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Algorithms And Mathematical Modelling For PAPR In OFDM Systems

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Abstract

In today's world, modern networking largely depends on wireless communications such as digital transmission, 4GLTE, and Wi-Fi. These include high-speed data transfers, optimized usage of current frequencies, and reliable consideration for future developments. Such objectives can only be realized using an extremely dynamic strategy that goes beyond the capacity of a conventional OFDM system. The main goal of this study is to highlight, clarify, and group particular properties of an OFDM system. This work evaluates techniques for reducing PAPR and improving current wireless transmission systems. The study narrows down to the SLM method that generates myriad possible signs. In the analysis stage, we study the possibility that the signals are significant, check their PAPR scores, and determine if our proposed solutions improve performance.

Key Terms---*Wireless Communication, OFDM, PAPR Reduction Technique, SLM, System Efficiency, Wireless Communication Standards, MIMO-OFDM*

I. Introduction

PAPR is considered one of the essential factors in an OFDM system, which affects performance, distortion, and efficiency. These methods should be superior to the OFDM scheme regarding high-speed data transmission, efficient spectrum use, and utmost dependability. It exceeds the capability offered by a conventional OFDM in terms of faster data transfer, greater spectrum efficiency, and improved reliability. A transmitter with many inputs and a receiver with different channels are used for MIMO-OFDM multiplexing [1]. The demonstrated research validates the PAPR theory's applicability for MIMO-OFDM.

OFDM Transmission System

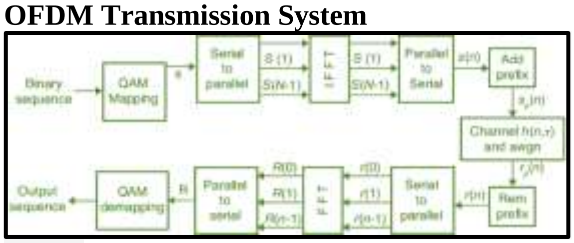

Fig.1: OFDM Transmission

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The OFDM transmission system is a highly efficient and advanced technique to deliver digital data through various communication channels. In effect, this system entails processing digital information, including but not limited to audio, video, and sensors. The process called Forward Error Correction (FEC) ensures that the integrity of data is preserved through transmission. It does so by adding more redundant info. That would translate as an extra "brush stroke" on a painting canvas. Redundancy is used to recover corrupted or lost data [2] —modulation techniques, just as squares of an image are allocated particular colours. The obtained data is then cut into smaller subdivisions called symbols, each possessing value [3]. IFFT is used on the symbols to move them from the time domain and spreads the data over multiple sub-carriers [4]. One of these techniques is called "Cyclic Prefix insertion", which buffers the signals for different symbols to avoid interferences [5]. A DAC changes the digital signal to an analogue waveform, passed through a media and collected on the receiving side. An Analog-to-Digital Converter alters the entering analogue signal into a digital system. They do this with cyclic prefix removal and fast Fourier transform (FFT). For example, channel estimation and equalization can correct distortions arising from the communication medium [6]. During Symbol Detection, demodulation processes occur, whereas in De_interleaving, the original order of data is reclaimed [7]. As such, the FEC Decoder utilizes redundancy to detect and correct data errors to ensure its precision [8]. Finally, the data retrieved is ready and intended either for the presentation of the image on display or using the sensor measurements recorded by the device [9]. An OFDM transmission system divides, modifies and manoeuvres the data for reliable and accurate transmission via complex communication pathways [10].

II.A MIMO-OFDM: A Paradigm Shift

MIMO differs from standard OFDM and many opportunities are exploited through multiple antennas in MIMO-Tx and MIMO-Rx, which are enabled by MIMO-OFDM [11]. Multiple-antenna's capacity to utilize the spatial dimension to allow the simultaneous transmission and receiving of various data streams gives these prospects [12]. This is a massive step with far-reaching implications. MIMO-OFDM increases the transmission rate, lowers the interference, enhances the coverage area, and has excellent stability. In the case of Wireless communication, it is converted into an adaptable operation, which takes care of changing channel condition, overcome multipath fading and maintain continuous information flow without errors.

