HYBRID PAPR REDUCTION TECHNIQUES IN OFDM AND MIMO-OFDM SYSTEM FOR DIFFERENT MODULATION SCHEMES

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A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE IN ELECTRICAL, ELECTRONIC AND
COMMUNICATION ENGINEERING

DEPARTMENT OF ELECTRICAL, ELECTRONIC AND
COMMUNICATION ENGINEERING

MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY
MIRPUR CANTONMENT, DHAKA-1216

2021

APPROVAL CERTIFICATE

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DEDICATION

To the Almighty and my family

ACKNOWLEDGEMENTS

First and foremost, all praises to Allah, the most benevolent and the almighty for His blessings throughout my research work for successful completion of the thesis.

I would like to take the opportunity of expressing my sincere gratitude to my thesis supervisor, Professor Dr. Md. Hossam-E-Haider, of the Department of EECE, MIST under whose continuous supervision, guidance, valuable suggestions and encouragement the thesis was carried out. I am greatly indebted to him not only for the time and effort he provided but also for his useful comments, sincere advice and encouragement in all stages of the research work that facilitated completion of the thesis.

Besides, this thesis would not have been completed without the guidance and the help of a few other people. I profoundly thank Lieutenant Colonel Hussain Md. Abu Nyeem, PhD, EME and Maj Md. Aminul Islam, PhD for their valuable suggestions and kind cooperation. I would also like to acknowledge my profound gratitude to Brigadier General A K M Nazrul Islam, PhD, Head of the Department of EECE, MIST for his genuine support during this research work. Moreover, I want to thank all the respected faculty members and staffs of EECE Department, MIST, for their kind support to complete the thesis. I also offer my sincere appreciation for the learning opportunities provided by MIST.

Finally, I would like to extend my sincere thanks to my family for their continuous inspiration and support that encouraged me to complete the thesis successfully.

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08 December, 2021

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ABSTRACT

Orthogonal frequency division multiplexing (OFDM) is the most prominent multi-carrier modulation scheme for existing as well as next generation wireless communication system. To meet the growing need for higher data rate with lower bit error rate, OFDM system has been combined with multiple input multiple output (MIMO) system which employs multiple antennas both at transmitter and receiver. In spite of having wide range of applications and advantages, the major drawback of OFDM system is having high peak to average power ratio (PAPR). For transmitting the signals with high PAPR, highly expensive high power amplifier is required with large dynamic range. Moreover, it may cause nonlinear distortion. This drawback makes the overall OFDM system less effective. Hence reduction of PAPR in OFDM system is a major challenge for designing efficient and cost effective wireless system. To solve the impediment, various PAPR reduction techniques have been proposed which may provide significant PAPR reduction but adversely affect the BER performance. To overcome the limitations of existing techniques, various hybrid PAPR reduction techniques are proposed by combining two existing techniques so that the advantages of both the PAPR reduction techniques can be utilized. This thesis work aims to analyze the performance of the existing PAPR reduction techniques and propose a new hybrid PAPR reduction technique from the combination of the most prominent existing PAPR reduction techniques for both OFDM and MIMO-OFDM system. The contribution of the proposed hybrid PAPR reduction technique is determined by comparing the performance with the existing PAPR reduction techniques. However, it is observed that the proposed hybrid PAPR reduction technique provides almost 88% PAPR reduction in OFDM and 82% PAPR reduction in MIMO-OFDM system, which is much improved than the existing PAPR reduction techniques.

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LIST OF ABBREVIATIONS

ADSL	Asymmetric Digital Subcarrier Line
AM	Amplitude Modulation
ASK	Amplitude Shift Keying
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CCDF	Complementary Cumulative Distribution Function
CDMA	Code Division Multiple Access
CFO	Carrier Frequency Offset
CR	Clipping Ratio
DAB	Digital Audio Broadcasting
DVB	Digital Video Broadcasting
EC	Exponential Companding
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
FM	Frequency Modulation
FSK	Frequency Shift Keying
GSM	Global System for Mobiles
ICI	Inter Carrier Interference
IDFT	Inverse Discrete Fourier Transform
ISI	Inter Symbol Interference
LTE	Long-Term Evolution
MCM	Multi Carrier Modulation
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
PM	Pulse Modulation
PSK	Phase Shift Keying
PTS	Partial Transmit Sequence
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SLM	Selected Mapping
SNR	Signal to Noise Ratio

STBC	Space-Time Block Codes
STO	Symbol Timing Offset
TI	Tone Injection
TR	Tone Rejection
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

LIST OF SYMBOLS

A_c	Amplitude of the sinusoidal signal
$argmin(.)$	Argument Function
$P_{average}$	Average power of the signal
α	Average power of the signal
f_c	Carrier frequency
$s_0(t)$	Carrier signal when information bit 0 was transmitted
$s_1(t)$	Carrier signal when information bit 1 was transmitted
h_{ij}	Channel Impulse Response
$y(t)$	Channel Output
A	Clipping level
$y(x_n)$	Clipped signal
d	Companding degree
$h(.)$	Companding function
c_n	Companded signal
b_m	Complex phase factors
$h^{-1}(.)$	Decompanding function
T	Duration of symbol
$E[.]$	Expected value
Δf	Frequency difference between the subcarriers
$h(t)$	Impulse response of channel
$I(t)$	In-phase component
X_n	Input data block
$x(t)$	Instantaneous value of the transmitted signal
P_{peak}	Maximum power of the signal
P_{noise}	Noise Power
y_n	Noise signal
M	Number of disjoint sub block
N	Number of subcarriers
s_n	OFDM signal
L	Oversampling rate
$\phi_{m,n}$	Phase factor
P_k	Power through the k^{th} antenna

$Q(t)$	Quadrature component
$r(t)$	Received Signal
r_n	Received signal
P_{rms}	Root mean square power level
$R_{m,n}$	Rotation factor
x_d	Sequence having least PAPR
$sgn(x)$	Sign function
P_{signal}	Signal power
σ	Variance of the signal

CHAPTER 1

INTRODUCTION

1.1 Introduction

The increasing requirement for multimedia and high speed internet services at higher data rates has prompted the development of many wireless standards, including IEEE 802.16 for broadband wireless access and IEEE 802.11a/g/n for wireless local area networks (WLAN) [1]. The growing demand for high speed wireless data communication systems has compelled researchers to choose modulation and coding schemes that can overcome the interference and noise generated by the channel, allowing the transmitted signal to be identified without misinterpretation at the receiving end. Moreover, providing multimedia services to undeveloped and rural areas via coaxial cable infrastructure is an expensive and difficult task. The aforesaid constraint can be resolved by using low cost wireless systems with a robust modulation method, which is a reasonable solution. In order to attain data rates greater than 2 Mbps, cable-free systems require physical layer state. Consequently, a robust modulation technique whose performance can be further enhanced by overcoming constraints across multiple channels, can enable effective data transmission between wireless devices and this is a promising area of research.

Orthogonal frequency division multiplexing (OFDM) is a resilient and spectrum efficient modulation technology that has received wide attention due to its inherent quality to ensure orthogonality between subcarriers. In a single carrier system, the available bandwidth is occupied by a single carrier. However, in OFDM, the bandwidth is shared by many orthogonal subcarriers, each of which has a smaller bandwidth than a single carrier system [2]. Moreover, due to the intrinsic ability of the modulation scheme with orthogonal subcarriers to prevent inter symbol interference (ISI), these schemes are successfully adapted for exiting wireless communication system as well as identified as potential for next generation wireless communication system.

The inclusion of multiple input multiple output (MIMO) technology with OFDM system has brought into a revolutionary change in the wireless communication system. The advantages of higher data rate through multiple antennas and improved BER due to application of advanced signal processing algorithms on the received data symbols by multiple antennas can be added to the equalization simplicity of the OFDM system [3].

However, high peak to average power ratio (PAPR) is the major drawback of OFDM system. High PAPR of OFDM signals necessitates the use of costly high power amplifier (HPA) with a large dynamic range, making the overall modulation process inefficient. As a result, reduction of PAPR in OFDM system is of great interest for designing cost effective and computationally efficient wireless systems.

1.2 Literature Review

There has been a considerable number of research works done to study the effects of PAPR on the OFDM and MIMO-OFDM system as the system performance is affected severely due to high PAPR. Various techniques have been proposed by the researchers to reduce the PAPR of OFDM and MIMO-OFDM system. In [11-21], different PAPR reduction techniques for multicarrier transmission such as clipping filtering, coding, selected mapping, partial transmit sequence, tone reservation, tone injection and active constellation extension are described. Many of these auspicious techniques have the capability to reduce PAPR significantly but at the cost of data rate loss, increased transmit signal power, increased BER and so on.

Clipping the high amplitude peaks is the basic PAPR reduction approach used in OFDM. In [22-23], PAPR reduction techniques with repetitive clipping and filtering is presented. However, repeated clipping can cause signal distortion, in band and out of band radiation. To reduce clipping noise and out of band power, a repeated clipping process is proposed in [24] where an oversampled time domain OFDM signal is processed through FFT based frequency domain filtering. However, in order to minimize the signal constellation, this approach distorts the in band signal components.

In [25], a μ-Law companding technique is proposed which reduces PAPR better than clipping but the proposed technique is unable to reduce the spectral regrowth due to the nonlinear operation of power amplifiers. A modified μ-Law companding technique is proposed in [26] to improve the PAPR reduction performance. However, in [27], a new nonlinear companding technique entitled exponential companding is proposed, which adjusts both large and small signals while maintaining a uniform signal amplitude distribution and retaining the average power at the same level.

In [28], selected mapping technique is proposed by rotating the phase of data blocks identical to the original data blocks. The approach can be used with any signal constellation and any number of subcarriers. This approach can reduce PAPR significantly, but it comes at a considerable cost in terms of complexity. Different algorithms to minimize the complexity of the SLM technique are proposed in [29].

In [30], an efficient PAPR reduction technique for OFDM system is proposed with indefinite number of subcarriers and unbounded signal set by optimally merging the partial transmit sequences. The traditional PTS technique requires a comprehensive search over all possible phase factor combinations. But the search complexity increases exponentially with the number of subblocks. In [30], effective PTS algorithms are proposed with significantly reduced search complexity.

Different hybrid strategies are developed from the combination of existing techniques outlined in [34-40] to improve the performance of existing PAPR reduction techniques. The existing techniques are combined to form hybrid techniques so that the advantages of the existing techniques can be utilized. In [43], a novel hybrid approach is proposed that combines clipping and companding technique. Similarly, in [44], PTS and SLM techniques are merged, in [45] SLM and DCT technique is combined and in [46] SLM technique is combined with a modified clipping schemes to create hybrid technique for reducing PAPR.

According to the literature reviewed, the PAPR reduction technique should be specifically chosen based on the various system requirements, as no single PAPR reduction technique is the optimal option for all multicarrier systems. Many of the proposed PAPR reduction techniques may result in significant PAPR reductions but have an adverse impact on BER performance. In this thesis, an efficient hybrid PAPR reduction technique is developed with improved BER performance of the system.

1.3 Research Motivation

With the technological advancement, the requirement for higher data rate and lower bit error rate in wireless communication is increasing day by day. The implementation of MIMO with OFDM is an effective and more attractive technique for high data rate transmission and provides robust reliability in wireless communication. OFDM system provides high spectral efficiency, low inter symbol interference (ISI), less non-linear distortion, high power efficiency, robustness to multipath delay and frequency selective fading. The wide-ranging applications of the OFDM system include 4G and 5G mobile communication, power line devices, wireless local area networks (LAN), wireless personal area networks (PAN), asymmetric digital subcarrier line (ADSL), and digital audio and television broadcasting, etc. In spite of all those advantages and applications, the major drawback of OFDM system is having high peak to average power ratio (PAPR). The output of OFDM system is obtained by superpositioning multiple subcarriers which results in instantaneous power output higher than the average power of the system. For transmitting the signals with high PAPR, highly expensive high power amplifier is required with large dynamic range. Moreover, it may cause nonlinear distortion. This drawback makes the overall OFDM system less effective [11]. Hence reduction of PAPR in OFDM system is of great interest for designing efficient and cost effective wireless system.

To overcome the impediment, various PAPR reduction techniques have been proposed such as clipping and filtering, partial transmit sequence (PTS), selected mapping (SLM), block coding, tone reservation (TR), tone injection (TI) and companding technique etc. However, many of these existing techniques provide significant PAPR reduction but adversely affect the BER performance [12]. Clipping technique limits the PAPR of OFDM signals below a certain threshold level but reduces spectral efficiency and introduce signal distortion. In companding process, the modulating data symbols get distorts from their original constellation. The channel noise is expanded at the receiver resulting in an increases number of errors in the recovered data symbols [13]. SLM and PTS technique may statistically improve the characteristics of PAPR distribution of OFDM signals by avoiding signal distortion but with the cost of increasing computational complexity [13]. To overcome the limitations of existing techniques, various hybrid methods are proposed by combining two existing techniques. In this way, the advantages of both the PAPR reduction techniques can be utilized. The research presented in this thesis, thus, aims to analyze the effectiveness of the existing PAPR reduction techniques and propose a new hybrid PAPR reduction technique with improved performance from the combination of the most prominent existing PAPR reduction techniques.

1.4 Research Objectives

The main objective of this thesis is to develop a new hybrid PAPR reduction method for both OFDM and MIMO-OFDM system, whose performance is improved than the existing PAPR reduction techniques. To achieve this thesis aim, the following objectives are set and followed:

a. To study the existing peak to average power reduction (PAPR) techniques in OFDM and MIMO-OFDM system.

b. To develop new hybrid techniques for PAPR reduction for both OFDM and MIMO-OFDM system.

c. To analyze the performance of the developed techniques and to compare with the existing techniques.

1.5 Research Methodology

A significant number of research papers and thesis books are reviewed with a view to understanding the effect of high peak to average power ratio on OFDM and MIMO-OFDM system. The detailed enquiry of these literature has made the significance of reducing PAPR very apparent for OFDM and MIMO-OFDM system. This gives rise to an ultimate question whether a new method can be developed to reduce the PAPR more efficiently. To properly justify the answer a thorough research has been done on reducing PAPR and the outline of methodology is as follow:

a. The performance of the existing PAPR reduction techniques is studied for different modulation schemes in OFDM and MIMO-OFDM system by using MATLAB.

b. Different values of oversampling factor and number of subcarriers is considered to determine their effect on peak to average power ratio.

c. The bit error rate (BER) vs signal to noise ratio (SNR) plays a significant role in this investigation.

d. Then new hybrid models are developed by combining two existing efficient PAPR reduction techniques.

e. The performance of the developed hybrid techniques is analyzed in terms of CCDF and BER performances.

f. The contribution of the hybrid techniques on PAPR reduction for both OFDM and MIMO-OFDM system is determined by comparing their performances with the existing techniques.

1.6 Thesis Outline

The remainder of this thesis is outlined as below:

Chapter 2 presents the working principle of basic OFDM and MIMO-OFDM system. Relevant topics to these two systems such as modulation schemes, space-time block coding, Alamouti scheme and AWGN channel are also discussed in this chapter. Some important parameters for measuring the performance of the PAPR reduction techniques such as CCDF, BER and SNR are described and the effect of subcarriers and oversampling factors on PAPR is analyzed in this chapter.

