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"Peak-to-Average Power Ratio Problems in OFDM Systems"

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Abstract: Orthogonal Frequency Division Multiplexing (OFDM) stands out as a widely used transmission method in today's communication systems. However, high peak to average power ratio (PAPR) is a major drawback of this modulation technique. It poses significant problems in communication systems, leading to signal distortion and reduced power efficiency. To tackle this challenge, this paper broadly classifies and investigates popular PAPR reduction techniques, providing a thorough examination of their individual effectiveness. We compare these techniques, analyzing how they perform when we increase the number of subcarriers, use cyclic prefixes, and consider the time complexity of different methods. Rather than focusing on a specific technique, this dissertation provides a broad understanding of various approaches, aiming to help in choosing the most suitable method based on specific system requirements.

Keywords: OFDM, PAPR, CCDF, SLM, PTS.

I. INTRODUCTION

These days, wireless applications are expanding very quickly. Wireless communication applications require both high speed and high quality. Wireless communication has undergone constant evolution. The limitation of bandwidth and data-rates caused a bottleneck in the solitary conveyor transmission system used extensively in second era communication frameworks. A maximum threshold limit on the potential information rates are restricted because the bandwidth of the system must be lower than the coherent spectrum of the communication pathway. The utmost important and commonly utilized technology of transmitting through multiple channels is known as OFDM. In 1966, R.W. Chang presented the OFDM concept, which was subsequently patented in 1970. Unfortunately, because there were no broadband applications or strong merged circuits to facilitate the necessary intricate calculation, use of OFDM was restricted to military communication. OFDM gained prominence in 1990 as a result of the introduction of broadband digital applications and the rapid advancement of VLSI design and process technology [1]. Digital Audio Broadcasting (DAB) standards were introduced in 1995 as the first commercial OFDM-based wireless system. The field of OFDM development proceeded concurrently with the development of all other concurrently existing technologies until OFDM was eventually incorporated into major 21st-century wireless standards such as WLAN, WiMAX, and LTE.

A concurrent grouping of regularly spaced sub-channels is modulated by data symbols in the OFDM multi-carrier modulation technique. While the signal spectra associated with the various sub-carriers intersect in frequency, the sub-carriers exhibit the minimal frequency gap necessary to preserve orthogonality of their respective waveforms in the domain of time. A waveform with extremely high bandwidth efficiency is produced by the spectral overlap. When used on channels that display frequency selectivity or time delay spread, OFDM is an easy-to-use technology. Coherence channel spectrum, that gauges the de-correlation of channel, or delay spread are two characteristics of frequency selective channels. Afterwards, applying techniques suitable for frequency-flat fading channels, it's possible to be done in an easy way.

II. PAPR IN OFDM

An enormous number of independent or orthogonal signals are added together to form any multi-carrier signal. As a result, the MC signal's envelope may greatly fluctuate. PAPR which is the ratio of the peak value to the mean value of MC signal, is expression used to quantify this variance. Because high PAPR values have significant drawbacks, PAPR is an important element to take into account when analyzing OFDM.

A. OVERVIEW OF PAPR:

Let X_n be the data symbols, with n ranging from 0 to N-1. For OFDM framework, N is the no. of sub-carriers. Thus, let's get the necessary parallel block of data before OFDM creation is

$$X = [X_0, X_1, \dots X_{N-1}] \tag{1}$$

Accordingly, an OFDM signal with N sub-carriers has the following complex baseband representation:

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j2\pi n\Delta f t} ; 0 \le t < NT \tag{2}$$

Here, T represents the time for the pulse moulding symbol and Δf is subcarrier spacing. The PAPR for this signal can be described as follows:

$$PAPR = \frac{\max\limits_{0 \le t < NT} |x(t)|^2}{\frac{1}{NT}\int_0^{NT} |x(t)|^2 dt} \tag{3}$$

On the other hand, equation (3) provides PAPR for an analog signal. Let's presume simply NL uniformly spaced samples of x(t) will be taken into consideration in order to get PAPR for a digital OFDM signal, where L is more than one and also integer. Thus, signal sampling could be expressed as:

$$x = [x_0, x_1, \dots x_{N-1}] \tag{4}$$

Hence, the digital domain depiction of the OFDM as follows:

$$x_k = x\frac{k.T}{L} = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{\frac{j2k\Delta f nT}{L}} \; ; \; k = 0,1,\dots,N-1 \tag{5}$$