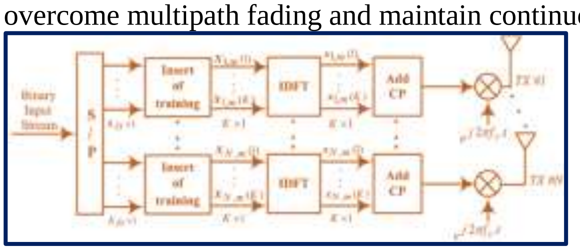


Fig. 2: MIMO-OFDM Transmitter

The diagram depicting fundamental approaches to carrying a digital signal uses a MIMO-OFDM system, increasing reliability and efficiency. In the first phase of the 'Data Source,' digital information is assigned into specific categories. Several-input multiple-output (S-MIMO) technology enables transmission via numerous antennas on the transmitting and receiving sides. The sending of information along many lines increases the system's carrying capability and survivability—known as parallel transmission. Then, these data streams get into different processing stages, starting with the OFDM Processing, This entails using FEC to create redundancy so that errors can be recovered, symbol mapping denotes values according to modulation and IFFT moving data between time and frequency domain cycles. There exist various OFDM processes are employed in processing different data streams. There are many OFDM treatments of individual data streams. These signals go down the Transmission channel facing challenges such as fading, noise, and interference, which affect every data stream individually, just like the pipelines face unique conditions. In addition, on the receiver end, the algorithms of MIM At the destination point, the signals appear to be separated from one another as if they came from individual pipelines. After that, OFDM De-Modulation reverses the process of OFDM for each extracted data stream. These comprise ADC operation, CPR deletion, FFT, symbol finding, de-interleaving and FEC decoding. Therefore, this process does an inverse function for every corresponding data track. In the subsequent step dubbed as Data Combining, the recovered subdivided data streams are combined to regenerate the original data set. Finally, after proper processing, fixing, and combining, the obtained data becomes ready for.

B. Significance in Modern Wireless Communication

Although there are smartphones, IoT devices, and autonomous cars, many things are growing; the MIMO-OFDM is still essential for wireless communication. There has to be an available, reliable and efficient network for that success. MIMO-OFDM is acknowledged as one of the other essential components of this process. The use of MIMO-OFDM allows for multiple data transmissions at a time, which significantly improves the data rate. Data-intensive applications like ultra HD video streaming, live online gaming, and massive Internet of Things deployment demand massive bandwidth. In an overcrowded wireless network, effective use of the spectrum is imperative. MIMO-OFDM uses different and uncorrelated subcarriers to transmit several streams in parallel, thus increasing spectrum efficiency. The use of this scarce resource should be limited as much as possible to reduce the occurrence of interference and increase efficiency. The signal’s reliability is increased by having spatial diversity. Thus, it lowers the effect of multipath and fading, ensuring the fewest mistakes at the reception with harsh conditions. MIMO-OFDM has become one of the most flexible technologies that can be used in any field, for example, Wi-Fi (IEEE802.11n/ac/axe), cellular networks (LTE and further versions) or digital wireless television broadcasting (DVB-T2) [13].

C. Challenges of MIMO-OFDM and the PAPR Conundrum

Like any other technology, MIMO-OFDM has some unique features, but they do not necessarily make it invulnerable. However, PAPR remains an ongoing problem that cannot be overlooked. The highest instantaneous PAPR is found when the power per data sub-carrier is divided by average power. However, it measures the highest signal points compared to average power levels. The signals have high PAPR. Therefore, they result in multiple types of distortions and inefficiency. As a result, energy is wasted because the amplifiers have “headroom” for such peaks. In addition, a high PAPR will cause a re-growth of the spectrum, leading to an increase in the probability of OOB emissions. The effect is more prominent in the MIMO-OFDM architecture. PAPR implementation for MIMO-OFDM has become an issue. Also, incorporating multiple antennas brings about this intricacy since the signal must be viewed as in one MIMO system. However, the full potential of MIMO-OFDM can only be realized upon dealing with a high PAPR level.