Chapter 3 discusses the four popularly used PAPR reduction techniques which are clipping and filtering, exponential companding, SLM and PTS technique. The CCDF and BER performance of these four techniques are analyzed in both OFDM and MIMO-OFDM system with appropriate explanation.

Chapter 4 presents the concepts of hybrid PAPR reduction techniques. In this chapter six hybrid PAPR reduction techniques are developed from the combination of the existing four PAPR reduction techniques. The performance of the hybrid PAPR reduction techniques are analyzed in OFDM and MIMO-OFDM system. Among these six hybrid PAPR reduction techniques, the most prominent technique is identified and proposed. Moreover, the performance improvement of the proposed hybrid method is measured by comparing with the exiting techniques in this chapter.

Chapter 5 presents the conclusion of the thesis with major contributions of the research work and identifies the future scopes to enhance the outcomes of the work.

CHAPTER 2

RELATED TOPOLOGIES

In this chapter a brief description of OFDM and MIMO-OFDM system, effect of high PAPR on OFDM and MIMO-OFDM system, importance of reducing PAPR, description of some relevant parameters and their effect on PAPR are presented.

2.1 OFDM System

Orthogonal frequency division multiplexing (OFDM) system is a multicarrier modulation scheme where the available high rate data stream is divided and transmitted through numerous orthogonal subcarriers [1]. Orthogonal subcarriers mean the spectrum of each carrier has a null at the center frequency of neighboring carriers on either side of it. Due to orthogonality, the subcarriers can overlap with each other without inter symbol interference (ISI) and consume lesser bandwidth. As multiple symbols can be transmitted in parallel without interference, high spectral efficiency can be achieved in OFDM system [2]. The spectrum of orthogonal subcarriers in OFDM system and the spectrum of ordinary FDM system is shown in Figure 2.1.

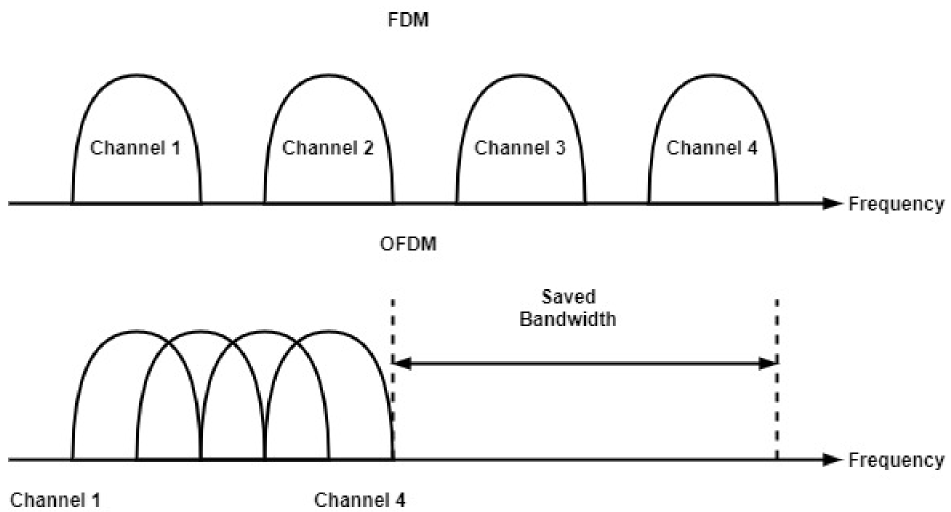

Figure 2.1: Frequency spectrum of FDM and OFDM system

2.1.1 OFDM system model

In OFDM system, the input data of each orthogonal subcarrier is commonly modulated with phase shift keying (PSK) or quadrature amplitude modulation (QAM) and inverse discrete Fourier transform (IDFT) is applied at the transmission side to originate the OFDM signal [2]. The FFT algorithm is used in the receiving end to demodulate the signal. The transmission and receiving process of the OFDM system is illustrated in Figure 2.2.

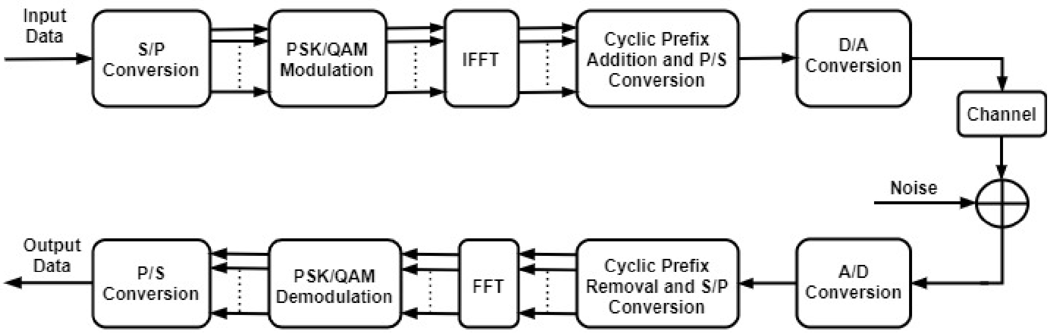

Figure 2.2: Transmission and receiving process of the OFDM technique

If the input data block of an OFDM signal is $X = [X_0, X_1, X_2, \dots, X_{N-1}]^T$, then the continuous time signal $x(t)$ of the input data block can be expressed as in Equation (2.1).

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j2\pi n \Delta f t}; \qquad 0 \leq t \leq T \tag{2.1}$$

Where,

N = Number of subcarriers

T = Duration of symbol

Δf = The frequency difference between the subcarriers

In order to eliminate ISI, the OFDM system inserts a cyclic prefix to the OFDM signal. The prefixing of a symbol with a repetition of the end is known as cyclic prefix. The cyclic prefix samples are usually discarded by the receiver. The time period of an OFDM symbol with a cyclic prefix is longer than the channel's delay spread. It assures that the subcarriers are free of ISI and orthogonal.

2.1.2 Advantages of OFDM system

The advantages of OFDM system include:

a. **Bandwidth Reduction:** In comparison to FDM system, the OFDM system uses less bandwidth. As illustrated in Figure 2.1, multiple distinct carriers are spaced apart without overlapping in the FDM technology, where as in the OFDM system, subcarriers can overlap due to orthogonal properties. The use of bandwidth and guard bands for subcarrier separation is significantly reduced as a result of subcarrier overlapping [2].

b. **Prevention of ISI:** Because of the longer symbol period (due to the lower data rate), the signal is less responsive to channel effects such as multipath dispersion, which causes ISI. It is immune to ISI due to the employment of cyclic prefix between sequential OFDM symbols.

c. **Easy implementation of modulators and demodulators:** The implementation of a group of modulators at the transmission side and demodulators at the receiving side is a challenging task in a multi carrier modulation (MCM) system. Instead of bank of modulators at the transmitter and demodulators at the receiver, the concept of data transportation can be easily accomplished utilizing IFFT and FFT, respectively.

d. **Uncomplicated equalization:** Equalization flattens the frequency channel in a single carrier system, but it severely amplifies noise in the frequency domain where channel responsiveness is limited. As a consequence, the throughput of single carrier system is hindered due to significant attenuation. The wideband channel in an OFDM system is segmented into flat fading sub-channels, which decreases the receiver's equalization complexity. As a result, maximum likelihood decoding can be used with acceptable complexity [2].

e. **Resistant to frequency selective fading:** OFDM system is highly resistant to frequency selective fading due to its parallel transmission capacity.

Due to these advantages, OFDM system is widely employed in high data rate wireless communication systems as well as in many wireless communication standards.

2.1.3 Applications of OFDM system

The wide ranging application of OFDM system includes:

a. 4G and 5G mobile communication

b. Wireless local area networks (WLAN)

c. Wireless personal area networks (WPAN)

d. Asymmetric digital subcarrier line (ADSL)

e. Digital audio broadcasting (DAB)

f. Digital video broadcasting (DVB)

g. Power line devices

2.1.4 Limitations of OFDM system

Despite of several advantages and applications, the OFDM systems also have some major problems like:

a. **High peak to average power ratio (PAPR) of the transmitted signal:** The existence of a large number of subcarriers of varied amplitude in an OFDM system results in a high PAPR of the system with a large dynamic range, which increases amplitude fluctuations and has a negative impact on the efficiency of the system.

b. **Synchronization of time and frequency at the receiver:** The performance of OFDM system is affected by symbol timing offset (STO) and carrier frequency offset (CFO). On the receiver side, proper timing between FFT and IFFT is required. Inter carrier interference (ICI) occurs because the OFDM system is highly sensitive to Doppler shifts, which affect the carrier frequency offset [2].

However, the PAPR problem in the OFDM system is the main focus of this thesis.

2.2 MIMO-OFDM System

Multiple input multiple output (MIMO) is an efficient radio antenna system that employs multiple antennas at the transmitter and receiver to transport data across numerous signal paths. Spatial diversity improves the performance of a MIMO antenna system by providing multiple versions of the same signal to the receiver. The implementation of multiple antennas at both the transmitter and receiver can simultaneously enhance the data transmission throughput and efficiency of spectrum utilization. The combination of MIMO and OFDM techniques is called MIMO-OFDM system which has become one of the most prominent data transmission method for next generation wireless communication system. The MIMO-OFDM system ensures that the benefits of both MIMO and OFDM technology are effectively utilized. The diversity gains and capacity of MIMO system is combined with the equalization simplicity of OFDM system [3]. In this system, the bit stream of an input data is modulated by OFDM technology and then supplied into space-time coding, and finally sent to antennas for transmission. At the receiving end, incoming signals are sent through a signal detector and processed before the original signal is recovered. The block diagram of the basic MIMO-OFDM system is shown in Figure 2.3.

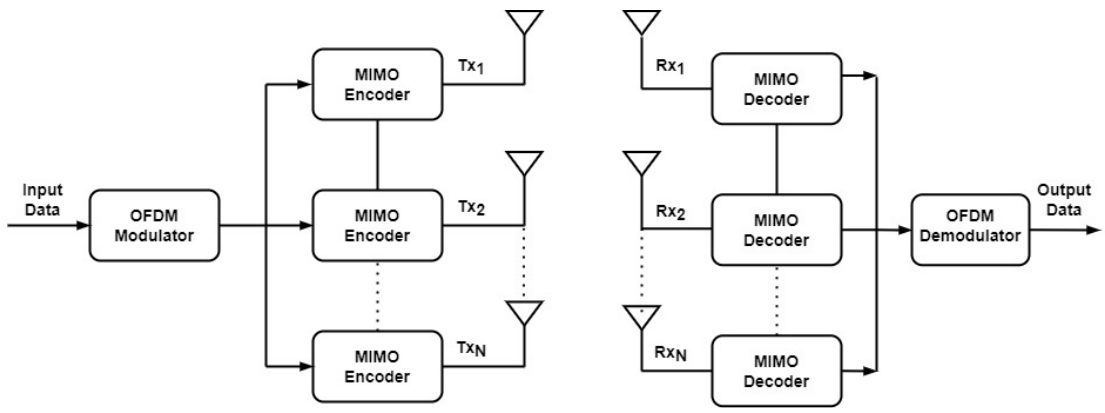

Figure 2.3: Block diagram of the NxN MIMO-OFDM technique

2.2.1 MIMO technology

Digital communication utilizing multiple input multiple output (MIMO) technology has evolved as one of the most important technical accomplishments in modern communications. In recent years, researchers have discovered that employing several antennas at the transmitter can provide many advantages as well as a large amount of performance gain of receive diversity. The development of transmission diversity approaches began in the early 1990s [3]. Since then, there has been a rapid increase of interest in this research topic. Because of the potential increase in data rate and performance of wireless networks afforded by transmit diversity and MIMO technology, we can expect MIMO technology to be a cornerstone of many wireless communication systems.

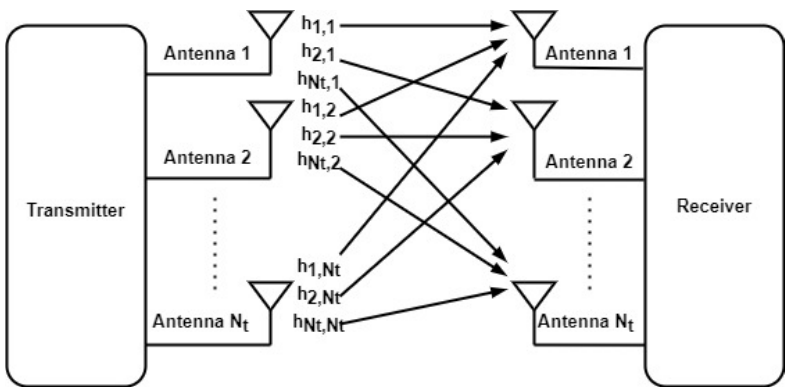

Figure 2.4: Block diagram of multiple input multiple output system

An arbitrary wireless communication system in which both the transmitting and receiving ends are configured with multiple antenna elements is known as a MIMO system. The block diagram is illustrated in Figure 2.4. The principle of MIMO technology is that the signals from the transmit and receive antennas are merged in such a way that the BER of the communication for each MIMO user is improved. Such a benefit can be used to significantly improve both the network's quality and the operator's revenue. The fundamental concept of MIMO system is space–time signal processing in which time is integrated with the spatial dimension involved in the usage of numerous spatially distributed antennas. As a consequence, MIMO systems can be viewed as a development of the smart antennas, a popular technology that uses antenna arrays to improve wireless transmission that has been around for decades. Another essential aspect of MIMO system is that each antenna element operates on the same frequency, alleviating the need for additional bandwidth. In addition, the total power transmitted through all antenna elements is less than or equal to that of a single antenna system [3].

$$\sum_{k=1}^{Z} P_k \leq P \tag{2.2}$$

Where,

Z = Total number of antennas

P_k = Power allocated through the kth antenna

P = The power if the system had a single antenna

Equation (2.2) ensures that a MIMO system consumes no additional power due to having multiple antenna elements.

2.2.2 Space-time block codes

MIMO system employs space-time block codes to facilitate the transmission of multiple copies of a data stream over multiple antennas and utilize the various received versions of the data to increase data transfer reliability. Space-time coding combines all copies of the received signal in the most efficient way to extract maximum possible information from each of them. Space-time block coding takes advantage of both spatial and temporal diversity to achieve considerable gains. This helps in optimizing difficulties like fading and thermal noise on the channel. Although there is redundancy in the data, some copies may arrive at the receiver less corrupted. Prior to transmission, the data stream is encoded in data blocks using space-time block coding and subsequently distributed among the multiple antennas, and the data is also time-spaced. In space-time block code, the data are encoded as a matrix with columns equal to the number of the transmit antennas and rows equal to the number of time slots required to transmit the data. At the receiving end, the received signals are combined before sending to maximum likelihood detector where the decision rules are applied [4].

Under the limitation of having a simple linear decoding algorithm, space-time block codes were created to obtain the largest diversity order for the given number of transmit and receive antennas. As a consequence, space-time block codes have become a very popular and commonly utilized method.

