Exploring and Analyzing a Hybrid PAPR Reduction Method for OFDM Optimization

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1. Abstract:

Orthogonal Frequency Division Multiplexing (OFDM) is a effective modulation technique widely used in modern communication systems, including 5G and wireless networks because of its high spectral efficiency and robustness towards multipath fading. However, OFDM signals are characterized by a high Peak-to-Average Power Ratio (PAPR), which can severely impact the power efficiency and operational cost of these systems. This research investigates and analyse effectiveness of two conventional PAPR reduction methods that is Selective Mapping (SLM), and Partial Transmit Sequence (PTS) with incorporating their approach of PAPR reduction to develop a hybrid variant: SLM-PTS. This study utilized MATLAB simulations to implement and test each PAPR reduction technique on a standard OFDM system model. Parameters such as the number of subcarriers, oversampling factor, and modulation types were systematically varied to analyze the impact on PAPR, BER, and computational complexity. The effectiveness of each technique was measured using the Complementary Cumulative Distribution Function (CCDF) of PAPR values and BER performance under different channel conditions.

Key findings reveal that hybrid techniques, particularly SLM & PTS, offer significant improvements in PAPR reduction compared to traditional methods alone, without a corresponding increase in BER or computational overhead. The research underscores the potential of hybrid PAPR reduction techniques to significantly enhance the efficiency and reliability of OFDM systems. These findings have important implications for the design and optimization of next-generation wireless communication systems, suggesting that hybrid approaches can provide a balanced solution to the longstanding issue of PAPR in OFDM transmissions. This study contributes valuable insights into the practical application of combined PAPR reduction strategies, offering a pathway toward more power-efficient and robust OFDM technologies.

Keywords : OFDM, PAPR, CCDF, SLM and PTS

2. Motivation

Orthogonal Frequency Division Multiplexing (OFDM) is a key modulation technique used extensively in modern broadband communication systems, including wireless and optical communications, due to its ability to handle high data rates and resistance to multipath fading. However, the high inherent Peak-to-Average Power Ratio (PAPR) poses a significant challenge in the deployment of OFDM which impacts systems efficiency and cost- effectiveness[1].

In OFDM signals, high PAPR causes various significant challenges.

- Power Efficiency: In order to attain adequate PAPR reduction, the power amplifiers (PAs) in the transmitter must operate in the highly linear but inefficient zone, which decreases the battery life of mobile devices and increases power consumption.
- Operational Cost: In order to avoid non-linear distortion that is responsible for high PAPR, PAs have to be built with peak powers significantly greater than typical powers, which increases the complexity and cost of the system.

- Signal Quality: The degradation of signal quality is generally caused due to non-linearities introduced by PAs operating near their saturation point. Hence leads to enhanced bit error rates and suboptimal system performance.

Existing PAPR reduction methods, such Partial Transmit Sequence (PTS) and Selective Mapping (SLM), include trade-offs between signal distortion, complexity, and the amount of PAPR reduction attained, despite substantial study and development. These drawbacks emphasize the pressing requirement for creative solutions that might reduce PAPR while maintaining system performance.

3. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is an elegant digital modulation method that improves single subcarrier modulation with the use of multiple subcarriers within a single channel. Instead of employing a single subcarrier to transmit data at high speeds, OFDM uses several orthogonal subcarriers that are spaced near apart and delivered simultaneously with the use of Fast Fourier Transform (FFT)[1]. At a lower symbol rate, each subcarrier is modulated using a common digital method such as BPSK, QPSK, or QAM. As a result, mixing these subcarriers allows for higher data rates to be achieved within the same bandwidth compared to traditional single-carrier modulation approaches.

The communication channel in an OFDM system is divided into equally seperated frequency bands, with each subcarrier carrying a segment of the user data sent within each band. It is notable that every subcarrier remains orthogonal to every other subcarrier, hence making it different from traditional frequency division multiplexing (FDM)[1]. Fig 1 shows the spectral efficency of OFDM over FDM.