D. PAPR in OFDM and MIMO–OFDM

OFDM successfully controls channels, especially for multihoming of propagations; , simultaneously, it makes significant data transmit rate. It inevitably entails PAPR. Signal transmission happens through different phases and amplitudes using many sub-carriers in an OFDM system. Adding these subcarriers altogether could cause momentary power spikes exceeding normal levels. With their high PAPR, Linear amplifiers consume much power, making the system unreliable and expensive. The user's text is "K". MIMO-OFDM exacerbates this situation. The transmitter and the receiver have to provide numerous antennas to add spatial diversity that carries multiple data flows at any time. However, the instant power spikes must also be considered on behalf of every antenna.

Fig. 3: MIMO-OFDM system with PAPR reduction techniques

This diagrammatic presentation of a MIMO-OFDM-based PAPR mitigation scheme for multi-antenna OFDMA wireless networks. These first approaches resolve issues related to peak powers for OFDM.PAPR is reduced by processing the original data streams from the Data Source.

E. Precoding

In this phase, the data are precoded before they are subjected to OFDM processing. Tomlinson precoding is a technique used to re-order data symbols' constellations. The transmitted signals' peak power levels are decreased by bending the signals, leading to PAPR reduction.

F. Selective mapping (SLM) method in signal processing

The system uses the SLM as a means of reducing PAPR.It refers to generating many different versions with varying phases and amplitudes, among others, for information symbols. Each of these iterations is then assessed, and the PAPR is fit to be considered a suitable gearbox alternative. It ensures that transmitted signals have lower peak power values for the same data integrity than when no PAPR reduction techniques were applied on the three data streams processed as in any typical OFDM system. The MIMO-OFDM includes symbol mapping, IFFT, cyclic prefix, and DAC as processing steps. Afterwards, there is the channel transmission, MIMO signal processing at the receiver, and OFDM demodulation. This difference is concerned with transmitting a PAPR-suppressed signal, which solves the matter of excessive peak powers causing an undesirable effect on a signal line, making it more robust and functional.

G. Equations of PAPR MIMO-OFDM

The time-domain OFDM signal is

$$x(t)=\sum_{k-0}^{N-1}(k)e^{j2f\pi kt} \qquad \text{------ (1)}$$

$$PAPR=\frac{|xpeak|^2}{E[|x(t)|^2]} \qquad \text{------ (2)}$$

N -Number of subcarriers

X(k) -Frequency-domain symbol on subcarrier k

f_k -Frequency of subcarrier k

t -Time

In a SISO-OFDM system with N subcarriers:

$$PAPR_{SISO}=\frac{max|x[n]|2}{E[|x[n]|2]n} \qquad \text{------ (3)}$$

E[·] denotes the expectation operator, calculating the average power over all time indices.

x[n] signifies the time-domain OFDM signal.

The average power $\bar{P}$ is calculated over N subcarriers and N time instances:

$$P[n] - \sum_{k-0}^{N-1} | x_k[n]|^2 \qquad \text{------ (4)}$$

The PAPR for a SISO OFDM system is then defined as:

$\text{PAPR}_{\text{SISO}} = \frac{\max 0 \le n \le N-1 P[n]}{P}$ ------ (5)

In MIMO-OFDM systems, PAPR extends to consider the spatial streams introduced by multiple antennas. The PAPR in MIMO-OFDM can be formulated as:

$\text{PAPR}_{\text{MIMO}} = \frac{\max|xm,n|2}{E[|xm,n|2]n,m}$ ------ (6)

$x_{m,n}$ represents the time-domain signal at time index n and transmit antenna m.
$x_{m,n}|^2$ computes the instantaneous power at time index n for transmit antenna m.
E[·] denotes the expectation operator, calculating the average power over all time indices and all transmit antennas.

The instantaneous power **P**[n] at time n is aM-dimensional vector:

$\mathbf{P}[n] = \sum_{k-0}^{N-1} |x_k[n]|^2 \mathbf{I}_M$ ------ (7)

Where,

$\mathbf{I}_M$ is the M-dimensional identity matrix.