2.2.3 Alamouti scheme

The space-time coding approach is based on the Alamouti scheme [5]. The encoder and decoder of the Alamouti scheme system is shown in Figure 2.5 and Figure 2.6, respectively. Here the information to be transmitted is modulated and supplied in to the space time encoder. As part of the multiple input multiple output technology, the space time encoder has two broadcast antennas. As a result, the data is transmitted through two different antennas. A channel exists for each transmitting and receiving antenna pair, which is represented by separate channel coefficients. The system's architecture is greatly influenced by these channel coefficients. The complexity of the system increases as the number of antennas at both ends of the channel increases.

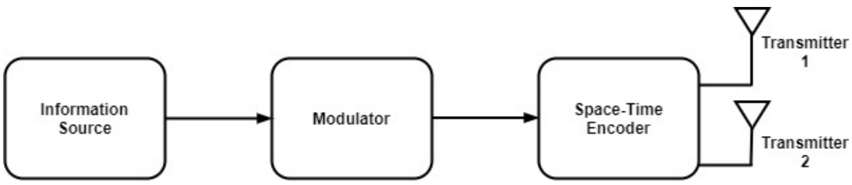

Figure 2.5: Block diagram of Alamouti space-time encoder [5]

The received signal is forwarded to the channel estimator in the decoder. The maximum likelihood detector receives the estimated coefficients of the channel and the combiner as input. The demodulator receives the detected signal and returns the original data that was transmitted.

In this thesis, we consider 2x2 MIMO-OFDM system and the Alamouti code for two transmitters and two receivers is discussed in this section. Consider the following two modulated symbols, x_1 and x_2, which are encoded as indicated in Table 2.1. The received vectors after first time slot and second time slot are shown in Equation (2.3) and (2.4), respectively.

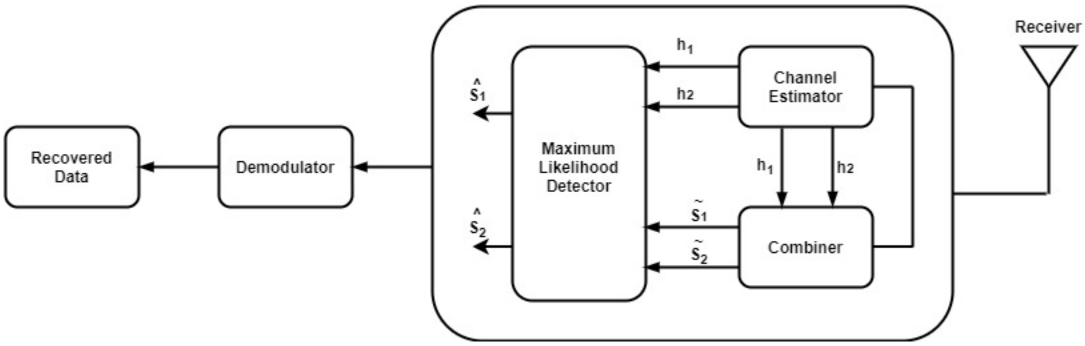

Figure 2.6: Block diagram of Alamouti space-time decoder [5]

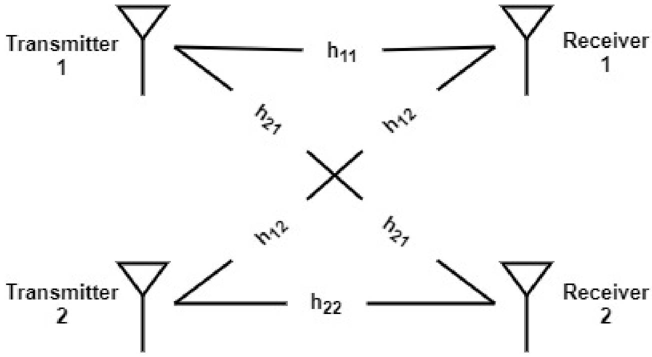

Figure 2.7: Alamouti scheme for 2x2 MIMO system [5]

Table 2.1: Encoded symbols of 2x2 MIMO system for two different time slots

Time	Transmitter 1	Transmitter 2
t	x_1	x_2
t+T	-x_2^*	x_1^*

$$\begin{bmatrix} y_{11} \\ y_{12} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_{11} \\ n_{12} \end{bmatrix} \tag{2.3}$$

$$\begin{bmatrix} y_{21} \\ y_{22} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} -x_2^* \\ x_1^* \end{bmatrix} + \begin{bmatrix} n_{21} \\ n_{22} \end{bmatrix} \tag{2.4}$$

Where, $[y_{11}\ y_{12}]^T$ represents the received vector in the first time slot by antennas 1 and 2 respectively, $[y_{21}\ y_{22}]^T$ represents the received vector in the second time slot by antennas 1 and 2 respectively, h_{ij} denotes the impulse response of channel from

j^{th} transmit antennas to i^{th} receive antenna which remains constant during the two time slots, $[n_{11}\ n_{12}]^T$ denotes the AWGN noise vector during time slot 1 and $[n_{21}\ n_{22}]^T$ denotes the AWGN noise vector during time slot 2. After combining the two equations the following single matrix equation is achieved:

$$\begin{bmatrix} y_{11} \\ y_{12} \\ y_{21}^* \\ y_{22}^* \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{12}^* & -h_{11}^* \\ h_{22}^* & -h_{21}^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_{11} \\ n_{12} \\ n_{21}^* \\ n_{22}^* \end{bmatrix} \tag{2.5}$$

This equation can be simply written as $Y = HX + N$, where H is an orthogonal matrix.

2.3 Modulation Schemes

Modulation is the process of changing the properties of a carrier signal in response to a modulating signal, which usually contains data to be transmitted. The modulator is the device that performs the modulation process at the transmitter end, while the demodulator is the device that recovers the relevant data signal at the receiver end. In wireless communication system, modulation is used to convert the information content of a message signal into a form that is less susceptible to noise and interference. In analog modulation, the modulation is applied continuously in response to the analog information signal and in digital modulation, a discrete signal modulates the analog carrier signal. Analog modulation is classified into three types:

a. Amplitude modulation (AM) is the form of modulation in which the amplitude of the carrier signal is varied in accordance with the instantaneous amplitude of the modulating signal.

b. Frequency modulation (FM) is the modulation process where the frequency of the carrier signal is varied in accordance with the instantaneous amplitude of the modulating signal.

c. Phase modulation (PM) is the modulation technique where the phase shift of the carrier signal is varied in accordance with the instantaneous amplitude of the modulating signal.

The basic digital modulation techniques are:

a. Phase shift keying (PSK) conveys data by modulating the phase of the carrier wave.

b. Frequency shift keying (FSK) transmits data through discrete frequency changes of a carrier signal.

c. Amplitude shift keying (ASK) is a form of amplitude modulation that represents digital data as variations in the amplitude of a carrier wave.

d. Quadrature amplitude modulation (QAM) conveys two digital bit streams by changing the amplitudes of two carrier waves using the ASK digital modulation scheme.

In this thesis, we consider QPSK, BPSK and 16-QAM modulation techniques as signal mapper. These three modulation techniques are described below.

2.3.1 BPSK modulation scheme

Binary phase shift keying (BPSK) is the simplest form of phase shift keying which uses two phases separated by 180°. The constellation diagram of BPSK is shown in Figure 2.8. It makes no difference where the constellation points are positioned. In this diagram, they are depicted on the actual axis, at 0° and 180°. Within a bit duration T_b, the two different phase states of the carrier signal are denoted by $s_0(t)$ and $s_1(t)$ as in Equation (2.6).

$$s_0(t) = A_c cos(2\pi f_c t + \pi); \qquad 0 \leq t \leq T_b \tag{2.6a}$$

$$s_1(t) = A_c cos(2\pi f_c t); \qquad 0 \leq t \leq T_b \tag{2.6b}$$

Where,

A_c = Amplitude of the sinusoidal signal

f_c = Carrier frequency

T_b = Bit period in seconds.

$s_0(t)$ = Carrier signal when information bit 0 was transmitted

$s_1(t)$ = Carrier signal when information bit 1 was transmitted

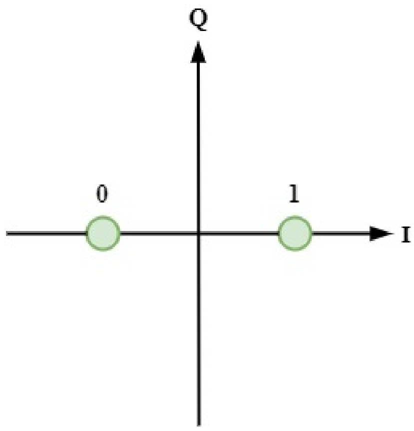

Figure 2.8: Constellation diagram of BPSK modulation scheme

Before the demodulator makes an incorrect decision, BPSK handles the maximum amount of noise or distortion. As a result, it is the most robust modulation technique among all the PSKs [6]. Because of this feature BPSK modulated data can travel longer distances when transmitted from base stations to subscriber stations. As a result, most cellular towers use BPSK modulation for long distance communication or data transmission. However, it can only modulate at 1 bit per symbol, making it unsuitable for higher data rate applications.

2.3.2 QPSK modulation scheme

Quadrature phase shift keying (QPSK) is a type of phase shift keying that modulates two bits at the same time. QPSK allows a signal to convey twice as much data in the same amount of bandwidth as conventional PSK. The QPSK signal within a symbol duration T_{sym} can be defined as in Equation (2.7).

$$s(t) = A_c cos[2\pi f_c t + \theta_n]; \qquad 0 \leq t \leq T_{sym}; \quad n = 1,2,3,4 \tag{2.7}$$

Where the signal phase is given by Equation (2.8).

$$\theta_n = (2n-1)\frac{\pi}{4} \tag{2.8}$$

Therefore, the four possible initial signal phases are $\frac{\pi}{4}$, $\frac{3\pi}{4}$, $\frac{5\pi}{4}$ and $\frac{5\pi}{4}$ radians. The constellation diagram of QPSK is shown in Figure 2.9.

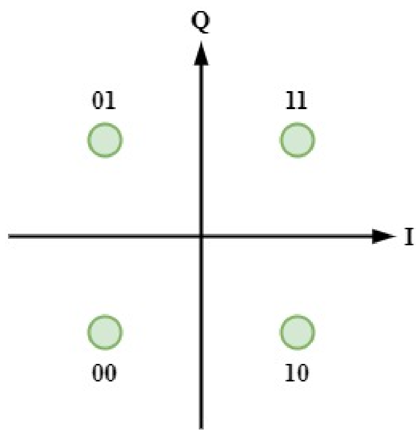

Figure 2.9: Constellation diagram of QPSK modulation scheme

QPSK scheme is used in various cellular wireless standards such as LTE, CDMA, GSM, 802.11 WLAN as well as in mobile WiMAX, satellite and cable TV applications [7].

2.3.3 16-QAM modulation scheme

Using an ASK digital modulation scheme or an AM analog modulation scheme, the Quadrature amplitude modulation (QAM) approach transmits two analog message signals or two digital bit streams by changing the amplitudes of two carrier waves. The two carrier waves of the same frequency are out of phase with each other by 90°. This condition is known as quadrature or orthogonality . The transmitted signal is formed by combining the two carrier waves. At the receiver, the two waves can be simultaneously demodulated due to their orthogonal property. The QAM approach can be classed into 8-QAM, 16-QAM, 32-QAM, 64-QAM, and so on, depending on the intended amount of bits per symbol. Higher order QAM can be accomplished by increasing the bit per symbol, however this comes at the expense of noise margin. In a QAM signal, one carrier lags the other by 90°, and its amplitude modulation is known as in-phase component, denoted by $I(t)$. The other modulating function is the quadrature component, $Q(t)$. If f_c is the carrier frequency, the waveform can be mathematically represented as in Equation (2.9).

$$s(t) = sin(2\pi f_c t)I(t) + sin(2\pi f_c t + \frac{\pi}{2})Q(t) \tag{2.9}$$

In this thesis, we consider 16-QAM modulation scheme where each symbol consists of 4 bits and the constellation diagram is shown in Figure 2.10.

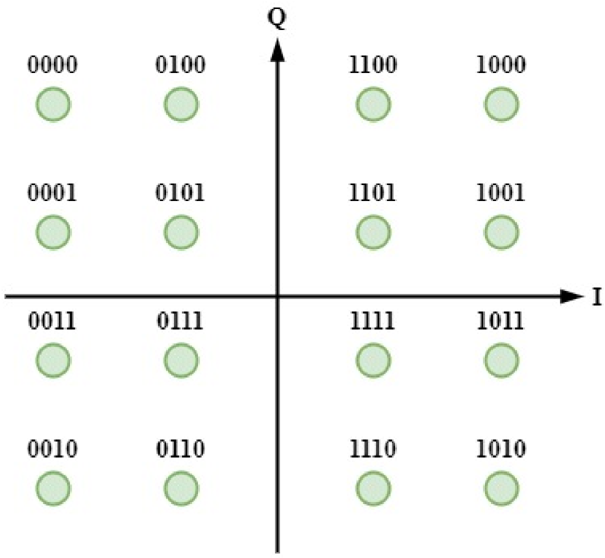

Figure 2.10: Constellation diagram of 16-QAM modulation scheme

QAM modulation scheme is widely used for digital telecommunication systems, such as in 802.11 Wi-Fi standards. By choosing a proper constellation size, QAM can achieve potentially high spectrum efficiency, limited only by the noise level and linearity of the communications channel [7].

2.4 Peak to Average Power Ratio (PAPR)

The output of OFDM is obtained by superpositioning multiple subcarriers which results in instantaneous power output higher than the average power of the system. In the OFDM system, PAPR is determined by the ratio of the maximum power (P_{peak}) to the average power ($P_{average}$) of the signal [11]. PAPR determines the amount of amplitude fluctuations. Mathematically, PAPR can be represented as in Equation (2.10).

$$PAPR(dB) = 10\log_{10}\frac{P_{peak}}{P_{average}} = 10\log_{10}\frac{max[|x_n|^2]}{E[|x_n|^2]} \tag{2.10}$$

Where,

x_n = The transmitted signal

$E[.]$ = The expected value

The PAPR of an MIMO-OFDM system with M transmit antennas and N subcarriers can be represented as in Equation (2.11).

$$PAPR = max(PAPR_1, PAPR_2, PAPR_3, \ldots, PAPR_M) \tag{2.11}$$

In this case, PAPR is actually the maximum PAPR value of all the transmit antennas [8].

2.5 Complementary Cumulative Distribution Function (CCDF)

Complementary cumulative distribution function (CCDF) is the probability that the PAPR of the transmitted signal exceeds a given threshold ($PAPR_0$) [12]. It is the most popular parameter for measuring the performance of the PAPR reduction techniques and can be expressed as in The PAPR of an MIMO-OFDM system with M transmit antennas and N subcarriers can be represented as in Equation (2.12).

$$CCDF = P_r(PAPR > PAPR_0) = 1 - (1 - e^{-PAPR_0})^N \tag{2.12}$$

In MIMO-OFDM system, CCDF is the probability that the PAPR of an OFDM symbol over all M transmit antennas exceed a predefined threshold [11].

$$CCDF = P_r(PAPR > PAPR_0) = 1 - (1 - e^{-PAPR_0})^{MN} \tag{2.13}$$

2.6 Bit Error Rate (BER)

Bit error rate (BER) is a unit less metric that is defined as the ratio of the number of error bits to the total number of transmitted bits over a specified period of time. Signal distortion, communication channel noise, fading effect, attenuation, inter symbol interference and synchronization difficulties are all variables that affect the BER performance of an OFDM system. However, the BER can be expressed as a function of signal to noise ratio (SNR) and can be improved by adopting any one or a combination of the strategies including strong signal strength, robust modulation techniques and channel coding techniques [6].

