G_1 = \left[0 \ldots., 0000, S_L^2, 0000, 0\ S_L^1 00, 0..000\ S_L^M\right] \quad (11c)$$

In the three aforementioned systems, the IFFT (Inverse Fast Fourier Transform) is utilized to convert these sub-blocks to the time domain. Subsequently, the output undergoes rotation through the application of a rotation factor Φ, and the results are combined to produce the transmitted signal $\tilde{x}$. This procedure is concisely represented by Eqs. (14)–(16).

$$g_i = IFFT\ G_i \quad Where\ i = 0, 1, \ldots, L-1 \quad (14)$$

$$x_i^{r_i}(n) = \phi_i g_i \quad (15)$$

$$\tilde{x} = \sum_{i=0}^{L-1} x_i^{r_i}(n) \quad (16)$$

The process involves multiple iterations, depending on varying sets of Φ. After each iteration, the candidate transmission signal is calculated, and the signal with the minimum PAPR is then transmitted.

4.THE HYBRID TECHNIQUE

A hybrid PAPR reduction scheme is proposed, combining the enhanced PTS scheme with either Mu-Law companding or clipping in the post-processing phase. The fundamental idea behind improving the PTS sub-block partitioning is to merge the advantages of both AD and IL partitioning schemes. This integration occurs in the post-processing phase, i.e., after summing up the rotated sub-block signals, and does not substantially increase the overall computational load. The enhanced partitioning combination is responsible for the initial improvement in PAPR reduction. The substantial correlation among data frames in OFDM signals leads to elevated PAPRs. Fixed permutation (IL and AD) sub-block partitioning techniques are used to break up the lengthy correlation patterns. The enhancement process starts in the frequency domain by generating M adjacent sub-blocks at the system's input. These blocks are then split up into smaller clusters C of size Z. Consequently, IL partitioning is employed to create G_i sub-blocks.

$$G_{Ci}^{K} = SB_{Ci}(k) \quad (17)$$

where G_{Ci}^{K} represents the Kth element in the generated cluster C for the partition G, and $SB_{ci}(k)$ is the Kth element in sub-block (ci) of the system's input data. Therefore, the chosen sub-block of size Z is merged from individual M sub-blocks to generate the IL partition block of size M.Z. The generated sub-blocks G are treated individually through IDFT as:

$$x_n^i = \sum_{K=0}^{Z-1} \sum_{C=0}^{M-1} G_{Ci}^{K} e^{-j2\pi(CL+iZ+K)n/N} \quad (18)$$

where $L = N/M$ represents the number of blocks from N subcarriers. The phase of the PTS sequences generated by Eq. (18) is rotated by ϕ, except the fundamental sequence x_n^0, which is maintained constant, or rotated by $\phi = 0$.

$$\tilde{x}_n^i = w_i . x_n^i \quad (19)$$

Where

$$w_i = e^{j\phi_i}\ i = 1, 2 \ldots..(\mathcal{B} - 1) \quad (20)$$

where $\mathcal{B}$ is the number of the enhanced blocks, and ϕ_i is the angle in the range $0 \le \phi \le 2\pi$, which is selected randomly. Hence, the candidate signal for transmission becomes:

$$\tilde{x} = \sum_{i=0}^{M-1} \tilde{x}_n^i \quad (21)$$

In the case of using clipping in the post-processing phase, the candidate signal for transmission, $\tilde{x}_n$, is given to the clipping block. The clipping operation can be expressed as:

$$|\tilde{x}_n| = \begin{cases} |\tilde{x}_n|, if\ |\tilde{x}_n| < A \\ A \quad , if |\tilde{x}_n| \ge A \end{cases} \quad (22)$$

where A is a preset clipping level.