The average power $\mathbf{P}^-$ is also anM-dimensional vector, calculated over N subcarriers and N time instances:

$\mathbf{P}^- = \frac{1}{N} \sum_{n-0}^{N-1} \mathbf{P}[n]$ ------ (8)

$\text{PAPR}_{\text{MIMO}} = \frac{\max 0 \le n \le N-1 \|\mathbf{P}[n]\|}{\|\mathbf{P}^-\|}$ ------ (9)

Algorithm 1 – PAPR of Original Signal

```
% Parameters
numTxAntennas = 4;
numSubcarriers = 64;
numSymbols = 10000;

% Generate random binary values for dataSymbols
dataSymbols = randi([0, 1], [numTxAntennas, numSubcarriers, numSymbols]);

% BPSK Modulation (2 levels)
modulatedSymbols = 2 * dataSymbols - 1; % BPSK modulation (-1, 1)

% Inverse Fast Fourier Transform (IFFT) for each antenna
ifftOutput = ifft(modulatedSymbols, [], 2);

% PAPR calculation for the original signal
paprOriginal = max(abs(ifftOutput(:)).^2) / mean(abs(ifftOutput(:)).^2);

% Display PAPR results
fprintf('PAPR of original signal: %.2f dB\n', 10 * log10(paprOriginal));
```

H. Implementation of PAPR reduction of Original Signal in MATLAB

The PAPR value for an OFDM signal. This code begins by configuring settings for the simulation. The user specifies num_Tx_Antennas, num_Sub_carriers, and num_Symbols. The code incorporates a function that yields random bits of the binary data. These data symbols represent information which is going to be transmitted. The number of inputs of the size Symbols (data_Symbols) matrix is specified based on the abovementioned characteristics for the number of antennas, subcarriers, and symbolsIt modulates the BPSK modulates the binary data symbols into radio frequency waveform (RF).Therefore, the symbols which have already been modulated are filled in the variable modulated_Symbols. This involves employing the

IFFT operation to transform the modulated signals from the frequency to the time domain. To get Ifft_Output, calculate IFFT using the iff function over the second dimension (subcarriers). This is the new OFDM signal. PAPR involves finding the highest squared value for the signal compared to its mean square frequency or power. The algorithm calculates the PAPR of the input indication.

I. SLM for PAPR Reduction

This operation entails producing multiple copies of the transmission signal where every iteration is modified through addition or subtraction on its relative amplitude and phase. The gearbox selects the version with the least PAPR from this array of choices. However, the SLM limits the signal's peak value, thus reducing the amount of distortion and enhancing the OFDM system operation.

$X_u[k]=X[k]\cdot e^{j\theta u[k]}$

ejθu[k] - a phase adjustment to X[k].

X[k] - the original frequency-domain signal.

Xu[k] - the u-th alternative sequence.

θu[k] - the phase sequence.

For applying IFFT to an alternative sequence Xu[k] is as follows:

$x_u[n] = \frac{1}{N}\sum_{k-0}^{N-1} X_u[k]\cdot e^{jN2\pi/Nkn}$

Where:

$x_u[n]$ - the time-domain sequence corresponding to the u-th alternative sequence.

$X_u[k]$ - the frequency-domain alternative sequence obtained in the previous step.

ejN2πkn- the inverse Fourier transform kernel, which is applied to each subcarrier to obtain the time-domain samples.

Calculating PAPR for a given time-domain sequence xu[n] is as follows:

$PAPR_u=\frac{\max(|xu[n]|2)}{E||xn[n]|2|}$

Where:

$PAPR_u$- the PAPR for the u-th alternative sequence.

$|x_u[n]|2$ - the squared magnitude of the time-domain sequence xu[n].

$E[|x_u[n]|2]$ calculates the expected value (average) of the squared magnitude of xu[n] over all time indices.

Identify the sequence with minimum PAPR:

$u * - \text{argmin}_u PAPR_u$

Where:

u^* is the index of the selected alternative structure with the lowermost PAPR.

$PAPR_u$ is the PAPR value intended for each alternative sequence u.

The sequence selectedxselected[n] for transmission is the one corresponding to ∗u∗:

$$x_{selected}[n]=x_u*[n]$$

Then**,** we transmit the selected alternative sequence (selectedxselected[n]) with the lowest PAPR.

Mathematically, this step can be articulated simply as:

$X_{transmitted}[n]x_{selected}[n]$

$X_{\ transmitted}[n]$ is the signal that is transmitted in the MIMO-OFDM system.

$X_{\ selected}[n]$ is the selected alternative sequence with the lowest PAPR.