2.7 Signal to Noise Ratio (SNR)

Signal to noise ratio (SNR) is the ratio of signal power to the noise power which is often expressed in decibels. A signal to noise ratio higher than 1:1 (greater than 0 dB) indicates that there is more signal than noise [7]. It can be represented as in The PAPR of an MIMO-OFDM system with M transmit antennas and N subcarriers can be represented as in Equation (2.14).

$$SNR = \frac{P_{signal}}{P_{noise}} \tag{2.14}$$

Where,

P_{signal} = Average signal power

P_{noise} = Average noise power

Both noise and signal power must be measured within the same system bandwidth and at the same points in a system.

2.8 Additive White Gaussian Noise (AWGN) Channel

The characteristics of a modulated signal is varied when it travels from transmitter to receiver through a radio channel. The change in signal characteristics depends on the distance and different paths travelled by the signal and constants of the communication medium. Hence it is mandatory to model the communication channel based on the characteristics of the transmitted and received signal. In this research, additive white Gaussian noise (AWGN) channel is considered.

AWGN is a linear communication channel which models the linear superposition of white or wide band noise with a constant power spectral density while the amplitude distribution is assumed to be Gaussian [7]. Since the channel model ignores interference, dispersion, fading, frequency selectivity, multipath fading and non-linear effects, AWGN is not suitable for terrestrial links. However, AWGN is a viable model for various satellite and wireless communication links in which OFDM is used for data transmission. Since the noise is well behaved in a AWGN channel, the channel response is represented as shift invariant system and is defined by the convolution integral as in Equation (2.15).

$$y(t) = \int_0^{\infty} h(t-\tau,\tau)x(t-\tau)d\tau \tag{2.15}$$

Where,

$x(t)$ = Channel input

$h(t)$ = Impulse response of channel

$y(t)$ = Channel output

By assuming that the digital information is transmitted within a time interval of $0 \leq t \leq T$, by employing M signal waveforms i.e. $s_m(t)$; $m = 1,2,\ldots,M$. The signal transmitted through the channel is corrupted by addition of white Gaussian noise and the received signal is expressed by Equation (2.16).

$$r(t) = s_m(t) + n(t); \qquad 0 \leq t \leq T \tag{2.16}$$

Where, $n(t)$ denotes a sample function of an AWGN process.

2.9 Effect of Subcarrier on PAPR

In this section the effect of subcarrier on PAPR is analyzed. While, the number of subcarrier is varied from 128 to 1024, the PAPR value in dB has increased from 10.1 to 10.9 at CCDF level of 10^{-2} as shown in Figure 2.11. From this result it is observed that, with the increase of the number of subcarriers, PAPR of the resulting system also increases. The reason for this is that when the number of subcarriers is large and they all are added in some positive or negative phases, the resulting amplitude also becomes large [8]. But, high data rate OFDM system uses high value of subcarriers and to get the high throughput performance, we consider $N = 1024$ for our further investigation.

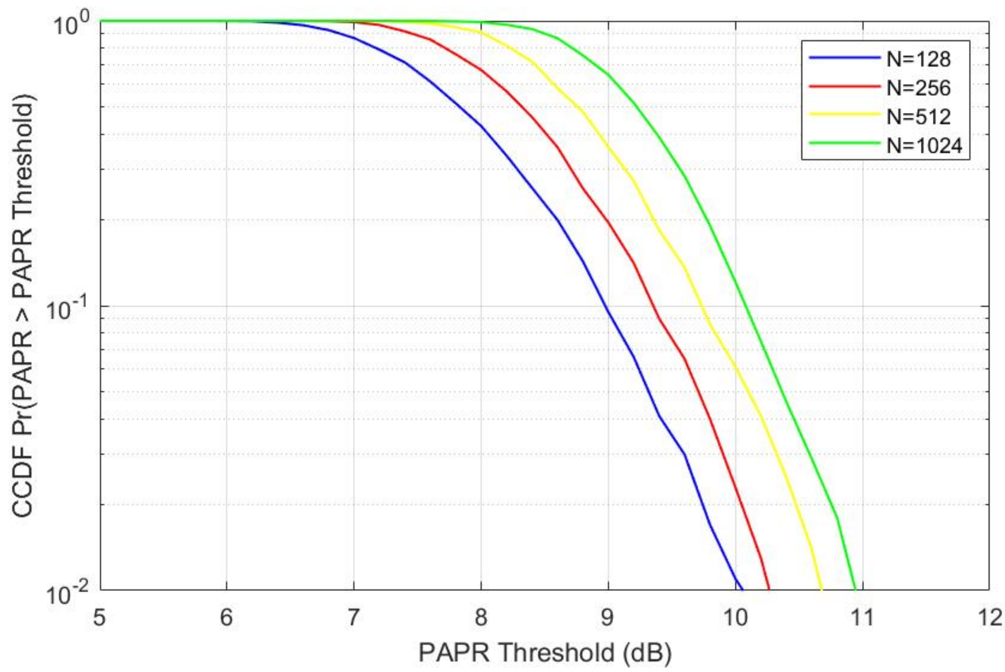

Figure 2.11: Effect of subcarrier on PAPR

2.10 Effect of Oversampling Factor on PAPR

In signal processing, oversampling is the method of sampling a signal at a sampling frequency significantly higher than the Nyquist rate. Theoretically, a bandwidth-limited signal can be perfectly reconstructed if sampled at the Nyquist rate or above it. The Nyquist rate is defined as twice the bandwidth of the signal. But, the continuous time domain OFDM signal when sampled at Nyquist rate is insufficient to represent the signal peaks and out of band radiation cannot be examined in details. So, the signal is oversampled by adding zeros in middle of the signal [12]. For example, if oversampling factor is L and number of subcarriers is N, then $(L-1)N$ zeros will be added between the subcarrier number of $\frac{N}{2}-1$ and $\frac{N}{2}$. Oversampling is capable of improving resolution and signal to noise ratio, and can be helpful in avoiding aliasing and phase distortion.

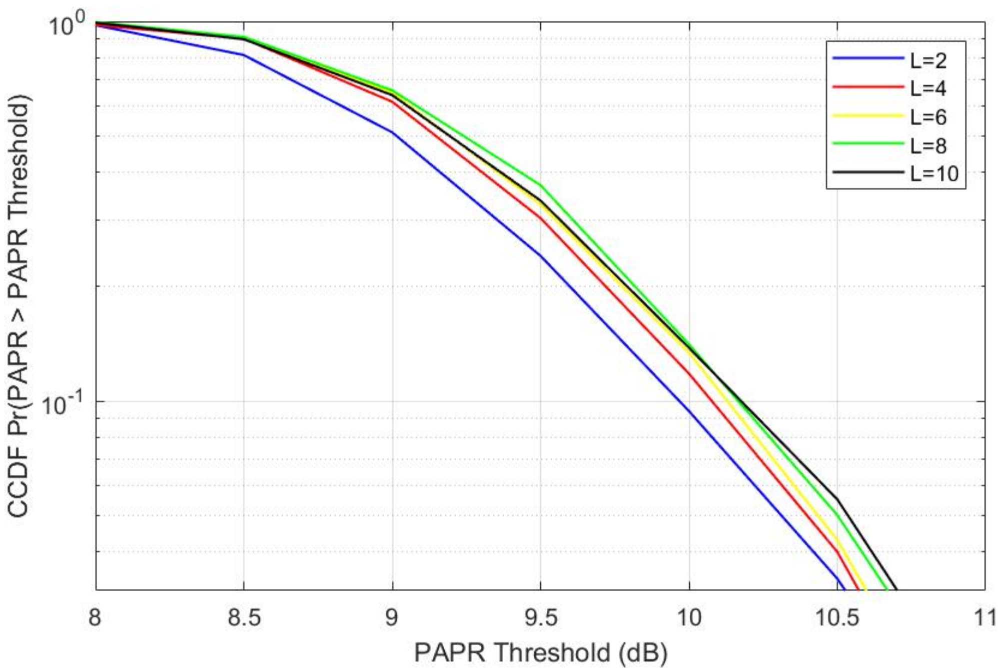

Figure 2.12: Effect of oversampling factor on PAPR

The effect of oversampling factor on PAPR is studied in this section. The oversampling factor is ranged from 2 to 10 and at CCDF level of 10^{-2}, the PAPR value in dB has increased from 10.51 to 10.7, which is shown in Figure 2.12. So, with the increase in oversampling rate, the PAPR value will also increase. However, the effect is found to be minimal, and it is proven that when the oversampling value is 4, accurate PAPR can be obtained [9]. As a consequence, we consider $L = 4$ for our research.

CHAPTER 3

EXISTING PAPR REDUCTION TECHNIQUES

To eliminate the undesired PAPR in the OFDM system, different approaches are suggested by the researchers such as: clipping and filtering, companding technique, selected mapping technique, partial transmit sequence, tone injection, tone reservation, and coding technique. Among these techniques, four popularly used PAPR reduction techniques are described in this chapter from section 3.1 to section 3.4. Moreover, the performance of these prominent PAPR reduction techniques are analyzed in OFDM and MIMO-OFDM system in terms of CCDF and BER to measure their relative effectiveness and efficiency.

3.1 Clipping and Filtering

Clipping is a signal distortion technique. When the amplitude of the input OFDM signal is greater than the predetermined threshold level, the signal peak is clipped to that threshold level. Otherwise, the signal is transmitted without changing its amplitude and phase. The block diagram is shown in Figure 3.1.

Let the frequency domain input data block be expressed as $X_K, K = 1, 2, \ldots, N$. The signal peaks and out of band radiation cannot be accurately determined if the continuous time domain OFDM signal is sampled at Nyquist rate. To capture the signal peaks, oversampling is done by adding zeros in the center of the discrete time signal [21]. At first, the frequency domain signal, X_K, is padded with $(L-1)N$ zeroes between $K = (N/2) - 1$ and $K = N/2$ samples. Then IDFT is performed on the frequency domain signal to achieve the oversampled time domain discrete signal, which can be written as in Equation as in Equation (3.1).

$$x_n = \frac{1}{\sqrt{LN}} \sum_{k=1}^{LN-1} X_K e^{\frac{2\pi Kn}{LN}}; \qquad 0 \leq n \leq (LN-1) \tag{3.1}$$

Where, L denotes oversampling factor. The oversampled signal is then clipped with clipping level A. The clipped signal, $y(x_n)$, is expressed by Equation (3.2).

$$y(x_n) = \begin{cases} x_n, & \text{if } |x_n| \leq A \\ Ae^{j\phi(x_n)}, & \text{if } |x_n| > A \end{cases} \tag{3.2}$$

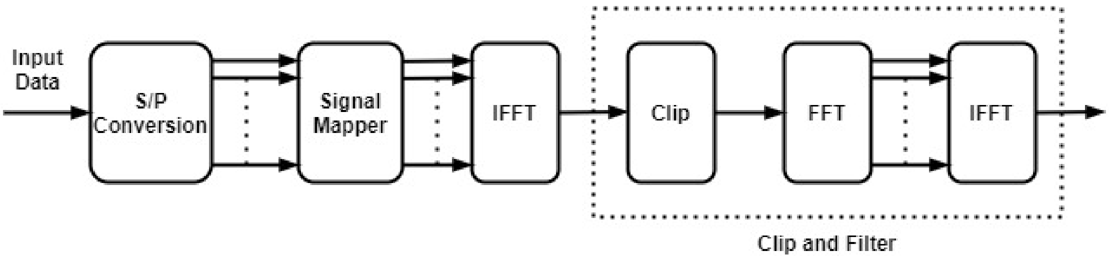

Figure 3.1: Block diagram of clipping and filtering technique [24]

In the amplitude clipping process, the clipping ratio (CR) is an important factor. It is defiend as the ratio of clipping level to the root mean square power level (P_{rms}) of the OFDM signal. After clipping process, the modified PAPR can be determined by Equation (3.3).

$$PAPR = \frac{A^2}{E[|y(x_n)|^2]} \tag{3.3}$$

The OFDM signals become distorted because of amplitude clipping, resulting to in band and out of band radiation. In band radiation degrades error performance, while out of band radiation reduces spectral efficiency [22]. The filter with two FFT operations is involved in the clipping and filtering process. The clipped signal is converted to a discrete frequency domain signal by the first FFT, and the out of band components are removed by the second IFFT. By this filtering process in band components are passed while out of band discrete frequency components are removed [23]. Since the filter operates on symbol to symbol basis, so ISI does not occur although it causes some peak regrowth. For reducing overall peak regrowth, clipping and filtering operation is repeated where several iterations are considered until the signal's amplitude reaches to an acceptable level [24].

3.2 Companding Technique

Companding technique is also an efficient technique for reducing PAPR. In this technique compression of the signals takes place at transmission side and expansion of the signals is done at receiver side to keep the signal level above the noise level and less out of band interference. This companding process is relatable to speech signal processing. The large signals in the OFDM signal occur infrequently, similar to speech signals. So, the same companding technique can be applied to improve the performance of OFDM system [25].

Based on the companding function used, the technique is divided into two categories: linear and non-linear companding. In linear companding process, only the small signals are expanded where as in non-linear companding process the signals with large magnitude are compressed as well as the signals with small magnitude are expanded. In an OFDM system, the non-linear companding method performs better in terms of PAPR reduction, phase error reduction and BER improvement [26-27].

In our research we study about the Exponential Companding (EC) transform which belongs to non-linear companding transform. The technique was proposed by Tao Jiang and Yang Yang [27]. The main concept of the exponential companding technique is to distribute the signals' amplitude uniformly by compressing the large signals and expanding the small signals. As a consequence, the average power increases and PAPR is reduced significantly.

Out of band interference can be eliminated and a consistent average power level can be maintained using the exponential companding transform. This approach can reduce PAPR without increasing system complexity or signal bandwidth for various modulation schemes and subcarrier sizes. The EC transform also results in fewer side lobes in the spectrum. The block diagram of exponential companding technique is shown in Figure 3.2.