$$A = \max(\tilde{x}_n).\alpha \quad (23)$$

where α is the clipping factor, take a fraction of one value. It means no clipping at $\alpha = 1$ because A equals the maximum value of the OFDM signal; however, clipping increases with decreasing α due to the decrease in A. Using various sets of phase rotation values, the procedure is iterated (first iteration process). The PAPR of the signal is measured in each iteration. The OFDM signal with minimal PAPR is then transmitted. On the other hand, when enhanced PTS is integrated with the Mu-Law scheme, the signal determined by Eq. (21) is directed to the Mu-Law block. The Mu-Law companding operation can be expressed using Eq. (24).

$$x_\mu(t) = \frac{\ln\left[1+\mu\frac{|(\tilde{x}_n|}{mzx(\tilde{x}_n)}\right]}{\ln(1+\mu)} \max(\tilde{x}_n).Sgn(\tilde{x}_n) \quad (24)$$

Then, a second iteration process is applied by utilizing varying sets of Φ. The PAPR of the signal is measured and recorded at each instance. The signal with minimum PAPR is then transmitted. The overall operational procedure of the proposed hybrid scheme can be summarized as a sequence of the following flowchart.

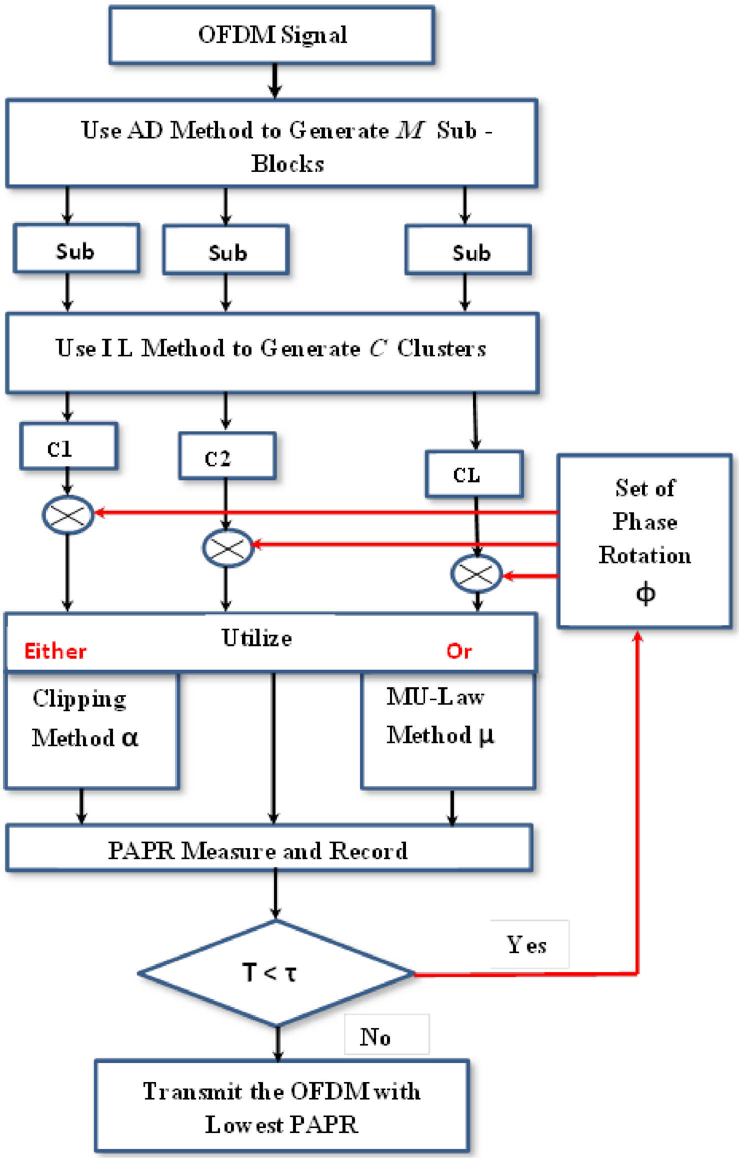

Fig. 5 Proposed Hybrid Scheme.