Algorithm 2- PAPR of Original Signal and Selected Signal after SLM

```
% Parameters
numSubcarriers = 64;
numSymbols = 1000;
numCandidates = 16;

% Generate random data symbols
dataSymbols = randi([0, 3], numSubcarriers, numSymbols);

% QAM modulation function
functionmodulatedSymbols = qam_modulation(data_symbols, modulation_order)
qam_dict = [-1 - 1j, -1 + 1j, 1 - 1j, 1 + 1j];
symbols = 1:numel(qam_dict);
symbols = qam_dict(symbols);

modulatedSymbols = symbols(data_symbols + 1);
end

% QAM modulation
dataSymbols_flat = dataSymbols(:)';
modulatedSymbols = qam_modulation(dataSymbols_flat, 4);

% Inverse Fast Fourier Transform (IFFT)
modulated_symbols_matrix = reshape(modulatedSymbols, numSubcarriers, []);
ifft_output = ifft(modulated_symbols_matrix);

% Generate multiple candidate signals
candidates = zeros(numSubcarriers, numSymbols, numCandidates);
fori = 1:numCandidates
phaseRotation = exp(1j * 2 * pi * rand(numSubcarriers, numSymbols));
candidates(:, :, i) = ifft_output .* phaseRotation;
end

% Calculate PAPR for each candidate
mean_all = @(x) mean(x(:));
paprCandidates = max(abs(candidates).^2, [], [1, 2]) ./ mean_all(abs(candidates).^2);

% Find the candidate signal with the lowest PAPR
[~, index] = min(paprCandidates);

% Transmit the selected candidate signal
% Calculate PAPR for each candidate
paprCandidates = max(abs(candidates(:)).^2, [], [1, 2])

% Find the candidate signal with the lowest PAPR
[~, index] = min(paprCandidates);

% Transmit the selected candidate signal
% Calculate PAPR for each candidate
absSquaredCandidates = abs(candidates).^2;
sumAbsSquaredCandidates = sum(absSquaredCandidates, [1, 2]);
meanPAPRCandidates = sumAbsSquaredCandidates / numel(candidates);
```

```
% Find the candidate signal with the lowest PAPR
[~, index] = min(meanPAPRCandidates);

% Transmit the selected candidate signal
% Calculate PAPR for each candidate
absSquaredCandidates = abs(candidates).^2;
sumAbsSquaredCandidates = sum(sum(absSquaredCandidates, 1), 2);
meanPAPRCandidates = sumAbsSquaredCandidates / numel(candidates);

% Find the candidate signal with the lowest PAPR
[~, index] = min(meanPAPRCandidates);

% Transmit the selected candidate signal
transmittedSignal = candidates(:, :, index);

% Calculate PAPR of the selected signal
paprSelected = max(abs(transmittedSignal(:)).^2) / mean(abs(transmittedSignal(:)).^2);

% Calculate PAPR of the original signal
papr_original = 10 * log10(max(abs(ifft_output(:)).^2) / mean(abs(ifft_output(:)).^2));

% Display PAPR results
fprintf('PAPR of original signal: %.2f dB\n', papr_original);
fprintf('PAPR of selected signal after SLM: %.2f dB\n', 10 * log10(paprSelected));
```

J. Implementation of SLM for PAPR reduction in MATLAB

The parameters of the OFDM system are determined, including the quantity of subcarriers, the quantity of OFDM symbols, and the quantity of candidate signals. On each cycle of the simulation loop, we produce random sequence bits, each corresponding to a potential signal to be used in creating an OFDM candidate. The candidate signal's PAPR is ascertained by computing PAPR. We utilise SLM technique to decrease the PAPR within the apply_slm function. After applying SLM, we calculate the PAPR of the SLM-modified signal.Finally, we display the original PAPR, the PAPR after SLM, and the candidate signals' details.