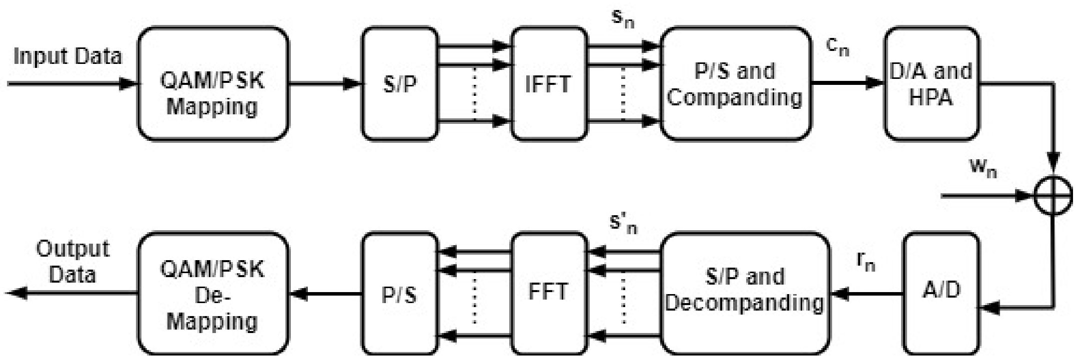

Figure 3.2: Block diagram of exponential companding technique [27]

By using the non-linear companding technique, the OFDM signals s_n are converted into analog waveforms and amplified by high power amplifier [21]. The companded signal c_n can be expressed as in Equation (3.4).

$$c_n = h(s_n) \tag{3.4}$$

Where, $h(.)$ represents the companding function which only modifies the amplitude of input signal. After that, the analog OFDM signals are transmitted through radio channel. In this thesis, we analyze the technique in an Additive White Gaussian Noise (AWGN) channel. If w_n is the noise signal from AWGN channel, the received signals r_n can be expressed as in Equation (3.5). Similarly, in receiver decompanding operation takes place and after decompanding process, s'_n is obtained as in Equation (3.6).

$$r_n = c_n + w_n \tag{3.5a}$$

$$r_n = h(s_n) + w_n \tag{3.5b}$$

$$s'_n = h^{-1}(r_n) \tag{3.6a}$$

$$s'_n = s_n + h^{-1}(w_n) \tag{3.6b}$$

Mathematically, the companded signal $h(x)$ and decompanded signal $h^{-1}(x)$ can be expressed as in Equation (3.7) and (3.8) respectively.

$$h(x) = sgn(x)\sqrt[d]{\alpha[1 - exp(-\frac{x^2}{\sigma^2})]} \tag{3.7}$$

$$h^{-1}(x) = sgn(x)\sqrt{-\sigma^2 log_e(1 - \frac{x^d}{\alpha})} \tag{3.8}$$

Where,

d = Companding degree

$sgn(x)$ = Sign function

α = The average power of the signal

σ = The variance of the signal

When the companding degree $d \geq 2$, the function can simultaneously compress the large signals and expands the small signals. The temporal waveform and power spectrum of the signal for $d > 2$ are similar to $d = 2$. Moreover, while the companding degree is 2 it provides less BER and phase error [27]. So, we consider the PAPR reduction performance of exponential companding transform with $d = 2$.

3.3 Selected Mapping Technique

Selected Mapping is also an efficient technique for reducing PAPR. In this technique, a set of data blocks are generated at the transmission side by modulating the subcarriers with random sequences. The data blocks are independent and the information carried by the data blocks is identical to the original signal. The PAPR of each data block is then calculated, and the signal with the lowest PAPR is sent to the receiving end. The block diagram of SLM Technique is shown in Figure 3.3. This technique can be described as below:

At first, M independent sequences representing the same information as the original data block are generated by modulating N different subcarriers with different random

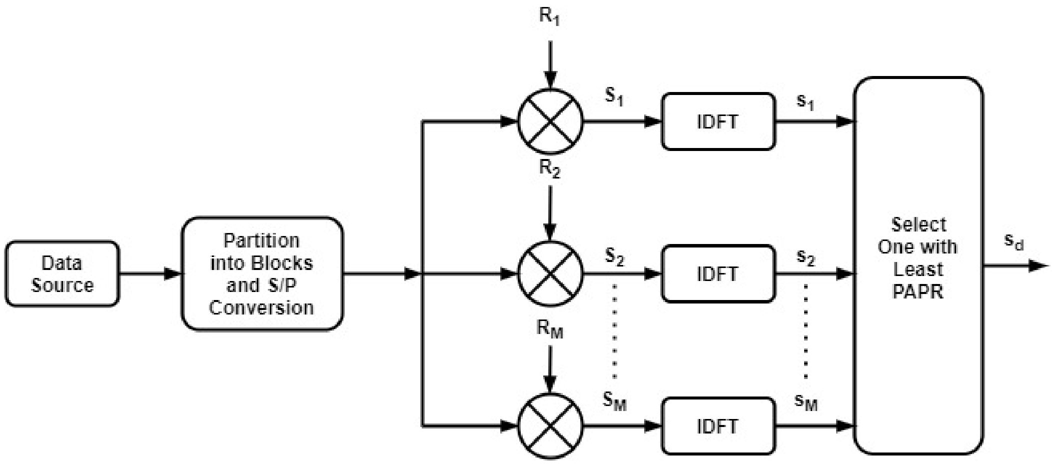

Figure 3.3: Block diagram of selected mapping technique [12]

sequences, which can be expressed as in Equation (3.9).

$$R_{m,n} = [R_{m,0}, R_{m,1}, \ldots, R_{m,N-1}]; \quad m = 1, 2, \ldots, M \tag{3.9}$$

Where, $R_{m,n} = e^{j\phi_{m,n}}$ represents the rotation factor and $\phi_{m,n}$ is uniformly distributed from 0 to 2π. The symbols in branch m can be expressed as in Equation (3.10).

$$S_m = [X_0 R_{m,0}, X_1 R_{m,1}, X_2 R_{m,2}, \ldots, X_{N-1} R_{m,N-1}] \tag{3.10}$$

Then the generated M independent data blocks are forwarded into IDFT operation for transferring these frequency domain OFDM signals to time domain signal and after that PAPR of the sequences are measured individually. Finally, the sequence having the least PAPR, s_d, is transmitted. The mathematical expression can be represented as in Equation (3.11). The $argmin(.)$ ensures that the argument of its value is reduced. However, the receiver must identify the sequence associated with the lowest PAPR among those distinct sequences in order to precisely demodulate the received signal. The transmission of the entire sequence of branch number m to the receiver as side information is an efficient way. But in practical, the route number of the vector sequence is transmitted rather than delivering the entire vector sequence [28].

$$s_d = argmin_{1 \leq m \leq M}[PAPR(s_m)] \tag{3.11}$$

Channel coding is also employed to provide a reliable transmission because side information is critical for signal restoration at the receiver. Any additional side information is not required once the channel coding technique is used throughout the data transmission process. In this way, all possible routes are detected at the receiving end from which the most probable one is chosen as the optimum [29].

SLM technique can be applied to any signal constellation with any number of carriers. At moderately increased complexity, selected mapping yields significant advantages. In fact, it can be used for any multiplexing technology that converts data symbols to a transmit signal [12].

3.4 Partial Transmit Sequence

Partial Transmit Sequence (PTS) technique has been proposed by Muller and Hubber which is effective and flexible for OFDM system [36]. In this technique, the input data frame is segmented into several non-overlapping sub-blocks and the phase of each sub-block is rotated by a constant phase factor. This phase factor selection process is done in an effective way that the PAPR of the combined time domain signal becomes less than the original signal's PAPR. The difference between the SLM and PTS techniques is that the SLM approach applies phase rotation to all subcarriers, whereas the PTS technique applies phase rotation to each sub-block. The block diagram of PTS technique is shown in Figure 3.4.

Consider the following input data block X, which contains N symbols and divided into M disjoint sub-blocks. In each sub-block, there are N/M numbers of non-zero elements while the remainder is set to zero. If the time domain signal is L times oversampled, then it can be achieved by taking IDFT on the frequency domain signal X_M which is chained with $(L-1)N$ zeroes. The time domain signal can be expressed as $x_m = [x_{m,0}, x_{m,1}, \ldots, x_{m,N-1}]; m = 1, 2, \ldots, M$.

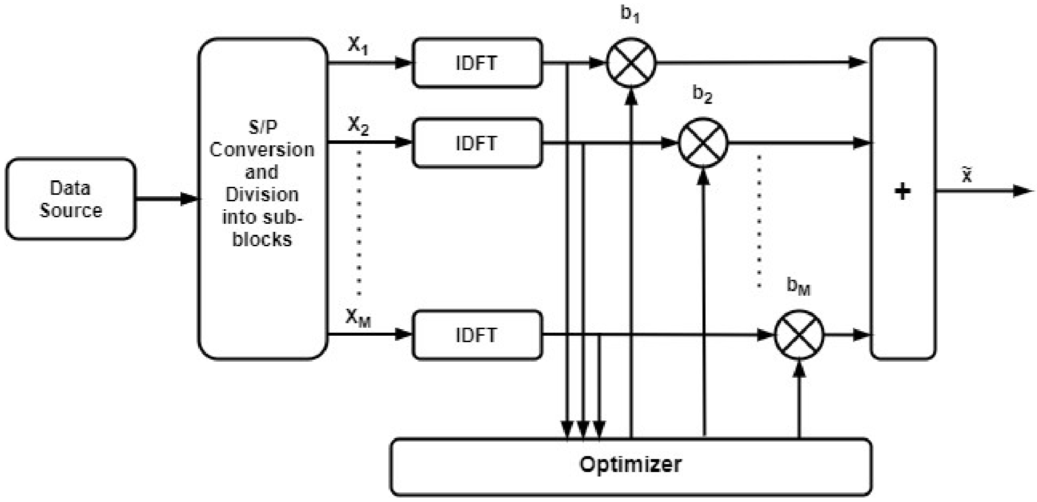

Figure 3.4: Block diagram of partial transmit sequence technique [12]

These partial transmit sequences are combined with complex phase factors, $b_m = e^{j\phi_m}$ where, $\phi_m \in [0, 2\pi]$. After combining, the time domain signal can be expressed as in Equation (3.12).

$$\tilde{x} = \sum_{m=1}^{M} b_m . x_m \tag{3.12}$$

The objective is to determine the set of phase factors for which the combined time domain signal has least PAPR. In practical, the phase factors are selected from a set of finite elements to lessen the complication of exploring the phase factor. To minimize the loss of performance b_1 can be set to 1. So, we have to find out remaining $(M-1)$ phase factors. The amount of PAPR reduction depends on the number of sub-blocks. While PAPR reduces more with the increase of sub-block's number, the search complexity increases exponentially along with the increase of sub-blocks [12, 30]. Several methods for reducing search complexity have been proposed, each of which can achieve significant reduction in search complexity with marginal PAPR performance degradation [31].

To recover the original data block, the side information must be sent to the receiver. These side information bits can be sent through a different channel than the data channel. However, including side information with a data channel is possible, but this would result in data rate degradation.

The sub-block partitioning has an impact on the PAPR performance of PTS approach. Sub-block partitioning techniques can be classified into three types: pseudo-random, adjacent, and interleaved. Among these, the pseudo-random is recognized as the best sub-block partitioning technique because of its performance [12].

3.5 CCDF Performance of the Existing PAPR Reduction Techniques for Different Modulation Technique

In this section, the CCDF performance of the exiting PAPR reduction techniques are analyzed in QPSK, BPSK and 16-QAM modulation schemes for both OFDM and MIMO-OFDM System. The aim is to determine the effect of modulation scheme on the PAPR reduction technique, make a comparison among the techniques and find out the most efficient technique. The system is designed using MATLAB and the simulation results shown in Figure 3.5 to Figure 3.10 are obtained by using the system parameters given in Table 3.1.

Table 3.1: Simulation parameter

Parameter Description	
Number of subcarriers, N	1024
Oversampling rate, L	4
Number of symbols	1000
Modulation	QPSK, BPSK, 16-QAM
Channel	AWGN
Clipping level, A	3 dB
No of disjoint sub block, M	4
Companding level, d	2
Number of Transmitter and Receiver for MIMO-OFDM System	2

In Figure 3.5 to Figure 3.7, the CCDF performance of the existing PAPR reduction techniques are analyzed in OFDM system considering QPSK, BPSK, and 16-QAM modulation scheme respectively. The PAPR values in dB are shown in X-axis cor-

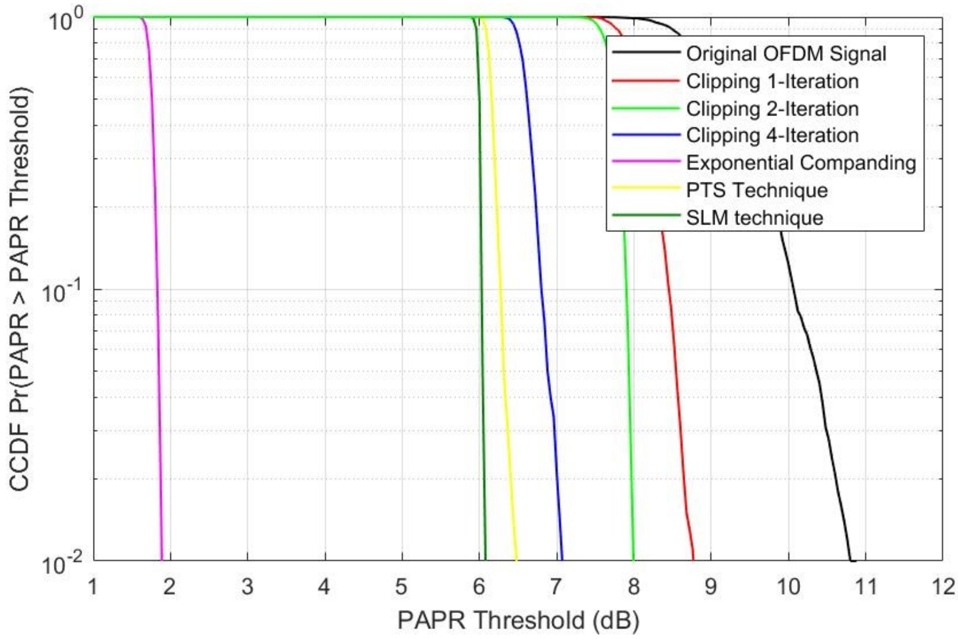

Figure 3.5: CCDF performance of the existing PAPR reduction techniques using QPSK modulation for OFDM system

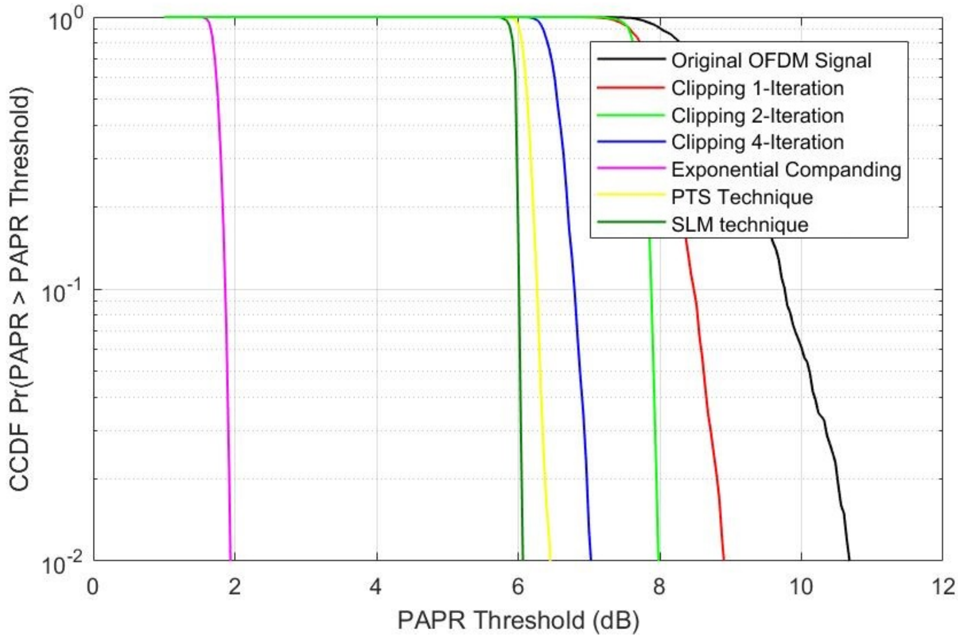

Figure 3.6: CCDF performance of the existing PAPR reduction techniques using BPSK modulation for OFDM system

responding to the different levels of CCDF presented in Y-axis. It is observed that, for any particular CCDF level, exponential companding technique provides the lowest