5.RESULTS OF SIMULATION

In this section, the evaluation and numerical comparison of the enhanced hybrid techniques are conducted with the performance of conventional PTS schemes (AD, IL, and PR), utilizing MATLAB. The assessment of PAPR reduction performance is conducted through the use of the CCDF, employing parameters specified in Table 1.

Table 1 Evaluation Setting Parameters.

		OFDM		Mu-Law		Clipping
Modulation	CCDF	Blocks	Subblocks (*M*)	Subcarriers (*N*)	μ	*α*
For the four Types	10^{-3}	2000	4	128	1	0.6

Figure 6 illustrates how conventional PAPR reduction schemes respond to minimizing the PAPR of an OFDM signal employing QPSK modulation. The graph distinctly indicates that the PAPR reduction achieved by the PR method at 7.2 dB surpasses that of the AD method at 8.5 dB, which is more effective than the response obtained by the IL method at 9.5 dB. Moreover, Fig. 6 also highlights that the proposed enhanced PTS schemes exhibit a superior process for PAPR reduction compared to conventional methods. Furthermore, the hybrid technique with the Mu-law method at 4.6 dB demonstrates better reduction than the hybrid technique with the clipping method at 5.1 dB.

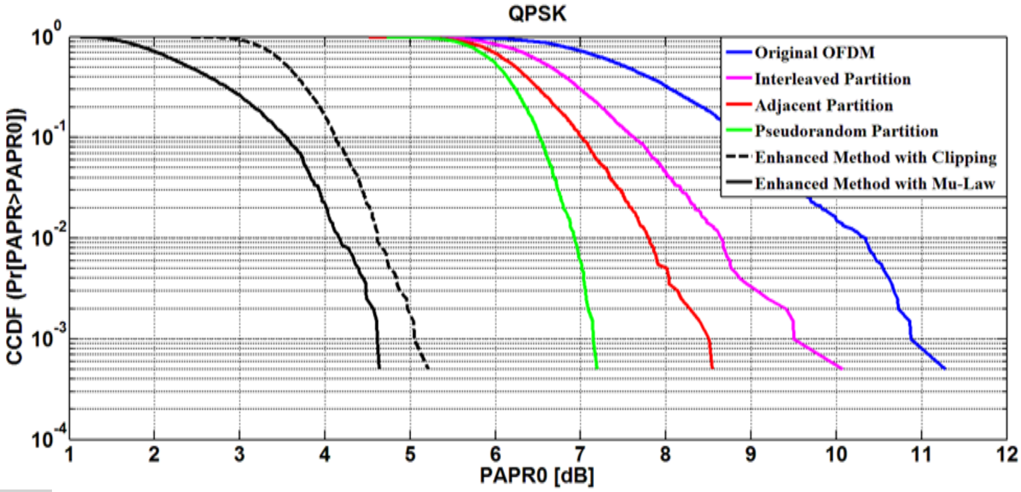

Fig. 6 The Response of the Hybrid and the Conventional Schemes with QPSK Modulation.

Figure 7 compares the PAPR reduction performance of both conventional PTS and the hybrid technique for an OFDM signal modulated with 8PSK. By configuring the CCDF value, the reduction processes of the suggested hybrid PTS technique, utilizing Clipping at 5.1 dB and Mu-Law at 4.4 dB, exhibit superior responses compared to conventional PTS schemes (IL, AD, and PR), as illustrated in Table 2. The figure indicates that the hybrid technique with Mu-Law delivers a more effective response in the reduction process compared to the method based on clipping.