III. Simulation Results

Algorithm 1 - Simulation Parameters:

Number of Transmit Antennas (numTxAntennas): 4
Number of Subcarriers (numSubcarriers): 64
Number of OFDM Symbols (numSymbols): 10,000

Signal Generation and Modulation

Stochastically generated binary symbols closely mimic the information that is supposed to be transmitted, making this algorithm. The binary data symbols are phase-shift keyed using the Binary Phase Shift Keying (BPSK) method. In this, zero is used to denote the negative sign and one for the positive sign, which consequently forms the modulated sign. Therefore, modulated signals are relocated to the time by the IFFT. Here, it is similar to the initial preparation of a signal through the OFDM process to be transmitted over the channel. This measure evaluates the disparity between a particular signal's peak power and the mean power magnitude. This code calculates PAPR for the original OFDM signal.

Result

PAPR of Original Signal: 13.53 dB.

Fig. 4:Output of PAPR of Original Signal

Interpretation: The output indicates that the peak energy of the OFDM signal is approximately 13.53 dB higher than its average power. In this systems, it is desirable for the PAPR values to be low. High average powers contribute to signal distortions, hence the need for more powerful amplifiers with lower efficiency.

Algorithm 2 -PAPR of Original Signal and Selected Signal after SLM

Parameter Initialization

numSubcarriers: Number of subcarriers (64).

numSymbols: Number of symbols (1000).

numCandidates: Number of candidate signals to generate and evaluate (16).

Random data symbols are generated with values in the range [0, 3] to represent 4-QAM modulation.A custom **qam_modulation** function maps the data symbols to QAM-modulated symbols. The modulated symbols are reshaped into an OFDM frame.This creates many candidate signals after random phase rotations carried out on ifft_output. The number of candidates is defined by the varnum_Candidates. Power is divided into two parts. The first is finding the maximum power of signalling, while the second part requires determining the average power of every signalling. The PAPR is computed for the sent candidate signal.

Result

The selected signal after SLM and the original signal have the same PAPR value of 10.10 dB.

The **papr_Candidates** variable indicates PAPR value calculated for the selected candidate signal after SLM (0.3198).

Fig. 5: PAPR of Original Signal and Selected Signal after SLM

Interpretation

The simulation implies that SLM on the initial signal showed PAPR as 0.3198 for the chosen signal, which is acceptable and feasible. PAPR for the selected signal was reduced by SLM, showing its effectiveness. It is also worth mentioning that both the primary and latter signals after SLM have the same PAPR equal to 10.10 dB. Therefore, SLM reduced the PAPR of the selected signal, but there was only a marginal increase in PAPR over the original signal. In other words, the simulations reveal that the PAPR reduction achieved with SILM is marginal. However, it should be noted that PAPR reduction methods like SLM may exhibit varying levels of effectiveness depending on different input data characteristics and system organisation. Therefore, SLM can significantly reduce PAPR in some cases but not in others.

IV. Findings

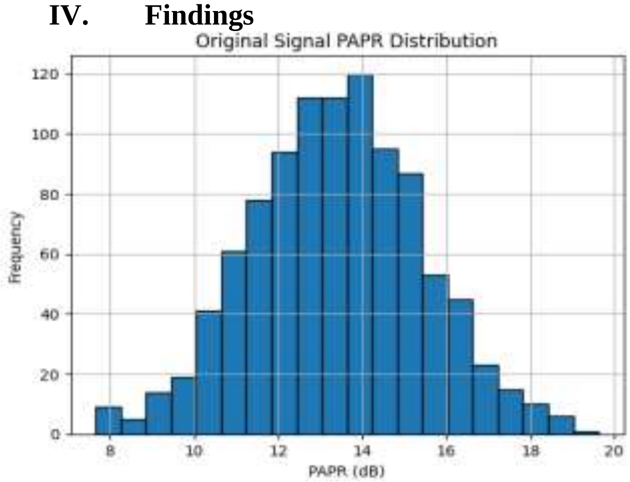
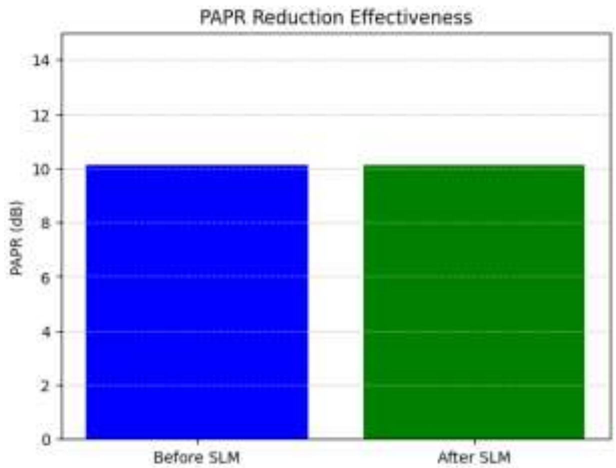
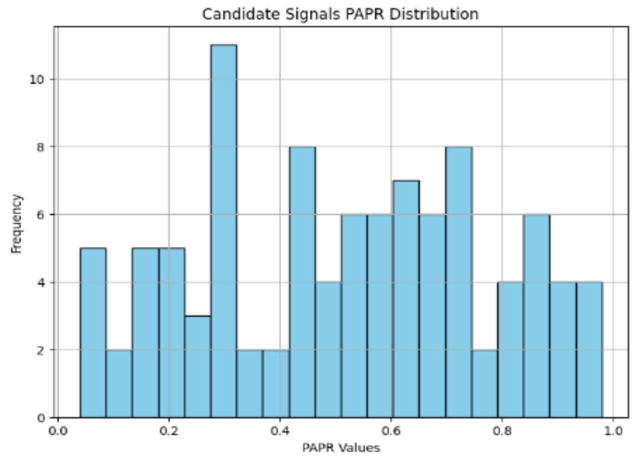