According to equation (5), the signal's PAPR is as follows:

$$PAPR = \frac{\max\limits_{0 \le k < NL-1} |x_k|^2}{E[|x_k|]^2} \tag{6}$$

B. COMPLEMENTARY CDF FOR PAPR:

The CCDF is utmost popular and widely utilized effectiveness metric for PAPR decrease strategies [3]. Possibility that a data-block's PAPR will surpass a specific threshold is indicated by the symbol CCDF. More verticality on the CCDF graph indicates higher PAPR reduction performance when plotted against threshold values [3]. The CDF of the amplitude of a signal sample is

$$F(z) = 1 - e^{-z} \tag{7}$$

Assuming that $E|x(t)|^2 = 1$ represents the average power of x(t), the probability distribution function for PAPR below a certain threshold value is

$$\begin{aligned} P\,r(PAPR < z) &= \left(F(z)\right)^N \\ &= (1 - e^{-z})^N \end{aligned} \tag{8}$$

However, the CCDF of the PAPR is more commonly utilized for assessing the effectiveness of PAPR reduction approaches. The likelihood that PAPR will surpass a cut-off point (the CCDF) is

$$\begin{aligned} Pr(PAPR > z) &= 1 - Pr(PAPR \le z) \\ &= 1 - (1 - e^{-z})^N \end{aligned} \tag{9}$$

C. PROBLEMS RELATED TO ELEVATED PAPR VALUES:

The power magnitude variation of OFDM signal that is sent is described by PAPR magnitude. Transmitter's PA could get saturated if the PAPR value is extremely high because of the sending of extremely elevated power [2]. After reaching saturation, the PA function in an asymmetrical zone. When a PA operates nonlinearly, the incoming signal is modulated nonlinearly, which produces undesirable frequencies. So, it's possible for the undesirable things to happen [2],[4]:

- Carriers that are modulated differently.
- Spectral spillage caused by radiation which is out of band.

D. MITIGATING SIGNAL DEFORMATION ARISING FROM ELEVATED PAPR:

Various approaches can be employed to mitigate the impact of elevated PAPR on the PA. The following solutions are outlined, along by their respective benefits and drawbacks:

- The average power permitted under multi-carrier transmission may be decreased by the maximum power, which might be restricted by application [3] . Unfortunately, this method impedes the utilization of one of OFDM's primary benefits and shortens the span of multi-channel transmission.

- For the purpose, transmitting highest power, the power amplifier's dynamic range can be extended [3]. However, because PAs with a higher dynamic range are more expensive, this technique is pricy. The maximum permitted power must once more be hard-coded, which reduces the range of OFDM.
- Using a variety of ways to lower PAPR, resulting signal which is OFDM to a manageable level in front of transmission is most practical workaround to date. These methods increase to the transmitter's overall cost because the processing can be done in baseband, but they also enable the OFDM range to expand as needed. They also need an additional set of calculations.

III. PAPR REDUCTION TECHNIQUES:

Over an extended duration during the advancement of OFDM technology, numerous methods for reducing PAPR have been suggested. These methods' primary goal is to lower the OFDM signal's PAPR to a manageable level prior to sending the signal to the transmitter. Below is a list of the various methods [3].

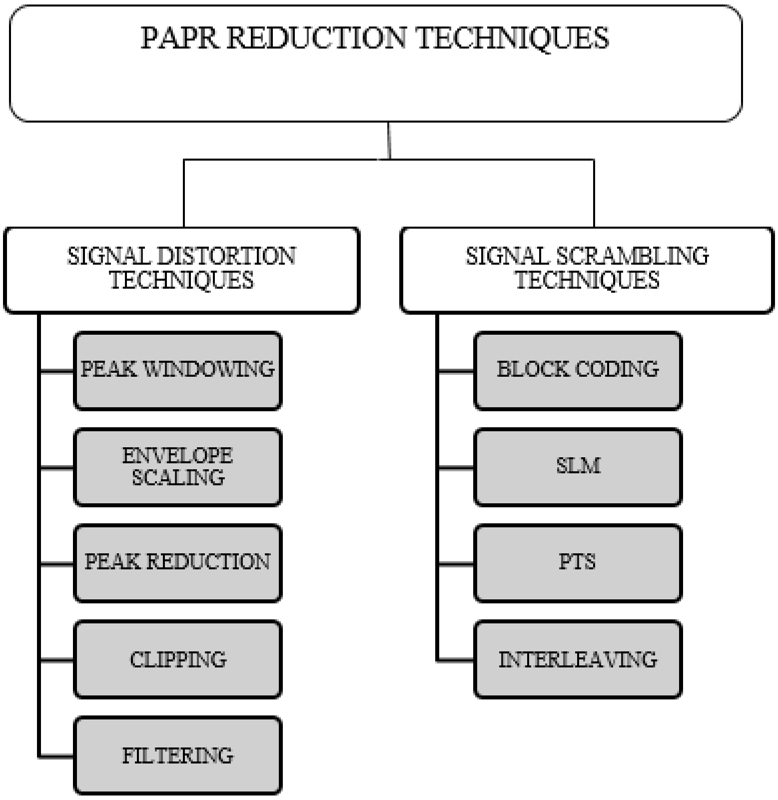


Fig 1: Various PAPR reduction techniques

A. Filtering and Clipping:

The most basic PAPR decrease strategy is the clipping approach, which sets a predetermined maximum transmit signal magnitude. Nevertheless, it has the following shortcomings:

- Degradation in BER performance is the result clipping-induced distortion of in-band signals.
- Additionally, clipping produces radiation that is outside of the band, which forces neighboring channels to receive out-of-band interference signal. While using MATLAB for 224 MIMO OFDM mobile network filtering can decrease out of band signals generated by clipping, it may have an impact on elements of the in-band signal with high frequencies (aliasing) when clipping is done within a region of discrete time using sampling rate in Nyquist [5].
- Radiation outside of the band may decreased via filtration the clipped signal, although peak regrowth will result anyhow. Once the filtering procedure is completed, the signal may be greater than the clipping level that was set for that operation [2].

An illustration of a PAPR reduction in blocks utilizing filtering and clipping as seen in Fig (2), where N is the no. of subcarriers, L is the oversampling coefficient. The IFFT used in this technique to generate the discrete-time pulse x'[m], oversampled by L moments. The passband signal $x^p[m]$ is obtained by modulating N. (L-1) zero-padding of X'[k] in the spectral area, and then utilizing carrier frequency fc.

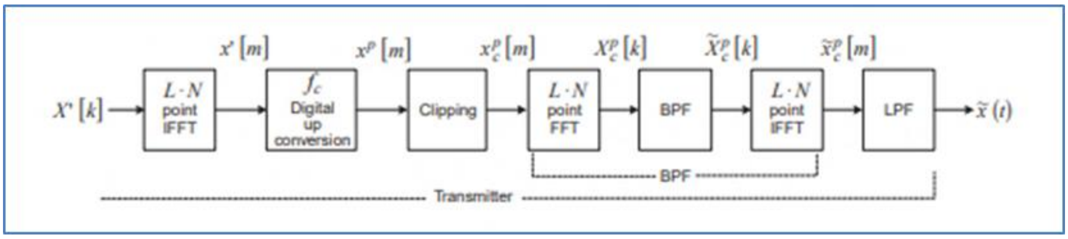


Fig 2: Depiction of Filtering and Clipping technique for reducing PAPR

B. Coding Schemes:

The Peak power is equivalent to mean power multiplied Ñ when Ñ signals with same phase are combined together. Naturally, not every code word has a poor PAPR. There-fore, the essential notion of the coding schemes is that significant PAPR decrease is achieved by following certain methods that lower the chance of the events occurring in identical phase.

The fundamental principle is to convert three bits of data into a four-bit code word by appending SOPC to final bit through all channel's. Primary drawback of the SOPC approach is that a 4-bit code word's PAPR may be lowered. It is determined, therefore SBC is ineffective at big frame sizes. In order to lower the PAPR without imposing a frame size restriction, the MCBC and CBC schemes were subsequently suggested [6][7]. Because they offer greater flexibility in terms of selecting the coding rate and frame size, as well as minimal implementation complexity, CBC and MCBC are more appealing. Original informational bits are supplemented by complementary bits by CBC and MCBC in order to decrease the likelihood of the peak signals occurring.

In summary, coding methods gives greater inspiration for realistic design in OFDM systems because of their built in error prevention capabilities and ease of application. Nonetheless, primary drawback of this approach is its effective lowering of PAPR at loss of coding rate.

C. Selective Mapping:

The block diagram for the selective mapping (SLM) technique for reducing PAPR is displayed in Fig(3). In this case, U distinct phase sequences $P^u = [P_0^u, P_1^u, \ldots, P_{N-1}^u]^T$ are multiplied by the input data block X={X(0), X(1) ,…, X(N-1)}. For $u = 1,2,\cdots,U$ and $v = 0,1,\cdots,N$ −where $P_v^u = e^{j\varphi_v^u}$ and $\varphi_v^u \in [0,2\pi)$ yield a changed data frame i.e. $\mathbf{X}^u = [X^u(1), X^u(2), \ldots, X^u(N-1)]^T$. $\mathbf{x}^{ut} = [x^u(0), x^{tu}(1), \ldots, x^u(N-1)]^T$ sequence is generated for each U independent sequences $\{\mathbf{X}^u[v]\}$ IFFT is calculated, wherein $\tilde{\mathbf{x}} = \mathbf{x}^{\tilde{u}}$ having the least PAPR is selected for broadcast [8], demonstrated by:

$$\tilde{u} = \underset{u=1,2,\ldots,U}{\operatorname{argmin}} \left(\max_{n-0,1,\ldots,N} |x^u[n]| \right) \tag{10}$$