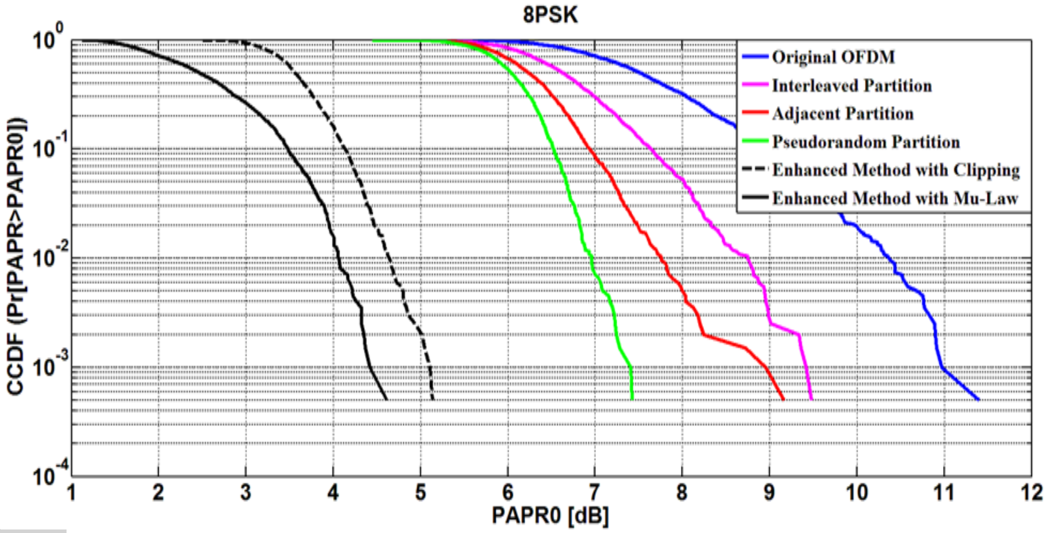

Fig. 7 The Response of the Hybrid and the Conventional Schemes with 8PSK Modulation.

Utilizing an OFDM signal modulated with 16QAM, Fig. 8 depicts the PAPR reduction performance of the hybrid PTS schemes proposed in this study, employing Mu-Law and Clipping methods. It also showcases the performance of the original OFDM signal alongside that of conventional schemes. A numerical comparison is conducted based on the CCDF value indicated in Table 1. This numerical analysis shows that the proposed schemes exhibit superior reduction compared to both the original and conventional methods as in Table 2, where the scheme based on Mu-Law method with 4.3 dB achieves a reduction less than original method by 7.4 dB, less than IL method by 5.1 dB, less than AD method by 2.9 dB, and less than PR method by 2.9 dB. Also, Fig. 8 shows that the PAPR reduction achieved by the proposed scheme, which combines the Mu-Law method with 4.3 dB, surpasses the reduction process of the scheme based on the clipping method with 5.2 dB by 0.9 dB. Figure 9 compares the proposed schemes and conventional schemes (IL, AD, and PR), as well as the original scheme based on an OFDM signal modulated with 64QAM. Regarding the CCDF value setting, the original signal exhibits a PAPR reduction of 11.1 dB, as shown in Table 2. Figure 9 also demonstrates that the PR method, AD method, and IL method achieved PAPR reductions of 0.9 dB, 2.9 dB, and 4.1 dB less than that of the original signal, respectively. The proposed hybrid scheme with the clipping method provided a reduction of 5.1 dB, which is less than the reduction of the original signal by 6 dB. However, the proposed scheme with Mu-Law surpasses the performance of all methods, achieving a reduction of 4.2 dB, which is 0.9 dB less than the reduction achieved by the proposed scheme with the clipping method.

Also, Table 3 compares the proposed work with some of the recent studies [10, 11, 17].