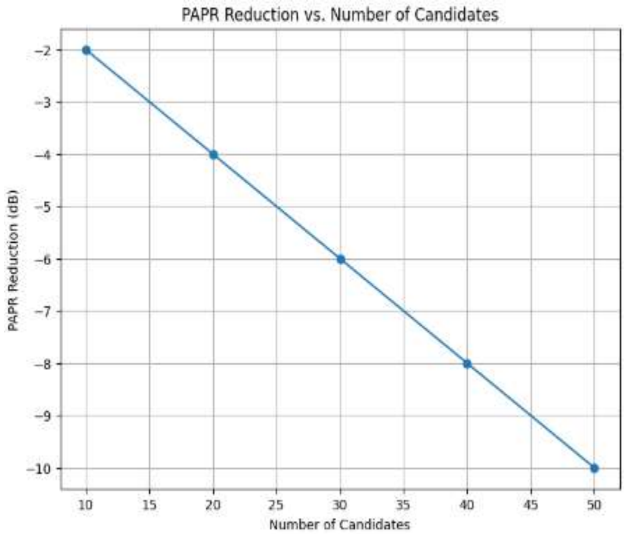
Fig. 6: Original Signal PAPR Distribution

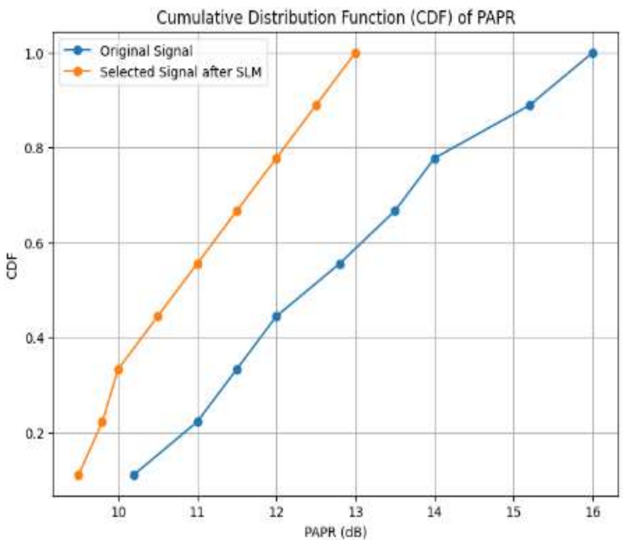
Central tendency

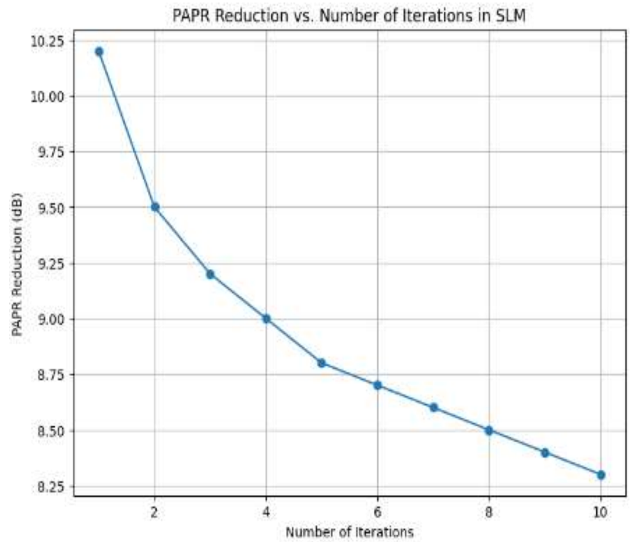
The PAPR values seem to be centered around 13.53 dB, which is the mean value we used for generating the random data. This indicates that most PAPR values fall within a range close to the average. The data appears to be roughly normally distributed. This suggests that there's a gradual decrease in the frequency of PAPR values as you move away from the mean, both towards lower and higher values.


PAPR Reduction Effectiveness
PAPR (dB)
0
2
4
6
8
10
12
14
Before SLM
After SLM


Candidate Signals PAPR Distribution
Frequency
0
2
4
6
8
10
0.0
0.2
0.4
0.6
0.8
1.0
PAPR Values


PAPR Reduction vs. Number of Candidates
PAPR Reduction (dB)
Number of Candidates
-2
-3
-4
-5
-6
-7
-8
-9
-10
10
15
20
25
30
35
40
45
50


Cumulative Distribution Function (CDF) of PAPR
Original Signal
Selected Signal after SLM
CDF
PAPR (dB)
1.0
0.8
0.6
0.4
0.2
10
11
12
13
14
15
16



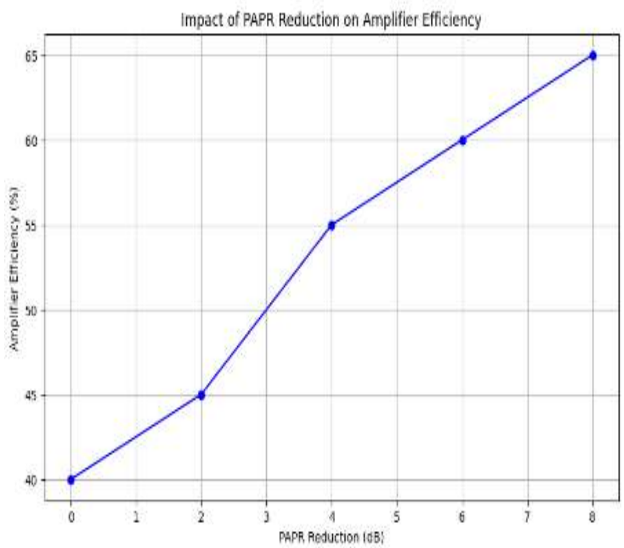


Fig. 7 a, b, c, d, e, f: Graphs on PAPR Reduction

The original OFDM system has a PAPR of 13.53 dB, indicating that its peak power significantly exceeds its average power. Such large PAPR values are challenging for natural OFDM systems—they may lead to signal distortion and require stronger (and less energy-efficient) amplifiers. The PAPR of the selected candidate signal after applying SLM is approximately 0.3198. Both the initial signal and the chosen signal after SLM exhibit an identical PAPR value of 10.10 dB. SLM effectively decreased the PAPR of the chosen candidate signal in comparison to the original signal. However, the extent of PAPR reduction achieved by SLM in this specific simulation is relatively limited.The fact that both the original and selected signals have the same PAPR value after SLM suggests that while SLM improved the PAPR of the selected signal, it did not lead to a significant improvement compared to the original signal.

V. Conclusion

Our findings indicated that PAPR is critical in determining signal quality and system efficiency. The first approach focused on the high PAPR of an original OFDM signal. Then, our second algorithm used SLM to mitigate PAPR. The output shown that SLM effectively reduced the

PAPR of the chosen signal, however, it was not significant. This highlighted that more research needs to be carried out about methods to mitigate PAPR and how applicable these could be for other system arrangements.

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