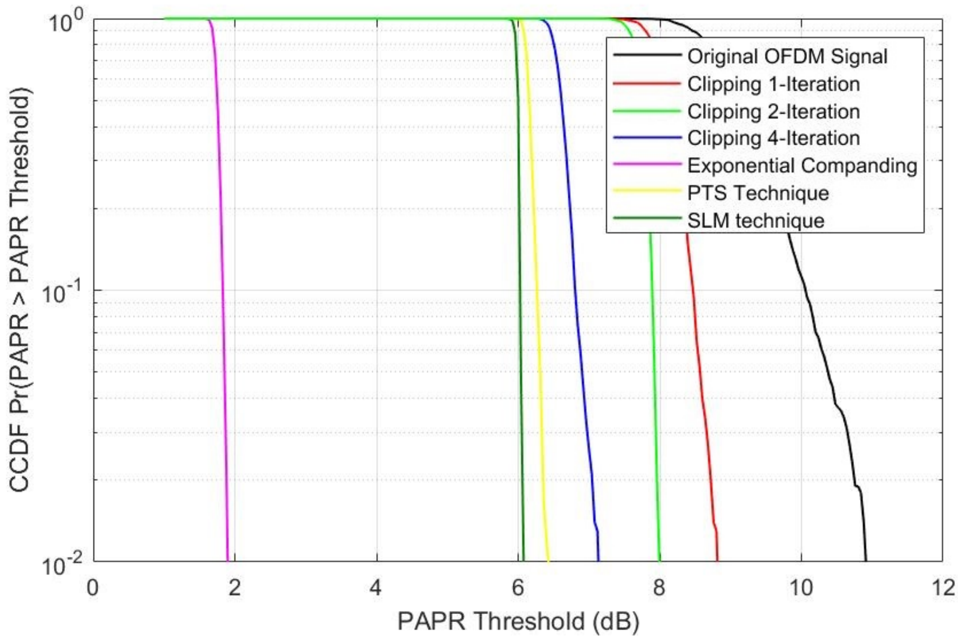

Figure 3.7: CCDF performances of the existing PAPR reduction techniques using 16-QAM modulation for OFDM system

Table 3.2: CCDF comparative analysis for existing PAPR reduction techniques in OFDM system

Method	PAPR (dB) for QPSK Modulation	PAPR (dB) for BPSK Modulation	PAPR (dB) for 16-QAM Modulation
Original OFDM Signal	10.8	10.74	10.88
Clipping 1- Iteration	8.76	8.88	8.8
Clipping 2- Iteration	7.96	7.96	7.92
Clipping 4- Iteration	7.28	7.2	7.36
Exponential Companding	1.88	1.9	1.88
PTS Technique	7	6.88	7.04
SLM Technique	6.2	6.2	6.36

PAPR value than the other PAPR reduction techniques. In Table 3.2, the PAPR values in dB at CCDF level of 10^{-2} are shown, which are achieved after applying the existing PAPR reduction techniques. Simulation results reveal that, the PAPR of the signal in OFDM system after applying exponential companding technique is 1.88, 1.9 and 1.88 dB for QPSK, BPSK, and 16-QAM modulation schemes respectively, which

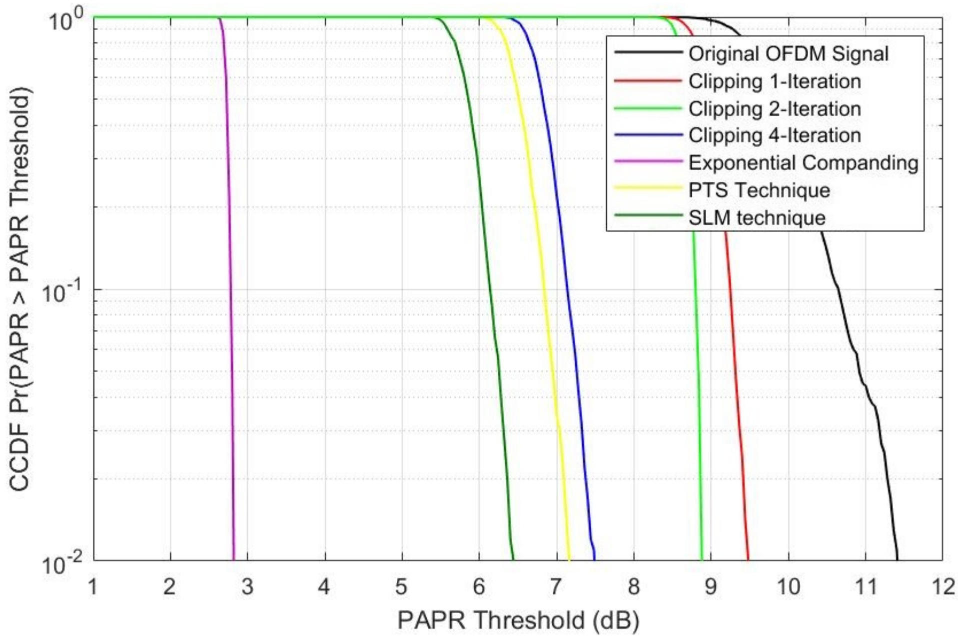

Figure 3.8: CCDF performance of the existing PAPR reduction techniques using QPSK modulation for MIMO-OFDM system

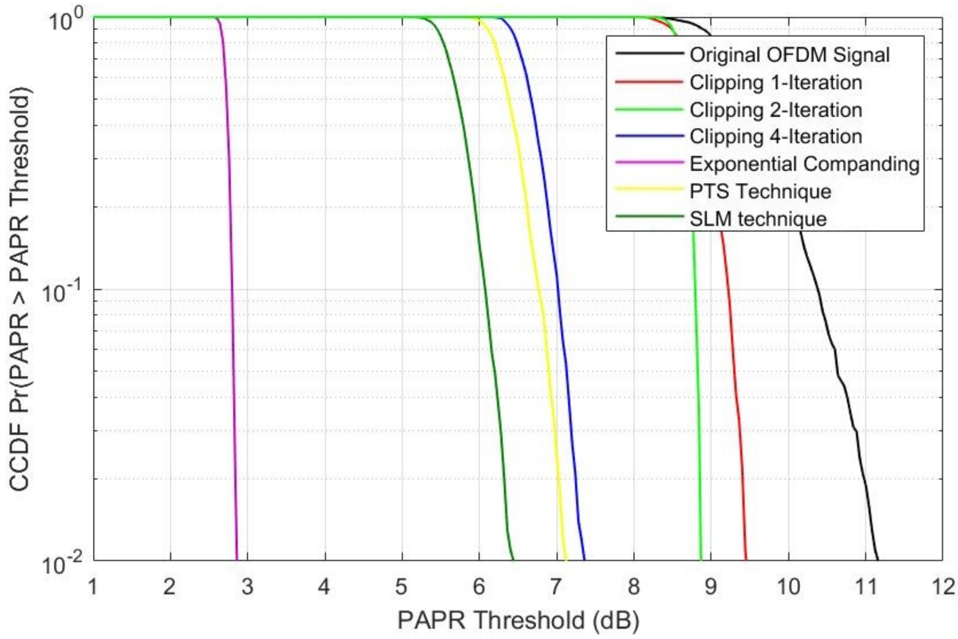

Figure 3.9: CCDF performance of the existing PAPR reduction techniques using BPSK modulation for MIMO-OFDM system

is the highest PAPR reduction among the four prominent PAPR reduction techniques considered in this research. Similar analysis is done for 2x2 MIMO-OFDM system

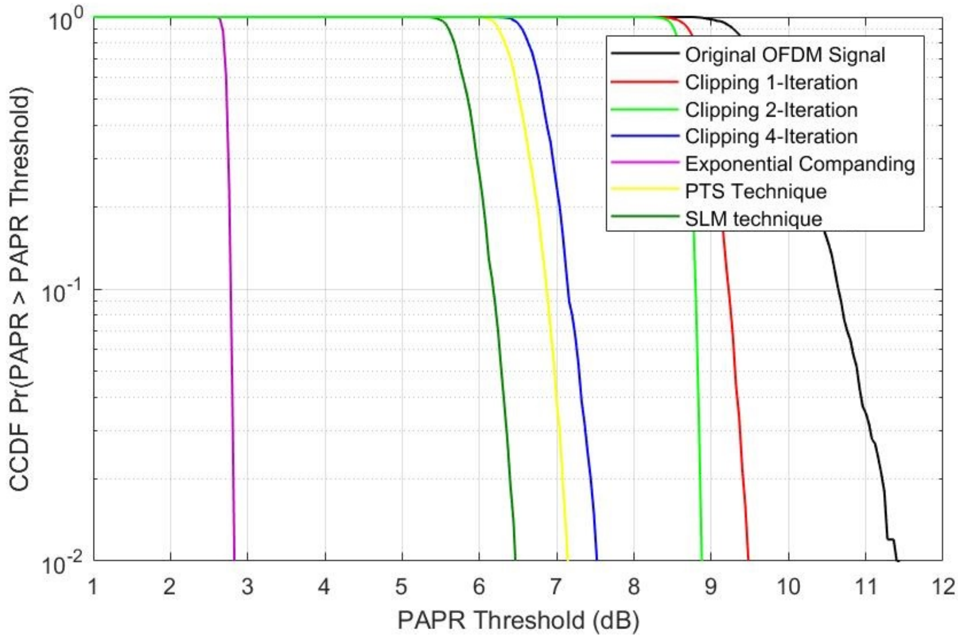

Figure 3.10: CCDF performance of the existing PAPR reduction techniques using 16-QAM modulation for MIMO-OFDM system

Table 3.3: CCDF comparative analysis for existing PAPR reduction techniques in 2x2 MIMO-OFDM system

Method	PAPR (dB) For QPSK Modulation	PAPR (dB) For BPSK Modulation	PAPR (dB) for 16 -QAM Modulation
Original OFDM Signal	11.36	11.12	11.4
Clipping 1- Iteration	9.48	9.44	9.48
Clipping 2- Iteration	8.84	8.84	8.84
Clipping 4- Iteration	7.44	7.36	7.48
Exponential Companding	2.84	2.8	2.8
PTS Technique	7.16	7.08	7.12
SLM Technique	6.4	6.4	6.44

and the results are shown in Figure 3.8 to Figure 3.10. The PAPR values after applying the PAPR reduction techniques at CCDF level of 10^{-2} are shown in Table 3.3. From simulation results it is observed that, the lowest PAPR value 2.84, 2.8, 2.88 dB for QPSK, BPSK, and 16-QAM modulation schemes respectively are also achieved after applying exponential companding technique in 2x2 MIMO-OFDM system.

So, simulation results reveal that for all the modulation techniques exponential companding technique provides almost 9 dB PAPR reduction from the original signal. This is the highest reduction among all the PAPR reduction techniques. Also the result depicts that there is negligible change in CCDF performance even if we change the modulation scheme as the amplitude of the signal remains same even after applying modulation technique [10]. These observations are valid for both OFDM and MIMO-OFDM system. As the effect of modulation scheme is negligible on the PAPR reduction techniques, we conduct the further research considering QPSK modulation.

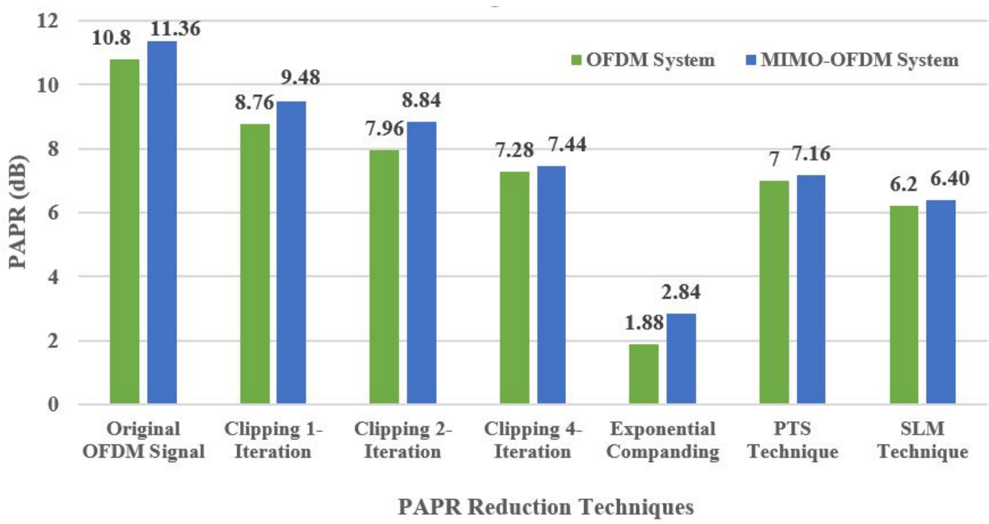

Figure 3.11: CCDF performance comparison of the existing PAPR reduction techniques between OFDM and MIMO-OFDM system

However, it is also observed that the values of PAPR in dB are less in OFDM system when compared with the values of PAPR in 2x2 MIMO-OFDM system for the same type of parameter. The comparison of the PAPR value for existing PAPR reduction techniques between OFDM and MIMO-OFDM system is shown in Figure 3.11 considering QPSK modulation at CCDF level 10^{-2}. In MIMO-OFDM system, multiple number of transmit antennas are employed and the system combines all the symbol subcarriers from all of the antennas, increasing the probability of large signal amplitude [8]. As a consequence, the CCDF performance remains better when the number of transmit antennas is less.

3.6 BER Performance of the Existing PAPR Reduction Techniques

In this section, the BER performance of the existing PAPR reduction techniques are analyzed in OFDM and MIMO-OFDM system considering QPSK modulation technique. The other simulation parameters as same as Table 3.1 and the simulation results are shown in Figure 3.11 to Figure 3.12. For comparison the values of BER at SNR level of 6 dB are shown in Table 3.3 after applying the PAPR reduction techniques in OFDM and MIMO-OFDM system.