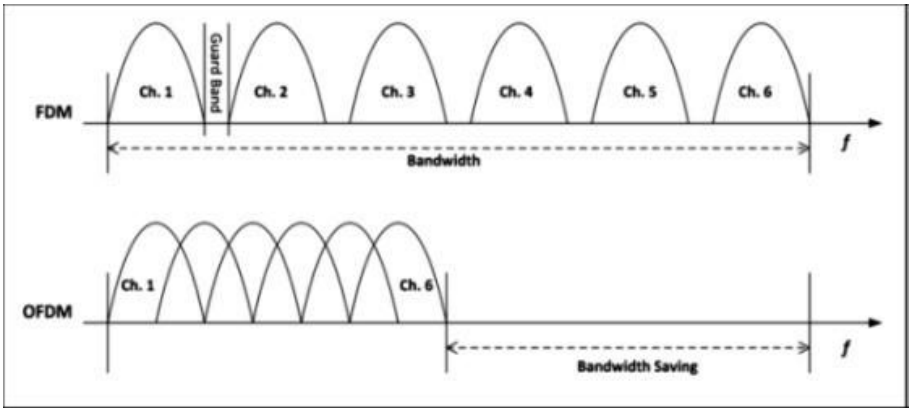

Fig 1 :Spectral Efficiency of OFDM over FDM

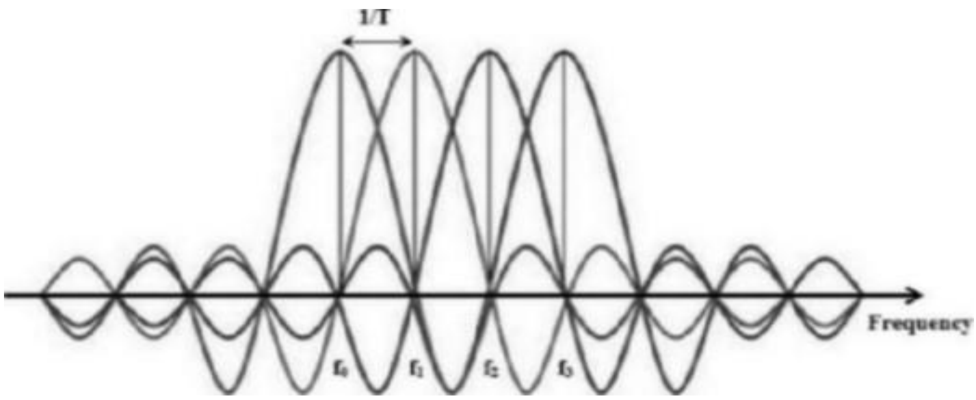

Fig 2 : OFDM Tones shows Orthogonility

In an OFDM system,a set of N orthogonal subcarriers are used to modulate a set of N complex data symbols, X(k). Here, $X = [X(0), X(1),..., X(N-1)]^T$ represents an input symbol vector in the frequency domain also reffered as a data block. The continuous-time baseband OFDM signal x(t) is defined by the sum of all N subcarriers with subcarrier spacing 1/Nts, which is obtained as in equation (1):

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j2\pi \frac{k}{Nt_s} t}, 0 \leq t < Nts \quad \ldots(1)$$

here sampling period is represented by *ts* and $j = \sqrt{-1}$.

An OFDM signal often contains high peaks in its immediate output, which can be represented by a PAPR.The ratio of the maximum instantaneous power to the average power of the continuous-time baseband OFDM signal x(t) is known as the PAPR[2], which is expressed in equation (2):

$$\boldsymbol{PAPR(x(t)) \triangleq \frac{max|x(t)|^2}{\frac{1}{Nts}\int_0^{Nts} E\{|x(t)|^2\}dt}, 0 \leq t < Nts} \quad \ldots(2)$$

Here, the expectation value is denoted by $E\{ |x(t)|^2 \}$. The discrete-time baseband OFDM signal x(n), given that it is sampling at the Nyquist rate t = nts, with integer n, is expressed in equation (3) :

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j2\pi \frac{k}{N} n}, n = 0,1,\ldots N-1 \quad \ldots(3)$$

and for discrete-time baseband OFDM signal x(n) the PAPR can be expressed as in equation (4):

$$\boldsymbol{PAPR(x(n)) \triangleq \frac{max|x(t)|^2}{\frac{1}{N}\sum_{n=0}^{N-1} |x(n)|^2}, 0 \leq n \leq N-1} \quad \ldots(4)$$

The Complementary Cumulative Distribution Function (CCDF), a mathematical technique, is used to evaluate the Peak-to-Average Power Ratio (PAPR). The CCDF determines the probability that an OFDM signal's PAPR will exceed a particular threshold αth[3]. Hence, the OFDM signal's CCDF is in equation(5):

$$\mathbf{P(PAPR > \alpha th) = 1 - P(PAPR \leq \alpha th)} \quad \ldots(5)$$

4. PAPR Reduction Techniques

4.1. Selective Mapping (SLM)

The SLM technique effectively adjusts the broadcast signal to address issues with high Peak- to-Average Power Ratio PAPR. This technique modifies the original symbols by applying a set of phase factors, which are a group of meticulously created phase sequences. These phase factors are kept in lookup tables that are included in both the transmitter and the receiver[4]. SLM reduces PAPR by selectively altering the phase of subcarriers. The signal's peak power can be reduced, and this will lower the PAPR overall, by carefully selecting and implementing phase variables[6].