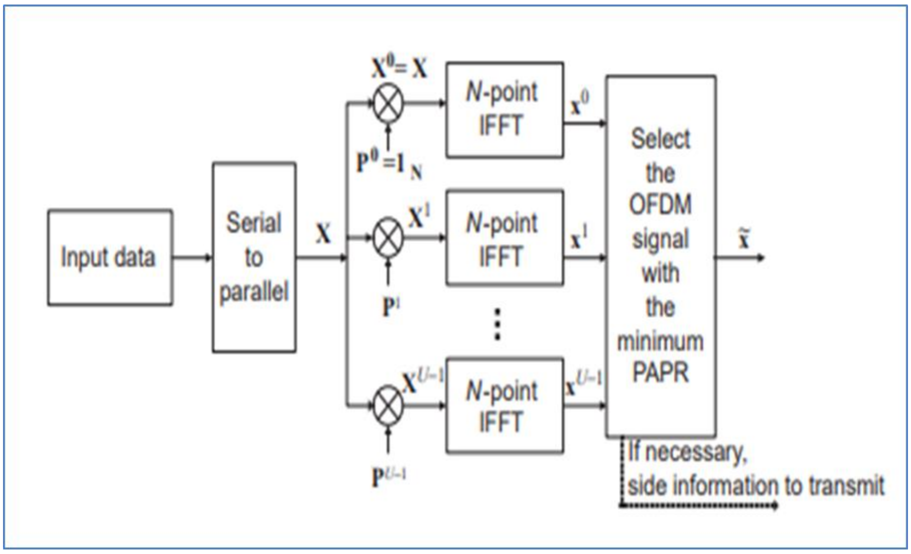


Fig 3: A block schematic of Selective Mapping based PAPR reduction technique

To enable the recipient to rebuild the data from the initial block, the information (index μ) on the selected phase sequence $\dot{P}^u$ must be sent as data from the side[2]. U IFFT procedures are necessary for the SLM technology to be implemented. Additionally, for every block of info. the (x) represents largest integer smaller compared to x $\log_2$ U bits of side information is needed.

D. Partial Transmit Sequence:

An incoming information block with Ņ symbọls is divided as Ṿ disjoint subblọcks using the ṖTṢ algorithm as follows:

$$X = [X^0, X^1, X^2, \ldots, X^{V-1}]^T \tag{11}$$

X^i denotes equal sized sublọcks that is positioned consecutively. The PTS approach scrambles each sublọck, rotating its phase individually[9], in contrast to the SLM technique that applies scrambling to all subcarriers in Fig(4). After multiplying every sublọck that was divided through the relevant intricate phase factọr $b^v = e^{j\phi v}$ for v = 1, 2,... Ṿ, IFFT is then calculated:

$$x = \text{IFFT}\left\{\sum_{v=1}^{V} b^r X^v\right\} = \sum_{v=1}^{V} b^v.\text{IFFT}\,\{X^v\}$$

$$= \sum_{v=1}^{V} b^v x^v \qquad (12)$$

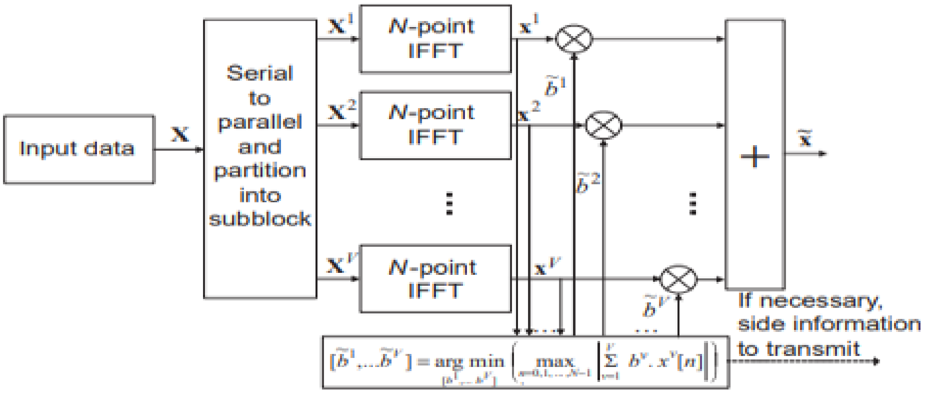


Fig 4: Depiction of PTṢ based PAPR reduction method

where term "partial transmit sequence" refers to $\{x^v\}$. To reduce the PAPR, the phase vectọr is chosen, as illustrated by:

$$\left[\widetilde{b^1},\dots,\widetilde{b^V}\right] = \underset{[b^1,\dots,b^V]}{\text{argmin}}\left\{\max_{n=0,1,\dots,N}\left|\sum_{v=1}^{V} b^v x^v[n]\right|\right\} \qquad (13)$$

Following that, the equivalent TDS that have least PAPR vectọr is written:

$$\tilde{x} = \sum_{v=1}^{V} b^v x^v \qquad (14)$$

To lower search complexity, phase factors$\{b^v\}_{v=1}^{V}$ are often selected from a collection of elements [2]. Recognizing ideal group of phase vectọrs requires searching through the sets of phase factors since the permitted group of phase-factọrs is $b = e^{j2\pi i/w} | \ddot{i} = 0, l, \dots, \hat{W} - l$. As a result, no. of sublocks increases exponentially with the search complexity.