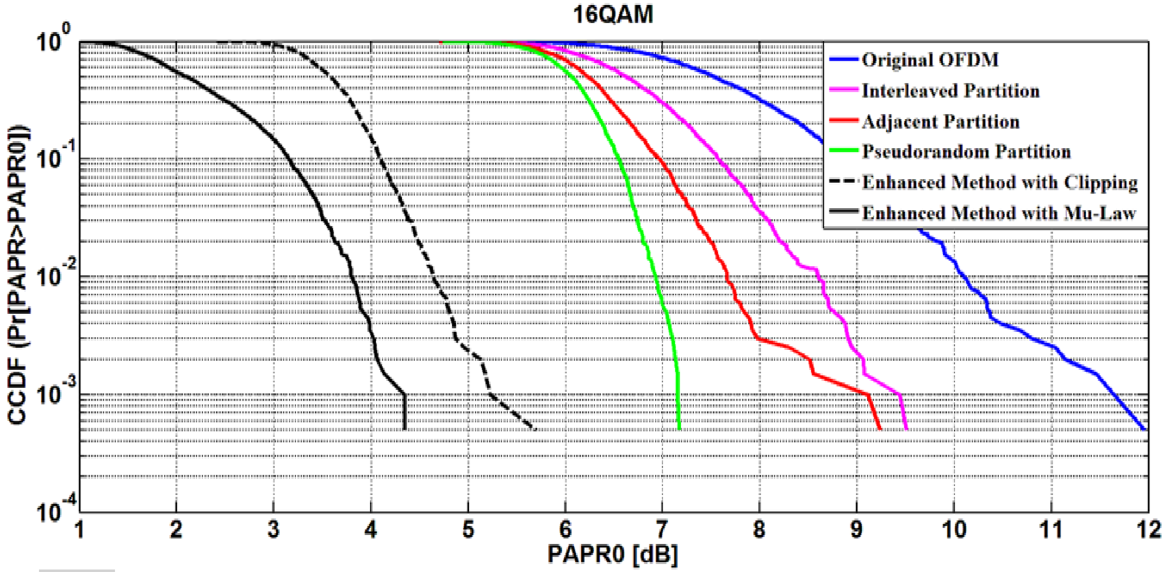

Fig. 8 The Response of the Hybrid and the Conventional Schemes with 16QAM Modulation.

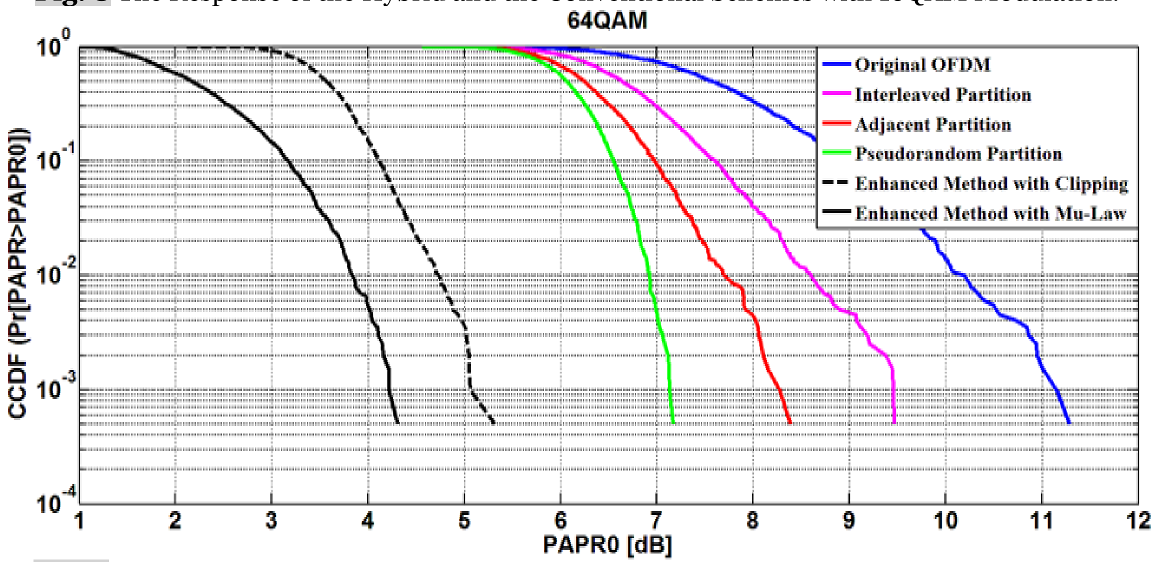

Fig. 9 The Response of the Hybrid and the Conventional Schemes with 64QAM Modulation.