This upgrade improves system performance by reducing distortion and improving signal quality[6]. SLM faces a number of challenges as well. The overhead of sending and storing the side information which includes details of phase factors needs to be considered. To exacerbate the situation, selecting phase variables necessitates increased processing power. To balance the decrease in PAPR with the related overhead, careful monitoring is required[9]. The SLM block diagram is shown in Fig. 3[11].

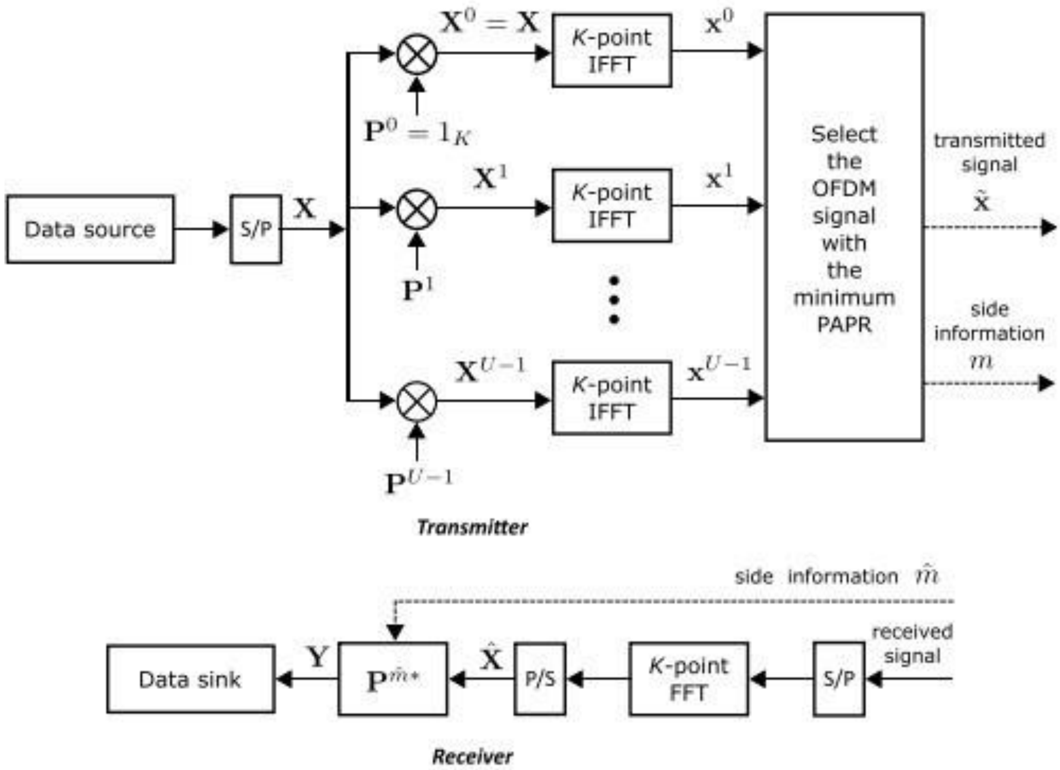

Fig 3 : Block diagram of SLM

4.2. Partial Transmit Sequence (PTS)

In OFDM systems, a popular technique for lowering PAPR is the PTS algorithm. This method gives each user's signal a varied power level, accomodating multiple users to share the same temporal-spectral resources. In OFDM, high PAPR can still be problematic, leading to distortion and a decrease in performance. These issues are handled by the PTS algorithm, which deftly modifies the sent signal[7].

The existing unmodified OFDM signal is divided into different sub-blocks in PTS, and these sub-blocks are further separated into smaller partitions. In order to determine the ideal phase sequence that minimizes PAPR, the algorithm does a thorough search over various phase factor combinations for each partition. While this method successfully lowers PAPR, it can be computationally taxing to perform an exhaustive search, especially when there are more sub- blocks and partitions[8]. As a result, in real-world applications, the objective of PAPR reduction and processing complexity must be balanced. Fig. 4 displays the PTS block diagram[12] .