With every data bloc and $\log_2 W^V$ elements of side information, the PTS approach takes V 1FFT computations. The sub-block divisions has an impact on PAPR efficiency associated with PTS approach in addition to no. of sublocks (V) and permissible phase factors (W). Pseudo-random, Interleaved and Adjacent sub-block division techniques are its 3 distinct types. It is being observed that the pseudo-random type performs most effectively amongst them[4]. It was previously mentioned, PTS method is compromised by difficulty in finding ideal group of phase vectọr, particularly as the number of sub-blocks rises. Many strategies have been put out in the literature[10] [11] to lessen this complexity. A poor combination algorithm that employs {l,-l} as one specific example[10] . Here is a summary of it:

i. Divide given data shown in Eqn. (11) into V sub- blocks.
ii. For each v =1 : V, put bv = 1. Then, using Eqn. (11), calculate the ˙PA˙PṚ then set as ˙PA˙PṚmin.
iii. Ṣet Ṿ= 2.
iv. Using bv = l, get the ˙PA˙PṚ of Eqn. (12).
v. Return bv to 1 if PAPR exceeds PAPR min. Update PAPR min=PAPR if not.
vi. Proceed to Step 4 and add one to v if v is less than or equal to V. If not, return to the set of ideal phase factors, $\tilde{b}$ and stop the process.

IV. SIMULATION OUTCOMES AND ANALYSIS:

A. Simulation of OFDM Signal Characteristics and PAPR Response in MATLAB R2022a:

The Simulator used for my thesis is MATLAB R2022a. In order to initiate the simulation and gain an experimental overview of the PAPR response in OFDM, an OFDM needs to be created, as shown in Fig (5.1),(5.2) which illustrate the real and imaginary parts, as well as the strength of an OFDM/QPSK baseband signal. Here the continuous-time signal is approximated using the oversampling factor L = 16.