The results indicate that the performance of the proposed hybrid scheme with the Mu-Law method surpasses that of other methods, including that proposed with the Clipping method. Further, Mu-Law companding has further advantages over clipping as [23]:

1- The signal generated using the Mu-Law companding method at the transmitter can be easily recovered accurately through the corresponding inversion of the nonlinear transformation function at the receiver. In contrast, the clipping method tends to truncate large signals when their amplitudes exceed the threshold level, rendering it impossible for the receiver to recover the clipped signals.

2- The nonlinearity introduced by the Mu-Law method enhances the resilience of small signals to noise by amplifying them and compressing large signals. In contrast, the clipping method insignificantly affects small signals.

Table 2 The Numerical Results.

Modulation	hybrid with Mu-Law(dB)	hybrid with clipping(dB)	PR (dB)	AD (dB)	IL (dB)	PAPR of original OFDM (dB)
QPSK	4.6	5.1	7.2	8.5	9.5	10.9
8PSK	4.4	5.1	7.4	9	9.4	11
16QAM	4.3	5.2	7.2	9.1	9.4	11.7
64QAM	4.2	5.1	7.1	8.3	9.4	11.1

Table 3 A Comparison Between the Proposed Work and Recent Studies.

	Proposed work	Mestdagh et al. [10]	Cheng et al. [11]	Aghdam et al. [17]
PAPR Reduction	Significant	Significant	Significant	Potentially significant
Complexity	Low	Moderate to High	High	High
Computation Requirements	Low	High	High	High
Resource Usage	No additional resource usage	Requires additional power and computational resources for injecting and managing tones	May reduce the effective data rate due to tone reservation	Requires substantial computational resources, particularly for training
Flexibility	Less flexible	Flexible	Less flexible	Highly flexible
Impact on Data Rate	No impact	Minimal to moderate impact	Potential reduction in data rate due to reserved tones	No direct impact
Real-Time Implementation	Easily	Complex	Challenge	Challenge

6.CONCLUSIONS

The high peak-to-average power ratio (PAPR) is a major drawback of the OFDM system due to its multicarrier nature. The present paper presents a hybrid PAPR strategy based on PTS and compares it against other existing PTS methods. The proposed technique enhanced the sub-block partitioning scheme of PTS by incorporating IL partitioning into the AD partitioning scheme, aiming to improve the PTS capability for PAPR reduction. This enhancement leverages the hybridization of enhanced PTS with simpler methods, such as Mu-Law companding or clipping, in the post-processing phase. Then, the enhanced system is implemented in two separate schemes, namely, the hybrid technique with Mu-Law and the hybrid technique with clipping. Simulation results demonstrate the PAPR performance of the hybrid schemes across different modulation formats, which surpasses that of currently utilized PTS systems. Notably, the hybrid approaches outperform PTS with PR, acknowledged in the literature for its superior PAPR reduction performance. Furthermore, the simulation results indicate that the performance of the hybrid technique with Mu-Law exceeds that of the hybrid technique with clipping.

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NOMENCLATURE

A	Predetermined clipping level
C	Block cluster
G	Sub-block partitioning
L	Disjoint subcarrier group
M	*Sub-Blocks*
N	Sub-Carriers
$S(t)$	Instantaneous amplitude
$S_{Max}(t)$	peak amplitude
X	*OFDM signal*
Z	*Cluster size*
Greek symbols	
α	Clipping factor
β	Number of the enhanced blocks
Ĉ(x)	Clipped signal
μ	Mu-Law compand parameter
Φ	Rotation factor

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