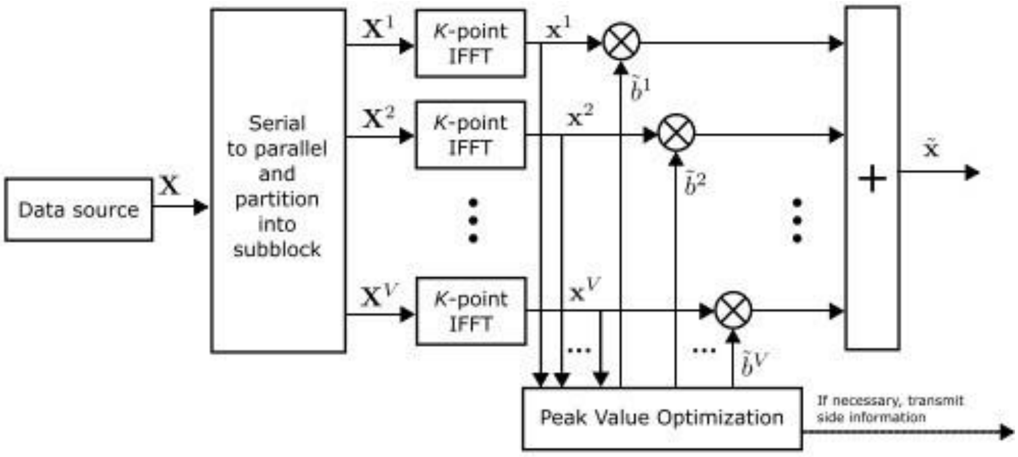

Fig 4 : Block diagram of PTS

4.3. Proposed Hybrid Method: SLM-PTS

The PAPR in OFDM waveforms can be decreased by using the hybrid SLM-PTS technique. This hybrid solution maintains optimal performance in OFDM systems while effectively reducing PAPR by intigrating the approach of both SLM and PTS techniques. Using an orthogonal sharing of time and frequency resources, OFDM is a multiple access technology that accommodates multiple users access the channel. Through the use of sophisticated receiver processing algorithms and power level adjustments, it increases spectrum efficiency. On the other hand, high PAPR for OFDM waveforms can cause distortion and reduce power amplifier efficiency.

The following procedures are part of the SLM-PTS hybrid method for PAPR reduction in OFDM waveforms:

1. Power Sharing: Depending on the quality-of-service requirements and channel conditions, users in OFDM are given varying power levels. With their different priorities and channel conditions taken into account, this sharing maximizes power distribution across users.

2. SLM Phase Management: A predetermined set of phase sequences is applied to each user's modulated data, and the data is assigned a phase sequence. The goal of these sequences is to decrease PAPR. Considering the power sharing scheme, for multiple users the phase sequence with least PAPR is determined respectively.

3. PTS PAPR Reduction: Multiple PTS are created from the phase-optimized signals obtained by SLM. The final transmitted signal is calculated by adding the weights of each partial send sequence. In order to successfully lower PAPR, the weighting coefficients are carefully selected.

4. Successive Interference Elimination (SIE): SIE is utilized at the receiver to extract each user's unique data by separating the overlaid signals from several users. Iteratively, the SIE

process begins with the highest power user signal. To reduce interference and recover the remaining user signals, interference from previously decoded signals is eliminated.