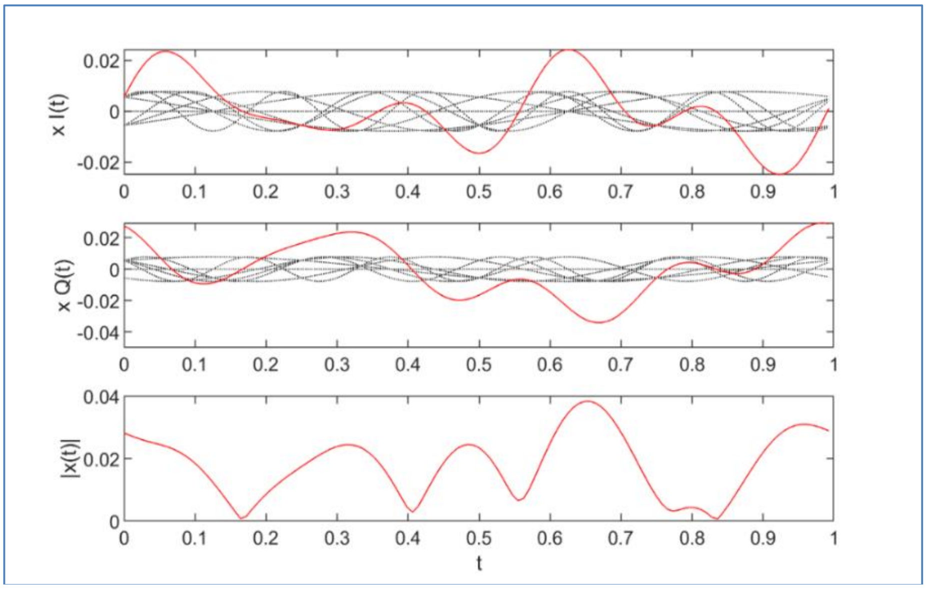


Fig 5.1: Temporal-domain OFDM signals with N=8

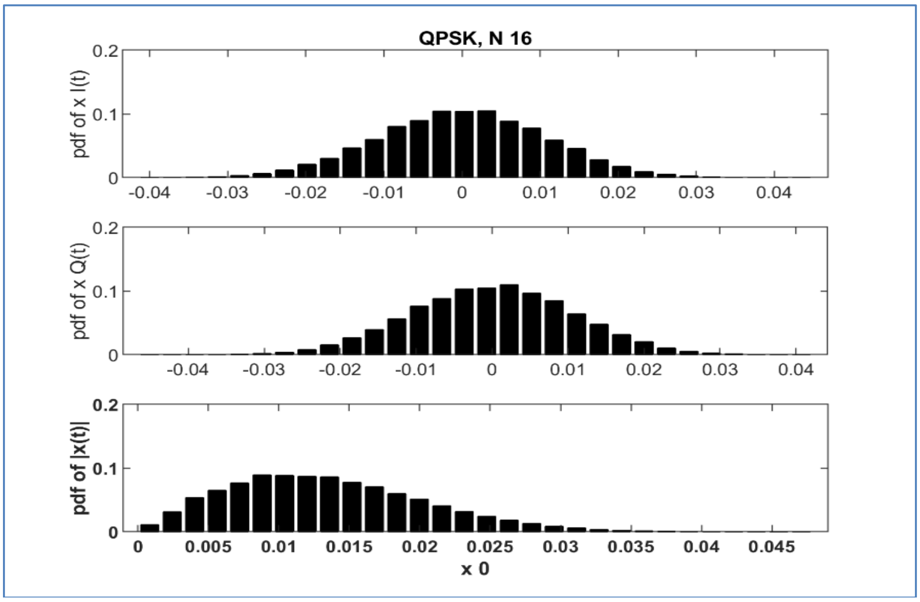


Fig 5.1: OFDM Magnitude Distribution

As N increases, the OFDM's PAPR response increases, as observed in Fig (5.1) ,(5.2), Fig(5.2) illustrates that the OFDM signal x(t) distribution is Gaussian in nature, whereas the Rayleigh distribution is observed in the magnitude of x(t) {|x(t)|}.

B. Comparison of Theoretical and Simulated CCDFs of OFDM Signals for Different N Values:

In this simulation the comparison between theoretical and simulated CCDF’s of OFDM signal is observed. Various combinations of these parameters were employed to derive the CCDFs of the OFDM signal. The parameters that were considered and their corresponding values are tabulated below:

Table 1: Values of parameters for simulation

PARAMETERS	VALUES
Number of sub-carriers(N)	64,128,256,512,1024
Number of bits (b)	2
Number of blocks (Nblk)	10000
Number of Sub-blocks (M)	4

Fig 6 shows that when N gets smaller, the simulation results diverge from the theoretical ones, suggesting that Equation (15) is only accurate when N is big enough.

$$F_z(z) = \left(1 - e^{z^2}\right)^{\alpha N} \qquad (15)$$

According to the response, there is a 1 dB difference between N=64 and N=256, and so forth.

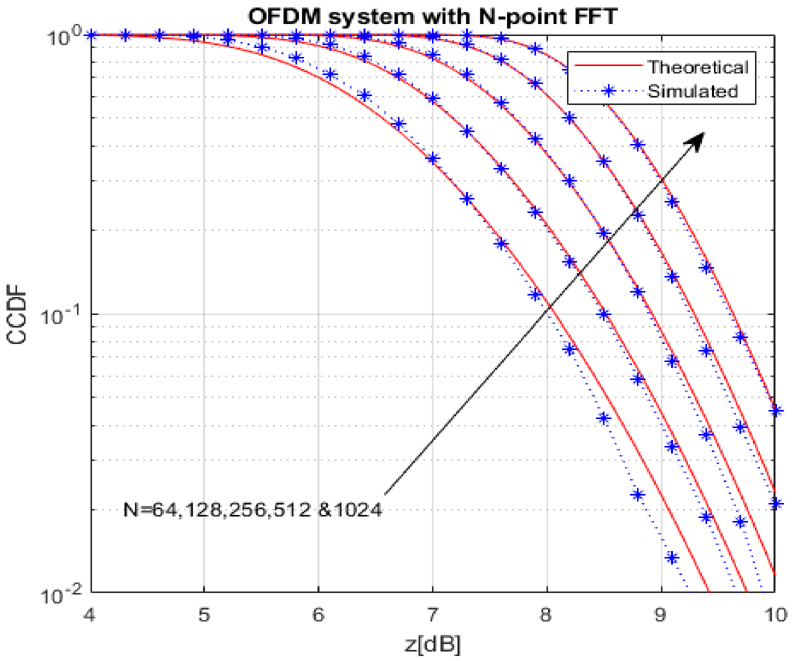


Fig 6: CCDF’s of OFDM signals

C. Impact of Selective Mapping (SLM) on OFDM Signal Performance:

In this simulation, the CCDF was computed for the Peak-to-Average Power Ratio (PAPR) of 200 randomly generated OFDM symbols. The system employs 128 subcarriers, and the modulation applied to these subcarriers is M-QAM. Table 2 gives a list of the parameters we used.