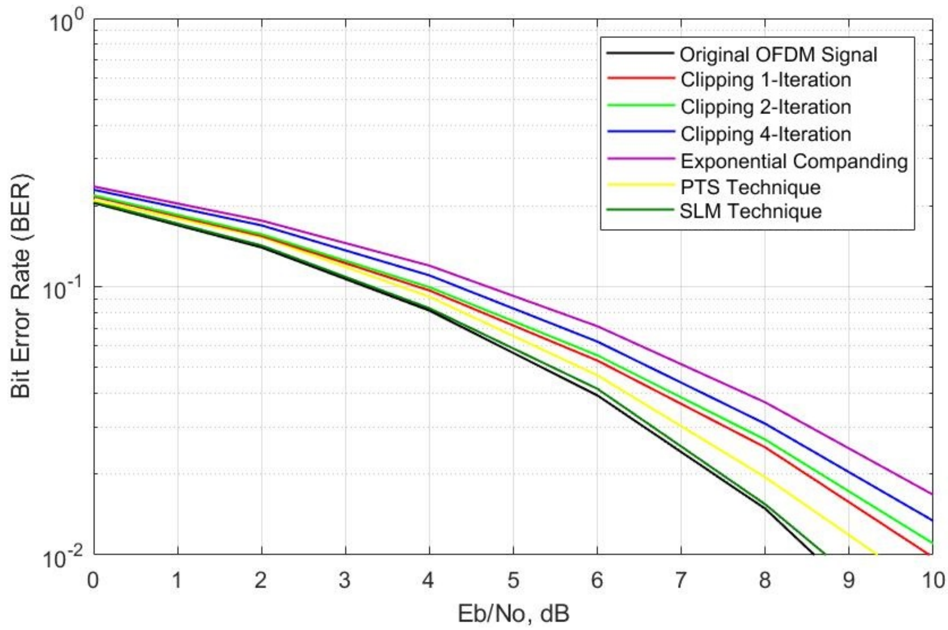

Figure 3.12: BER performance of the existing PAPR reduction techniques for OFDM system

Table 3.4: BER performance of the existing PAPR reduction techniques at SNR = 6dB

Method	OFDM System	MIMO-OFDM System
Original OFDM Signal	0.039	0.036
Clipping 1- Iteration	0.053	0.050
Clipping 2- Iteration	0.055	0.052
Clipping 4- Iteration	0.062	0.053
Exponential Companding	0.071	0.067
PTS Technique	0.047	0.043
SLM Technique	0.042	0.037

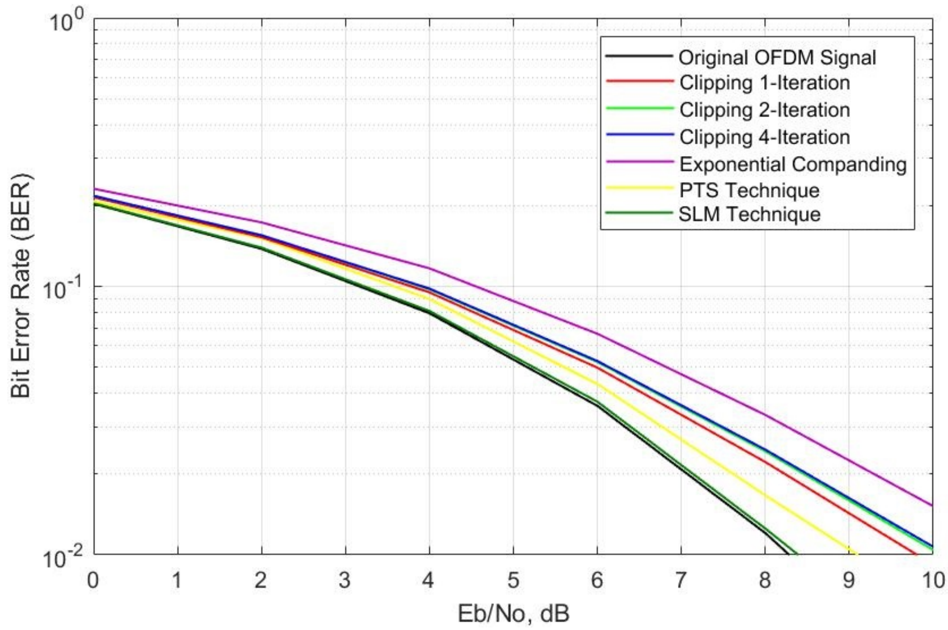

Figure 3.13: BER performance of the existing PAPR reduction techniques for MIMO-OFDM system

From simulation results it is observed that, for OFDM system the BER is 0.071 after applying exponential compandaing which is highest BER among all the PAPR reduction techniques. On the other hand, the BER is 0.042 in case of SLM technique which is the lowest value among all the techniques and very close to the original signal. Similar results are observed in 2x2 MIMO-OFDM system as the highest BER 0.067 and lowest BER 0.037 are determined after applying exponential companding and SLM technique respectively at SNR level of 6 dB. However, it is also observed that, the BER performance of the techniques are better in 2x2 MIMO-OFDM system than the ordinary OFDM system [32]. The comparison of the BER value for existing PAPR reduction techniques between OFDM and MIMO-OFDM system is shown in Figure 3.14 at SNR level of 6 dB.

So, simulation results reveal that, SLM technique provides the minimum BER whereas, the BER of exponential companding technique is maximum though its PAPR reduction amount is highest. The inverse relation between BER and PAPR of exponential compandng technique is due to the distortion of modulated symbols at the transmitter

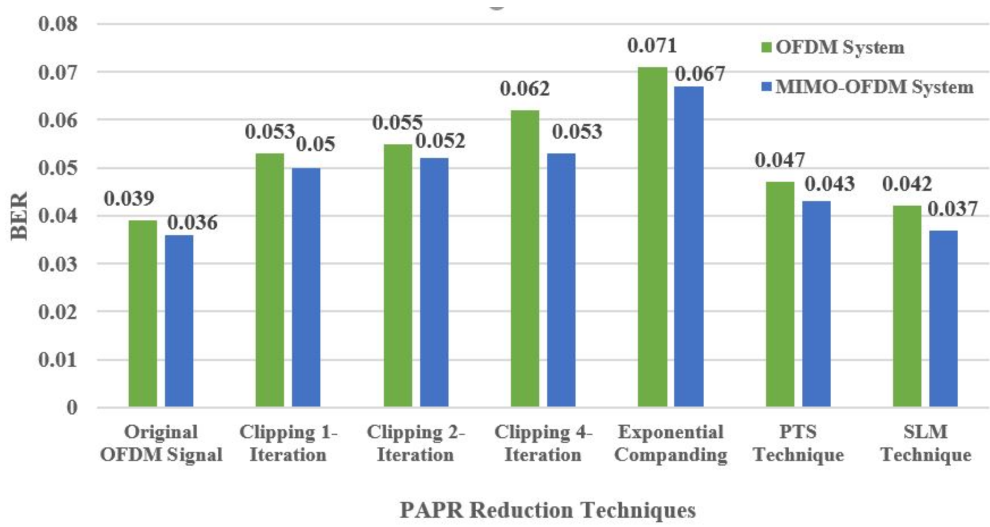

Figure 3.14: BER performance comparison between OFDM and MIMO-OFDM system at SNR = 6 dB

during companding process. Moreover, the channel noise also expanded in the receiving end during decompanding process, resulting in higher number of errors in the recovered data symbols and higher BER [13]. So, the drawback of existing technique is that, it may provide significant PAPR reduction but adversely affect the BER performance. To overcome the limitations of existing techniques, we consider the hybrid techniques from the combination of the existing techniques and compare their performance with the existing ones.

3.7 Chapter Summary

In this chapter a brief description of four existing PAPR reduction techniques: clipping and filtering, exponential companding, SLM and PTS technique are provided. The CCDF and BER performance of these four PAPR reduction techniques are analyzed in OFDM and MIMO-OFDM system for different modulation schemes. Various modulation techniques produce different PAPR performance. The input data sequences of both the OFDM and MIMO-ODFM system must be modulated by one of the modulation schemes before converting from frequency domain to time domain using IFFT to produce OFDM samples. In this thesis, QPSK, BPSK and 16-QAM modulation schemes are considered and it is found that, the effect of modulation scheme is negligible on

PAPR reduction performance.

From simulation results it is also found that, the exponential companding technique provides lowest PAPR value whereas the BER is highest for this technique. On the other hand, the BER provided by SLM technique is lowest and very close to original signal. The result is valid for both OFDM and MIMO-OFDM system.

Therefore, to improve the performance of the existing PAPR reduction techniques, six hybrid techniques are developed in the chapter 4 from the combination of these four techniques described in this chapter.

CHAPTER 4

PROPOSED HYBRID PAPR REDUCTION TECHNIQUE

4.1 Hybrid PAPR Reduction Techniques

Hybrid peak to average power ratio (PAPR) reduction technique consists of two or more existing PAPR reduction techniques which are combined together to significantly reduce the ratio of peak power to the average power of OFDM signal. Many of the existing PAPR reduction techniques provide significant PAPR reduction but adversely affect the BER performance [34-36]. To overcome the limitations of existing techniques, various hybrid methods are proposed by combining two existing techniques [44-46]. In this way, the advantages of both the PAPR reduction techniques can be utilized. In this thesis, six hybrid techniques are considered which are created from the combination of the basic four PAPR reduction techniques discussed in Chapter 3. The hybrid techniques are mentioned below:

a. **Combination of exponential companding and SLM technique:** In this technique, exponential companding technique is applied to the signal which is obtained from SLM technique as shown in Figure 4.1.

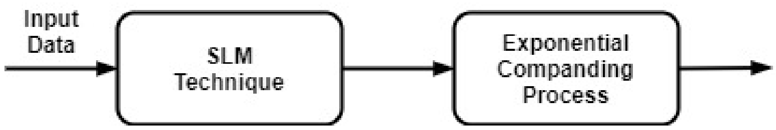

Figure 4.1: Flow diagram of exponential companding+SLM technique

b. **Combination of exponential companding and PTS technique:** In this technique, exponential companding technique is applied after generating signal from PTS technique as shown in Figure 4.2.

c. **Combination of exponential companding and clipping technique:** In this hybrid technique, the OFDM signal is first clipped to a threshold level and then processed for exponential companding as shown in Figure 4.3.

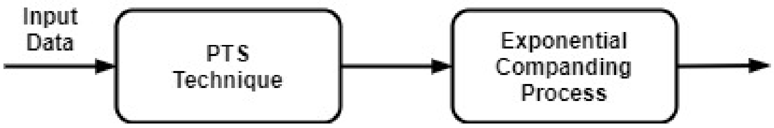

Figure 4.2: Flow diagram of exponential companding+PTS technique

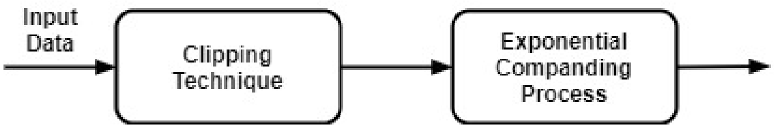

Figure 4.3: Flow diagram of exponential companding+clipping technique

d. **Combination of SLM and clipping technique:** In this hybrid technique, after applying the clipping and filtering process the clipped signal is processed for SLM technique as shown in Figure 4.4.

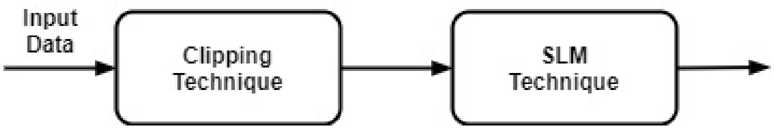

Figure 4.4: Flow diagram of SLM+clipping technique

e. **Combination of PTS and clipping technique:** In this technique, the input signal is clipped to a threshold level and processed for PTS technique as shown in Figure 4.5.

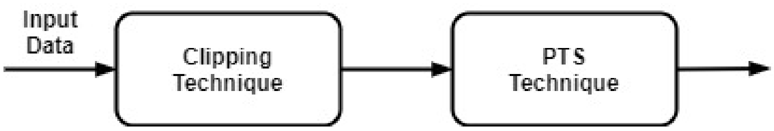

Figure 4.5: Flow diagram of PTS+clipping technique

f. **Combination of PTS and SLM technique:** In this hybrid technique, the signal with the least PAPR is obtained from SLM technique and then the signal is partitioned into sub-blocks and the PTS technique is followed as shown in Figure 4.6.

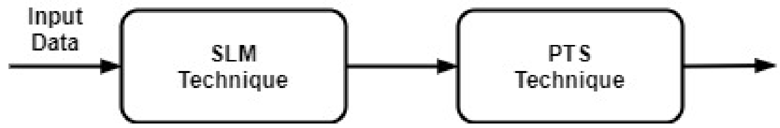

Figure 4.6: Flow diagram of SLM+PTS technique

4.2 Performance Analysis of the Hybrid PAPR Reduction Techniques

In this section, the CCDF performance of the six hybrid PAPR reduction techniques mentioned in section 4.1 are analyzed in OFDM and MIMO-OFDM system. The simulation results are shown in Figure 4.7 and Figure 4.8 respectively. The PAPR values in dB are shown in X-axis corresponding to the different levels of CCDF presented in Y-axis. For comparison the values of PAPR at CCDF level of 10^{-2} after applying the described hybrid PAPR reduction techniques are summarized in Table 4.1.