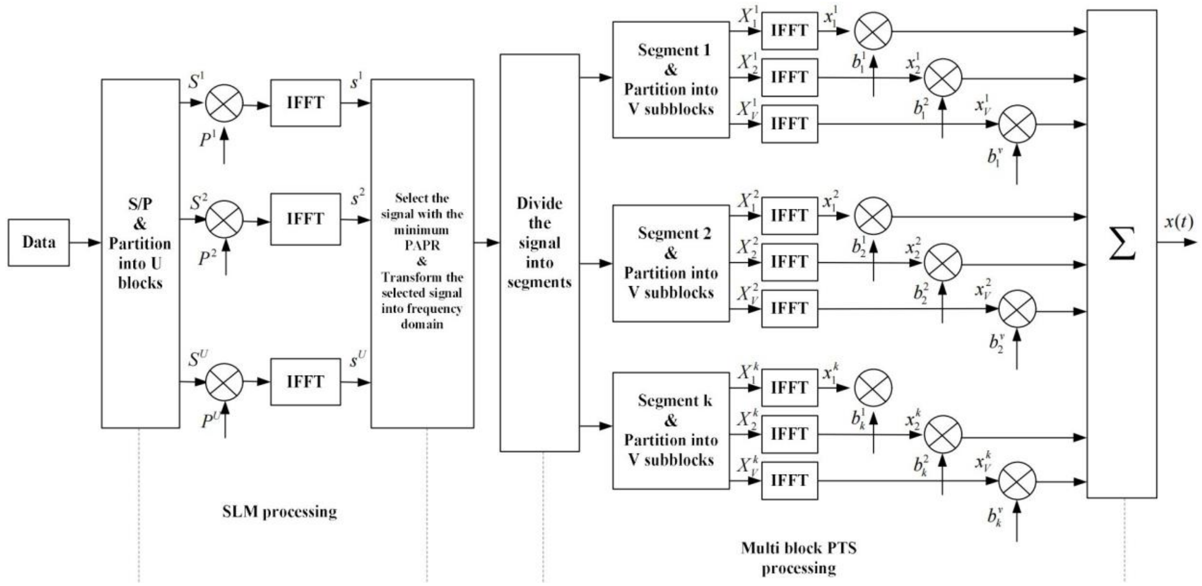

Fig 5 : Block diagram of proposed hybrid method SLM-PTS

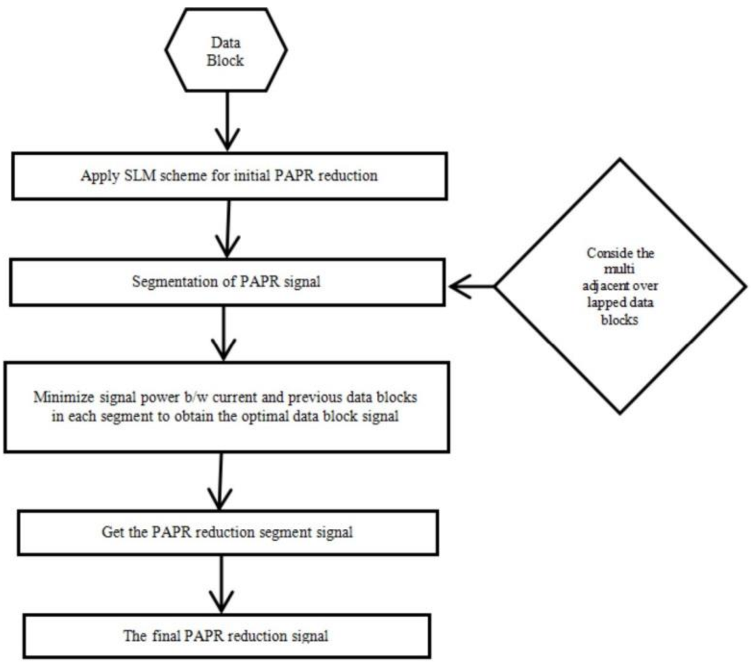

Fig 6 : The flow chart of hybrid method SLM-PTS

In OFDM systems, the SLM-PTS hybrid method combines the benefits of PTS's approach to reduce PAPR SLM's approach by optimizing phase and PTS's approach to minimize PAPR . Taking into account the power distribution method,for every user phase optimization method used in SLM in order to decrease the PAPR. PTS further lowers the PAPR by splitting the signals into partial transmit sequences followed by using weighted summing. In OFDM systems, the hybrid approach substantially decreases the PAPR while preserving better system performance as far as bit error rate and bandwidth optimization is considered. It makes it possible for numerous users to share temporal and spectral resources effectively, enhancing the system's throughput and capacity. It is crucial to consider that the hybrid SLM-PTS approach could be more complex because it combines complexity of both PTS and SLM approaches.

5. Simulation Results

5.1. Simulation : 1

OFDM Parameters

Number of Subcarrier *(N)* : 256 Data
Blocks count *(M)* : 16
Phase sequences Count for SLM *(U)* : 4
Sub-blocks Count for PTS *(V)* : 4