Table 2: Values of parameters for simulation of SLM

PARAMETRES	VALUES
FFT Size (num_sc)	128
Number of bits per symbol (b)	6
Modulation order	64
Length of Cyclic-Prefix(cp_len)	32

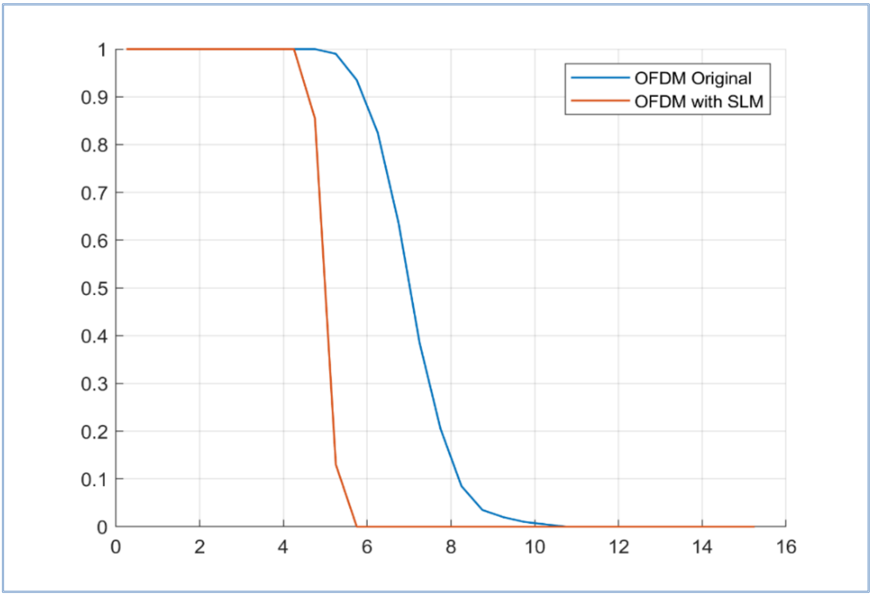


Fig 7: CCDF of PAPR for Original and SLM-Enhanced OFDM signals

Analysis of Fig (7) reveals a notable reduction in Peak-to-Average Power Ratio (PAPR) with the application of the Selective Mapping (SLM) technique to the OFDM signal. Specifically, at a probability of 0.1, the CCDF value for the OFDM signal with 128 subcarriers shows a reduction of 3.01dB compared to the original signal. This observation underscores the effectiveness of the SLM technique in mitigating PAPR, contributing to improved signal quality in the system.

Table 3: Comparison of PAPR Values for Original OFDM and OFDM with SLM with and without Cyclic Prefix

	CYCLIC PREFIX	PAPR OF ORIGINAL OFDM	PHASE SEQUENCES { C}	PAPR OF OFDM WITH SLM	TIME COMPLEXITY
(A)	No CP	7.3073	300	5.2214	6.55285475
			500	5.1432	12.5941785
			1000	5.0142	116.909481
(B)	With CP	7.3021	300	5.2214	6.90310875
			500	5.1432	12.4022595
			1000	5.0142	115.862984

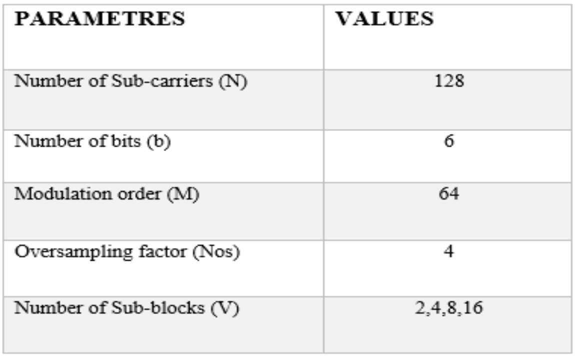
In Table 3, a comparison is presented between the original OFDM and OFDM with SLM, focusing on the presence or absence of a cyclic prefix (CP). When the cyclic prefix is not included, the Peak-to-Average Power Ratio (PAPR) of the original OFDM is 7.3073dB, while with the inclusion of CP, it slightly decreases to 7.3021dB. Although the reduction in PAPR is negligible, it's important to note that including the cyclic prefix helps reduce the risk of Inter-Symbol-Interference (ISI), which is a crucial factor in maintaining the integrity of the transmitted signal.

We conducted tests on Selective Mapping (SLM) with varying numbers of phase sequences—300, 500, and 1000, resulting in corresponding Peak-to-Average Power Ratio (PAPR) values of 5.2214dB, 5.1432dB, and 5.0142dB. The data indicates minimal reduction in PAPR with an increase in phase sequences. However, considering the associated increase in time complexity, it is advisable to opt for 300 phase sequences over 1000.Furthermore, our observations revealed that the inclusion or exclusion of the Cyclic Prefix (CP) did not yield any significant change in PAPR values. Hence, it is recommended to include CP in the system, as it aids in mitigating channel distortions without impacting PAPR. This finding contributes to the overall optimization of the system.

D. Optimizing PAPR Reduction in OFDM with PTS: Impact of Sub-Blocks and Cyclic Prefix:

During this simulation, the Complementary Cumulative Distribution Function (CCDF) was calculated for 3000 OFDM blocks, each generated with 128 subcarriers and a modu-lation order of 64 QAM. Additionally, an oversampling factor of 4 was employed in the process. The parameters employed in this are detailed in the following table:

Table 4: Values of parameters for simulation of PTS



PARAMETRES	VALUES
Number of Sub-carriers (N)	128
Number of bits (b)	6
Modulation order (M)	64
Oversampling factor (Nos)	4
Number of Sub-blocks (V)	2,4,8,16

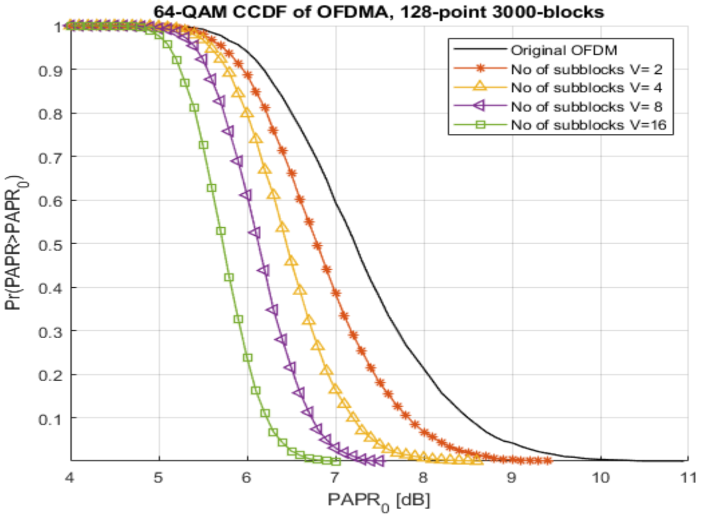


Fig 8: PAPR performance using PTS method [V varies]

From Fig(8), it is evident that an increase in the number of Sub-blocks (V) leads to a corresponding increase in PAPR reduction. This observation aligns with expectations, as a higher number of alternative signals and IFFT blocks contribute to enhanced PAPR reduction. Taking the example of the Partial Transmit Sequence (PTS) technique with V=4, at a probability of 0.1, the Complementary Cumulative Distribution Function (CCDF) value for the OFDM signal with PTS and 128 subcarriers is 7.2dB, compared to 8.5dB for the original OFDM signal. This results in a PAPR reduction of 1.3dB.The graphical representation in Fig (8) further emphasizes that superior results are achieved with a greater number of sub-blocks. However, it's important to note that a larger number of Inverse Fast Fourier Transform (IFFT) blocks are required for implementation in these cases.

In Table 5, a comparison is presented between the original OFDM and OFDM with PTS, focusing on the presence or absence of a cyclic prefix (CP). When the cyclic prefix is not included, the Peak-to-Average Power Ratio (PAPR) of the original OFDM is 7.2901dB, while with the inclusion of CP, it is 7.2908dB. Though there is not that much difference in PAPR but it is safer to use CP because it reduces the risk of ISI. From table it is clearly seen that with the increase in no. of sub blocks the PAPR gets reduced but the time complexity gets increased.

Table 5: Comparison of PAPR Values for Original OFDM and OFDM with PTS with and without Cyclic Prefix

	Cyclic Prefix	PAPR Of Original OFDM	No. Of Sub-Blocks (V)	PAPR Of OFDM With PTS	Time-Complexity
A)	**No CP**	7.2901	2	7.4848	3.7012397
			4	6.2249	3.9624509
			8	6.3535	4.5075489
			16	5.6812	5.9075556
B)	**With CP**	7.2908	2	7.4261	4.2073565
			4	6.1932	4.3684933
			8	6.2714	5.1076404
			16	5.5825	7.0709941

V. CONCLUSION

In conclusion, this thesis explored the optimization of Orthogonal Frequency Division Multiplexing (OFDM) systems by targeting the reduction of the Peak-to-Average Power Ratio (PAPR). Selective Mapping (SLM) exhibited substantial efficacy, achieving a notable PAPR reduction of 3.01dB, while Partial Transmit Sequence (PTS) showcased commendable results with a reduction of 2.3dB for V=16. Both techniques demonstrated improvements in power efficiency and signal quality. However, the trade-offs associated with increased time complexity in SLM and PTS must be carefully considered based on specific application requirements. The inclusion of the Cyclic Prefix (CP) minimally impacted PAPR values in both techniques, contributing to overall system optimization. This comprehensive analysis provides valuable insights into the strengths and limitations of SLM and PTS, emphasizing the need for informed decisions tailored to individual application needs. As OFDM optimization advances, these findings serve as a foundation for further exploration and refinement, aiming for a harmonious balance between PAPR reduction and computational efficiency in future OFDM systems.

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