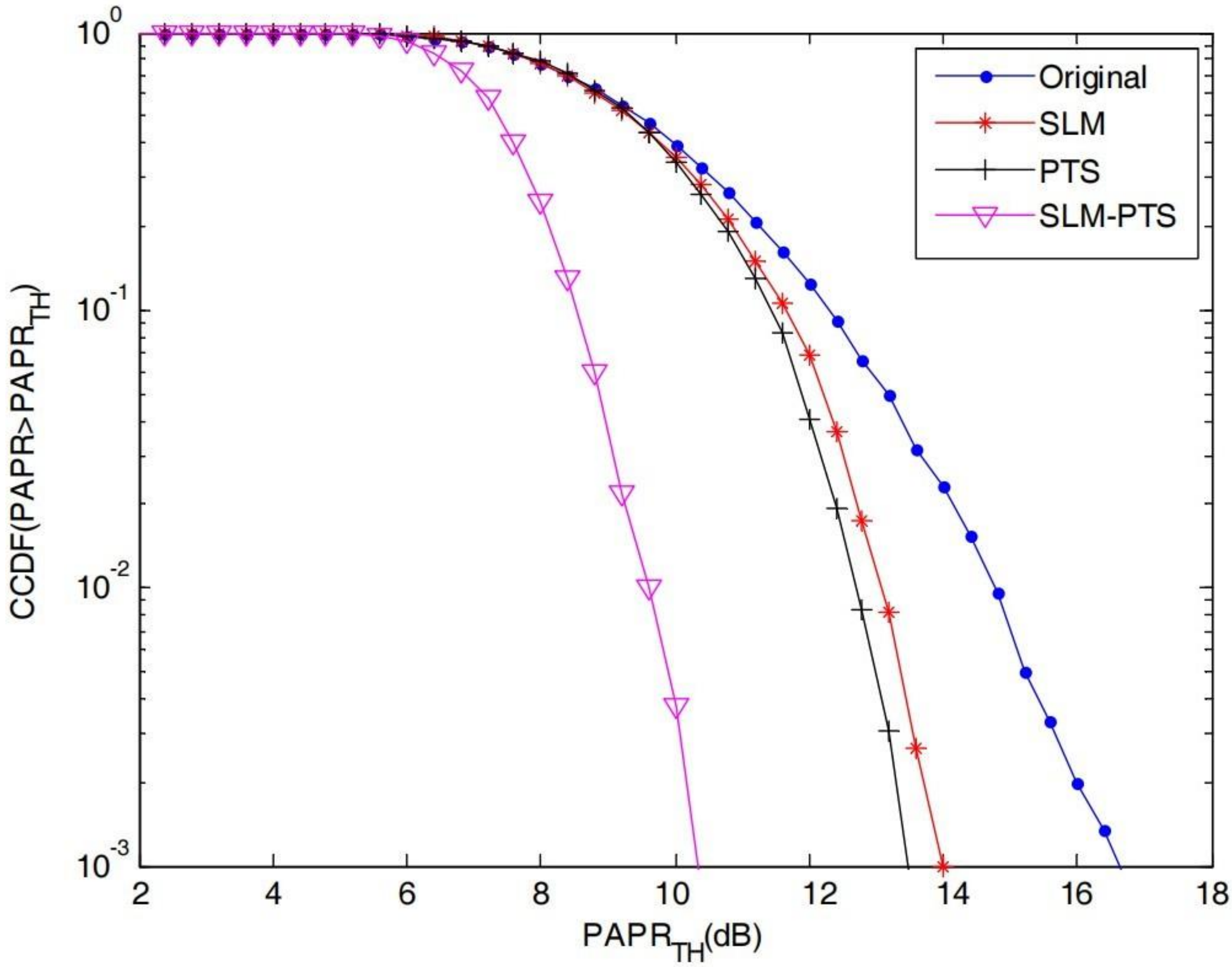

Figure 7 : PAPR Comparision for given parameters

Result for original OFDM: PAPR = **16.38 dB** Result for SLM method: PAPR = **13.76 dB** Result for PTS method: PAPR=**13.12dB**
Result for SLM-PTS method: PAPR = **10.08 dB**

The PAPR reductions for the suggested technique and the other two ways with N = 256, M = 16, U = 4, and V = 4 are shown in Figure 7. The "original" curve represents the OFFDM signal's CCDF without any PAPR reduction. The traditional SLM technique can lower the signal PAPR by approximately 2.62 dB when CCDF = 10−3, the traditional PTS scheme by approximately 3.26 dB, and the proposed hybrid method by approximately 6.3 dB.

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 08 Issue: 05 | May - 2024 SJIF Rating: 8.448 ISSN: 2582-3930

5.2 Simulation 2

OFDM Parameters

Number of Subcarrier *(N)* : 256 Data
Blocks count *(M)* : 16
Phase sequences Count for SLM *(U)* : 8
Sub-blocks Count for PTS *(V)* : 8

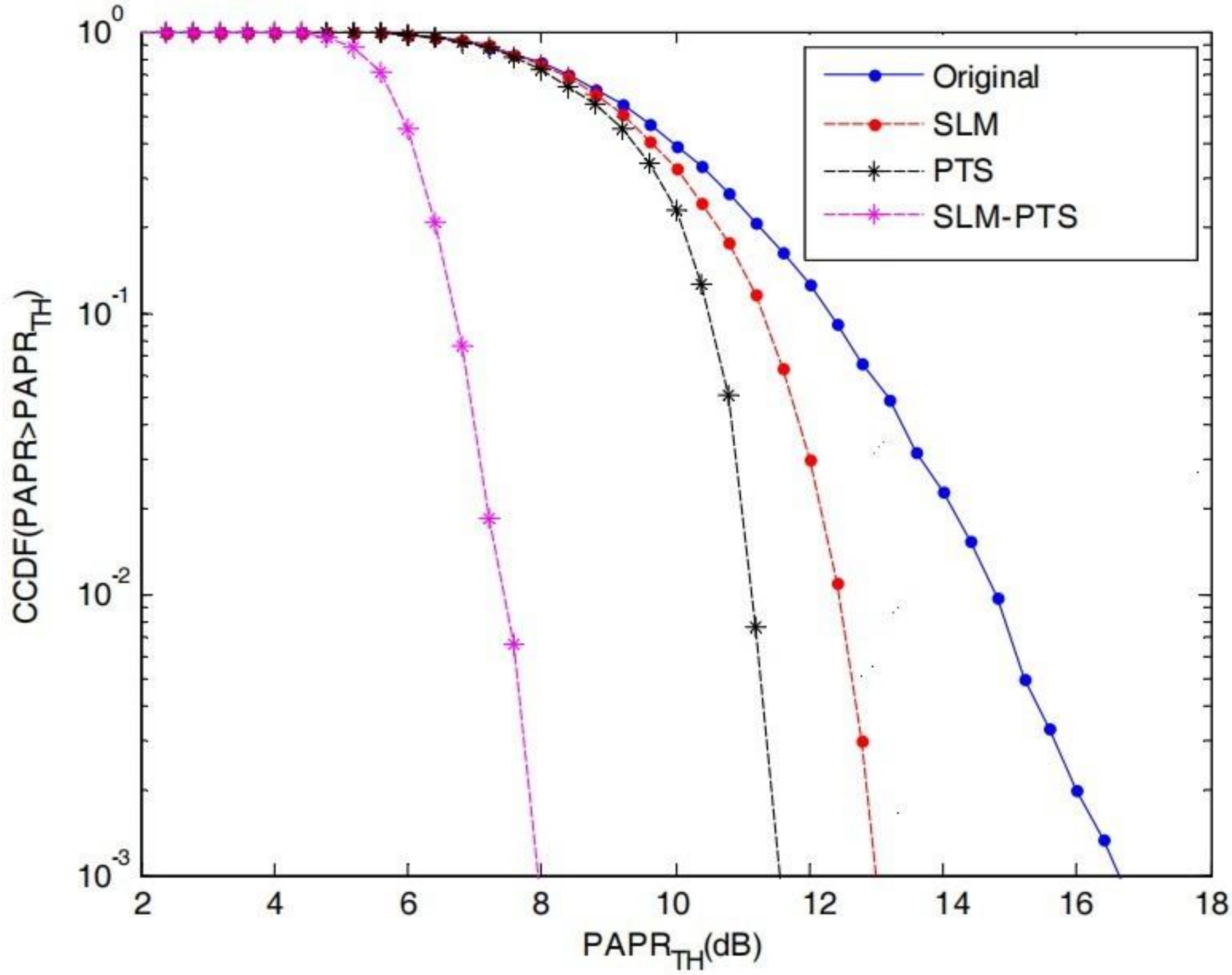

Figure 8 : PAPR Comparision for given parameters

Results for original OFDM: PAPR = **16.38 dB**
Results for SLM method: PAPR =**12.86 dB**
Results for Partial Transmit Sequence: PAPR = **11.74 dB**
Results for SLM & PTS: PAPR = **7.92 dB**

The PAPR reductions for the suggested approach and the other two ways with N = 256, M = 16, U = 8, and V = 8 are shown in Figure 8. The "original" curve represents the OFFDM signal's CCDF without any PAPR reduction. At CCDF = 10−3, it is seen that the signal PAPR may be reduced by approximately 3.52 dB using the conventional SLM method, 4.64 dB using the conventional PTS method, and 8.46 dB using the proposed hybrid method.

6. Conclusion

In OFDM systems, the classical PTS scheme performs better than the classical SLM scheme. It is evident that the PAPR of OFDM signals cannot be successfully reduced by these two traditional methods. Compared to the SLM and PTS schemes, the suggested approach (SLM- PTS) scheme performs better .In simulation 1, the hybrid SLM-PTS approach can outperform the standard SLM and PTS methods in terms of PAPR improvement by 3.68 dB and 3.04 dB, respectively. In simulation:2, the hybrid SLM-PTS approach can improve PAPR by 4.94 dB and 3.82 dB, respectively, over the standard SLM and PTS methods. This suggests that the hybrid approach based on nearby data blocks' overlapping effect can greatly lower the PAPR.

It is confirmed by the simulation findings that, in comparison to the two standard schemes used in OFDM systems, the suggested hybrid scheme performs better in terms of PAPR reduction. Because the overlapped data block structure is taken into account during the combined PAPR reduction process, this method is preferable. To improve the PAPR reduction impact, the peak of the overlapping signals should be lowered. In hybrid method, by combining the best features of both approaches, it may be possible to achieve extremely low PAPR levels. The double optimization procedure may make the method computationally more demanding, even though the PAPR reduction can be significant.

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Questions & answers

1. In comparison to conventional approaches, how successful are hybrid PAPR reduction techniques at reducing the peak-to-average power ratio?

In general, hybrid PAPR reduction strategies—such as SLM & Clipping or PTS & Clipping— achieve lower PAPR than their standalone equivalents. Hybrids are approaches that combine the best features of two approaches to overcome the shortcomings of one. For example, SLM can successfully limit peak amplitudes, while Clipping can dramatically lower PAPR without changing the signal's power spectrum. When both approaches are used together, the outcome usually minimizes PAPR more successfully and is more robust.

2. How do different channel circumstances affect the Bit Error Rate (BER) of OFDM systems when using hybrid PAPR reduction techniques?

Although hybrid approaches aim to lower PAPR, their effects on BER can differ. Clipping techniques have the ability to generate non-linear aberrations, which could increase the BER. Nonetheless, the increase in BER can be reduced with appropriate management (e.g., by filtering post-clipping or optimizing the clipping amount). In contrast, as both methods primarily modify phase characteristics without changing the signal's amplitude, combining SLM and PTS may preserve or even improve BER.

3. In real-time OFDM systems, what computational challenges come with applying hybrid PAPR reduction techniques?

Because hybrid approaches incorporate many processing processes, they typically involve increased computing complexity. For instance, SLM & PTS call for the generation of several signal candidates with various phase sequences, which are then further optimized by varying the phase of each of the sub-blocks. Under some circumstances, real-time implementation is viable despite the additional complexity because of the ways that contemporary computer resources and parallel processing techniques can help manage these demands.

4. Is it possible to reduce system efficiency and spectral integrity utilizing hybrid PAPR reduction strategies without significantly increasing out-of-band radiation or spectral spreading?

By reducing the negative effects of techniques like clipping, which can lead to spectral spreading, hybrid approaches seek to preserve spectral efficiency. Methods that combine controlled clipping or filtering with phase manipulation techniques (SLM, PTS) are especially good at preserving spectral integrity because they minimize the amount of amplitude adjustments required and use subsequent filtering to correct for any unintentional spectral spreading.

5. How responsive are hybrid PAPR reduction strategies to modifications in system specifications like transmission power, subcarrier count, and modulation type?

Depending on how they are built, hybrid PAPR reduction strategies provide moderate to high adaptability. For example, since the fundamentals of phase rotation hold true for various configurations, SLM-based hybrids can be easily modified to accommodate various modulation schemes and subcarrier counts. The major difficulty lies in fine-tuning the parameters (such as phase factors and clipping level) to maximize performance under various operating scenarios.

6. Which strategies may be created to balance the trade-offs in hybrid techniques between BER, computational complexity, and PAPR reduction?

Adaptive algorithms, which dynamically modify the parameters of hybrid procedures based on real-time system feedback, are a possible component of optimization strategies. In order to minimize the requirement for significant real-time computation, machine learning models could potentially be used to forecast the ideal settings for specific scenarios. Additionally, performance can be balanced without a significant computing burden by creating heuristic algorithms for rapid parameter estimate and adjustment.

7. How might machine learning algorithms improve the effectiveness and efficiency of hybrid PAPR reduction methods?

By extracting the best parameter values from large datasets and spotting trends that conventional analysis might miss, machine learning can greatly improve hybrid PAPR reduction strategies. In order to improve performance with the least amount of manual intervention and react to changing network conditions, machine learning algorithms have the ability to automate the optimization of phase sequences, clipping levels, and filtering parameters, possibly even in real-time.