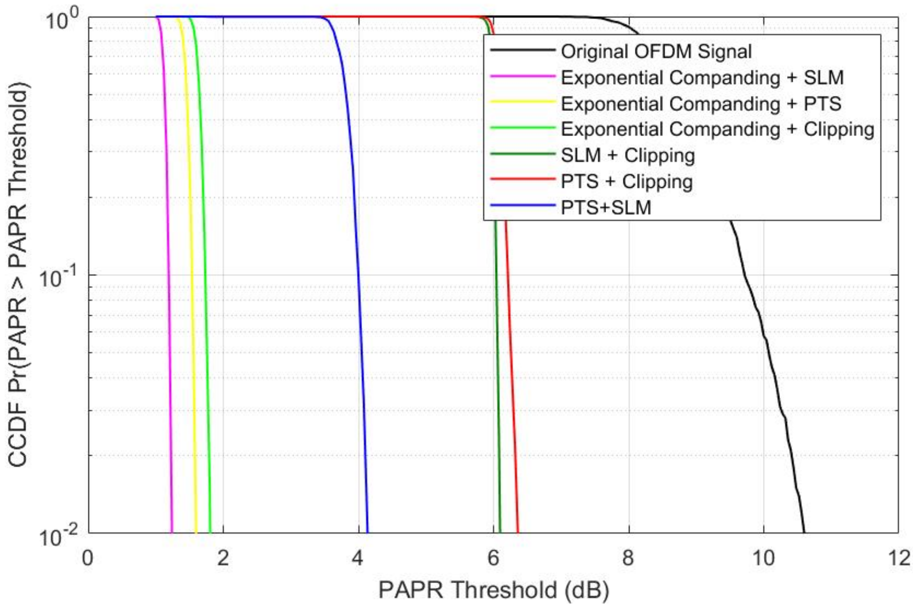

Figure 4.7: CCDF performance of the hybrid PAPR reduction techniques for OFDM system

Simulation results indicate that hybrid PAPR reduction techniques with exponential companding provide better PAPR reduction than other hybrid techniques. Moreover, the lowest PAPR value is 1.2 and 2.16 for OFDM and MIMO-OFDM system respectively after applying the hybrid technique combining exponential companding and

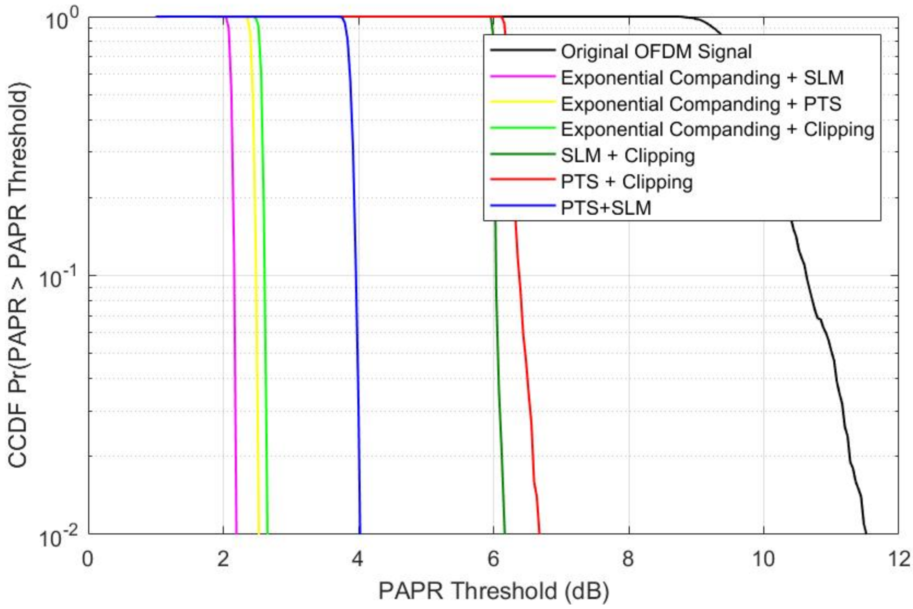

Figure 4.8: CCDF performance of the hybrid PAPR reduction techniques for MIMO-OFDM system

Table 4.1: CCDF comparative analysis for hybrid PAPR reduction techniques in OFDM and MIMO-OFDM system

Method	PAPR (dB) in OFDM System	PAPR (dB) in MIMO-OFDM System
Original OFDM Signal	10.8	11.44
Combination of Exponential Companding and SLM Technique	1.2	2.16
Combination of Exponential Companding and PTS Technique	1.56	2.5
Combination of Exponential Companding and Clipping Technique	1.76	2.68
Combination of SLM and Clipping Technique	6.08	6.12
Combination of PTS and Clipping Technique	6.48	6.64
Combination of PTS and SLM Technique	4.12	4.18

SLM technique. This is more than 9 dB PAPR reduction from the original signal, lowest PAPR value among the six hybrid techniques and improved than the existing PAPR reduction techniques considered in this research. Moreover, from the CCDF performance and the BER performance of the existing PAPR reduction techniques shown in chapter 3, it is observed that, exponential companding technique provides maximum

PAPR reduction and SLM technique ensures minimum bit error rate. So, combination of exponential companding technique and SLM technique has been considered as the potential hybrid PAPR reduction technique in this research.

4.3 Proposed Hybrid PAPR Reduction Technique

In this thesis, we propose a hybrid PAPR reduction method based on exponential companding and SLM technique to utilize the benefit of both the techniques.

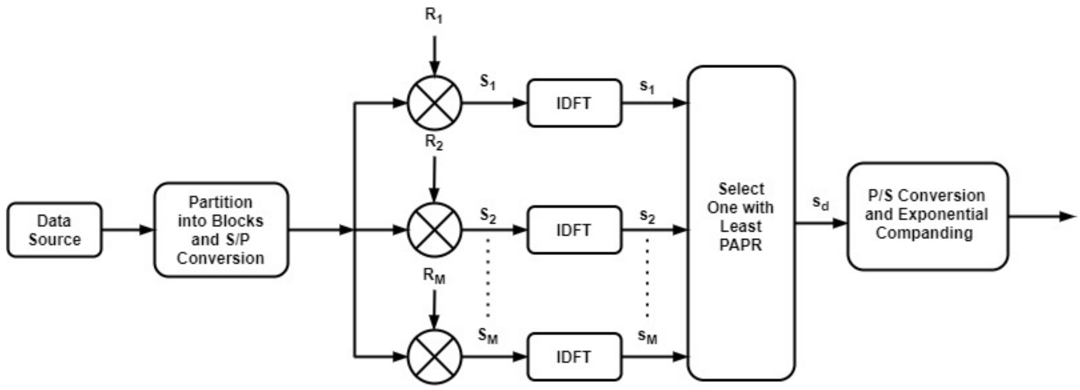

Figure 4.9: Block diagram of proposed hybrid PAPR reduction technique

The flow diagram of the proposed hybrid PAPR reduction method is illustrated in Figure 4.9 and the hybrid PAPR reduction method can be described as below:

a. This hybrid PAPR reduction method starts with the modulation of N subcarriers with random sequences, which can be represented as in Equation (4.1).

$$R_{m,n} = [R_{m,0}, R_{m,1}, \ldots, R_{m,N-1}]; \quad m = 1, 2, \ldots, M \tag{4.1}$$

Where, $R_{m,n}$ is the rotation factor and the range of $\phi_{m,n}$ is uniformly distributed from 0 to 2π. In this way, M independent data sequences representing the identical information as the original data block are created. The symbols in branch m can be represented by Equation (4.2).

$$S_m = [X_0 R_{m,0}, X_1 R_{m,1}, X_2 R_{m,2}, \ldots, X_{N-1} R_{m,N-1}] \tag{4.2}$$

b. Then, the IDFT algorithm is utilized to generate the time domain signal from the data sequences. The PAPR of each sequence is determined individually and the sequence having the lowest PAPR, s_d, is selected for companding process. The function used for exponential companding is shown in Equation (3.7).

c. Finally, the companded signal is transmitted towards the receiver with side information to recognize the sequence with the least PAPR which is created through the SLM technique.

d. On receiving side, decompanding process takes place and the decompanding function is shown in Equation (3.8).

4.4 CCDF and BER Performance of the Proposed Hybrid PAPR Reduction Technique

The CCDF and BER performance of the proposed hybrid PAPR reduction method are determined and compared with the existing exponential companding and SLM technique. In Figure 4.10 to Figure 4.15, the simulation results are shown and summarized in Table 4.2.

In Figure 4.10 the CCDF performance of the proposed hybrid PAPR reduction technique is compared with the existing SLM and exponential companding technique as the proposed technique is developed from the combination of these two techniques. The PAPR values in dB are shown in X-axis corresponding to the different levels of CCDF presented in Y-axis. From simulation results it is observed that, the PAPR of the signal at CCDF level of 10^{-2} in OFDM system is 6.4, 1.92 and 1.24 dB after applying SLM, exponential companding, and proposed hybrid technique respectively. Moreover, for any particular CCDF level, the PAPR value in dB after applying the proposed hybrid PAPR reduction technique is always lowest than the existing PAPR reduction techniques. To verify the observation, the number of subcarrier is varied from 128 to 1024 in X-axis and the corresponding PAPR value at CCDF level of 10^{-2} for the PAPR reduction techniques are shown in Y-axis. For all the subcarrier counts, the PAPR value of the proposed hybrid technique is lowest than the existing techniques as well.

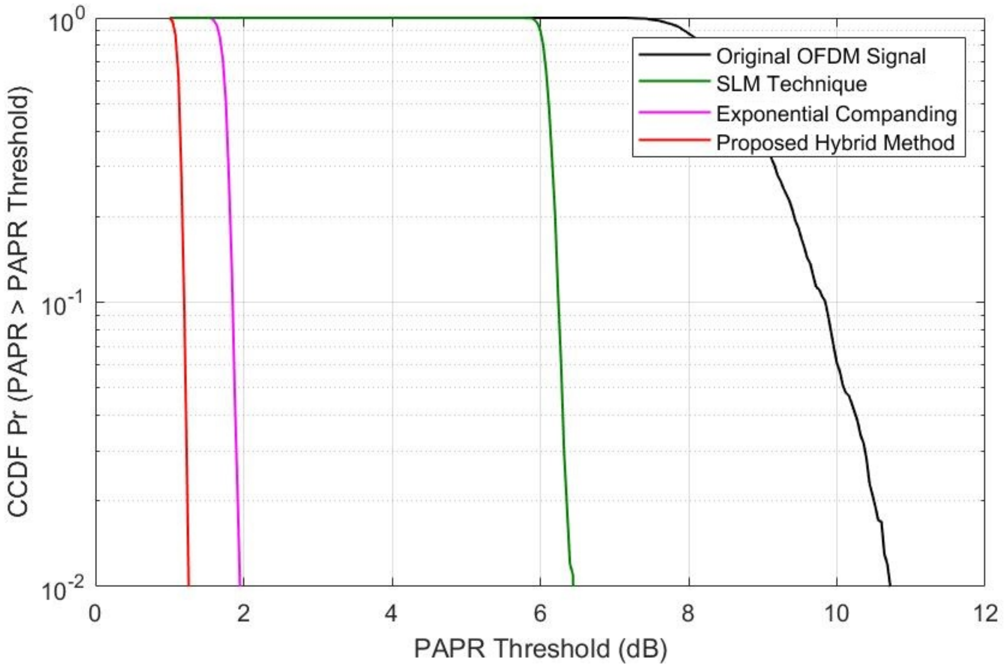

Figure 4.10: CCDF performance comparison among the PAPR reduction techniques for OFDM system

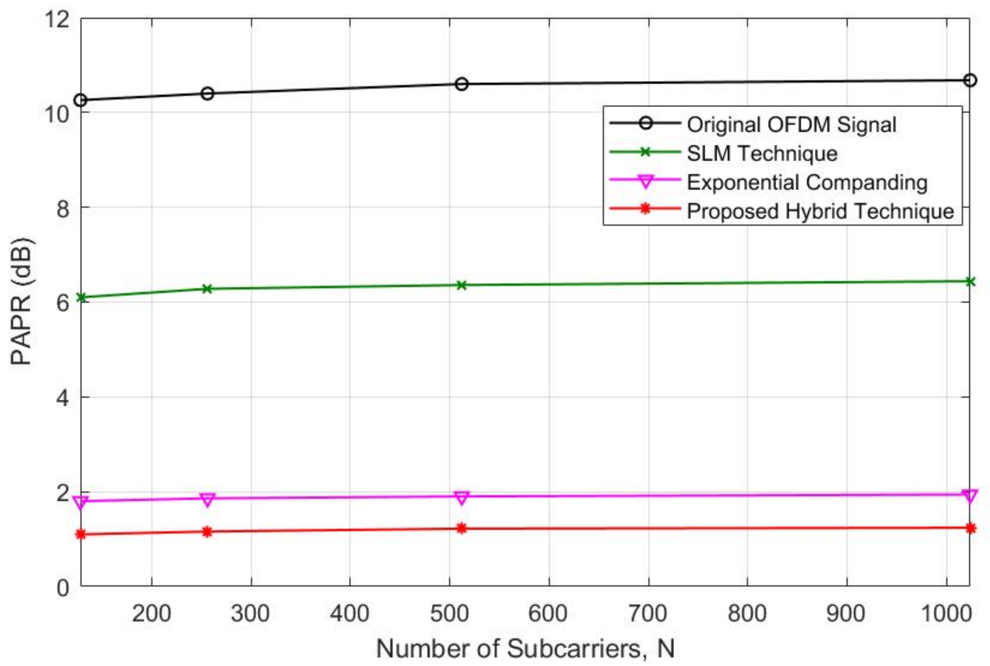

Figure 4.11: CCDF performance comparison among the PAPR reduction techniques for different subcarrier in OFDM system

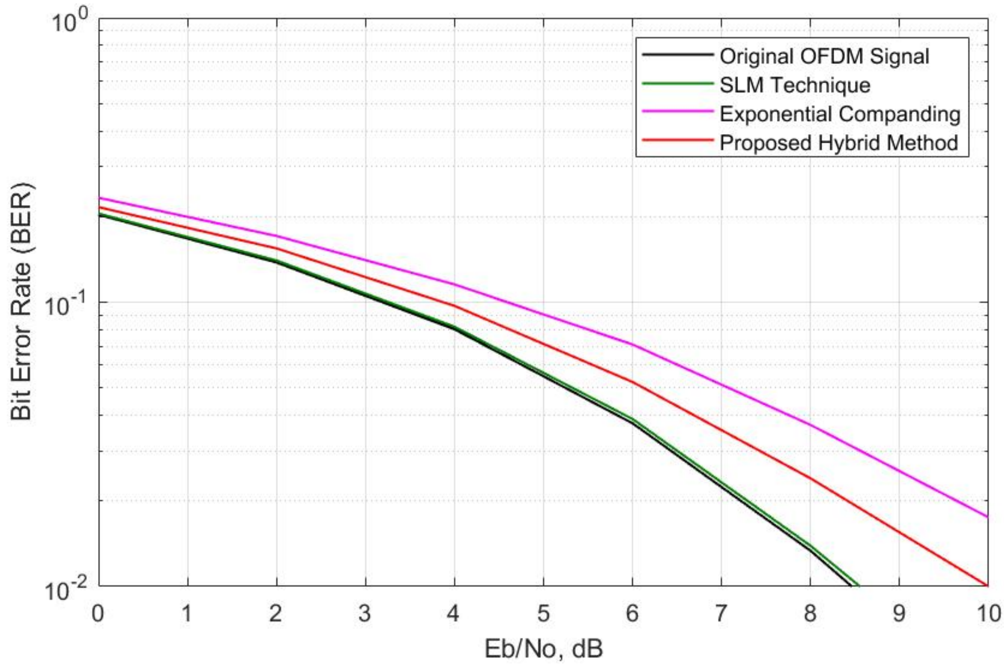

Figure 4.12: BER performance comparison among the PAPR reduction techniques in OFDM system

In Figure 4.12, the BER performance of the proposed hybrid PAPR reduction technique is compared with the existing technique for OFDM system. Simulation results reveal that, The BER of exponential companding, proposed hybrid method, and SLM technique in OFDM system is 0.071, 0.052, and 0.042, respectively, at SNR level of 6 dB. It is observed that the BER of the proposed hybrid method is much improved than the existing exponential companding technique.

Similar analysis is done for 2x2 MIMO OFDM system and from Figure 4.13 it is observed that the PAPR of the signal at CCDF level of 10^{-2} is 6.6, 2.8 and 2.08 dB after applying SLM, exponential companding, and proposed hybrid technique respectively. So, the proposed hybrid technique also provides highest reduction than the existing PAPR reduction techniques in MIMO-OFDM system and the result is valid for different subcarrier values as shown in Figure 4.14. Also the BER of exponential companding, proposed hybrid method, and SLM technique in MIMO-OFDM system is 0.068, 0.049, and 0.037 respectively, at SNR level of 6 dB, as shown in Figure 4.15.

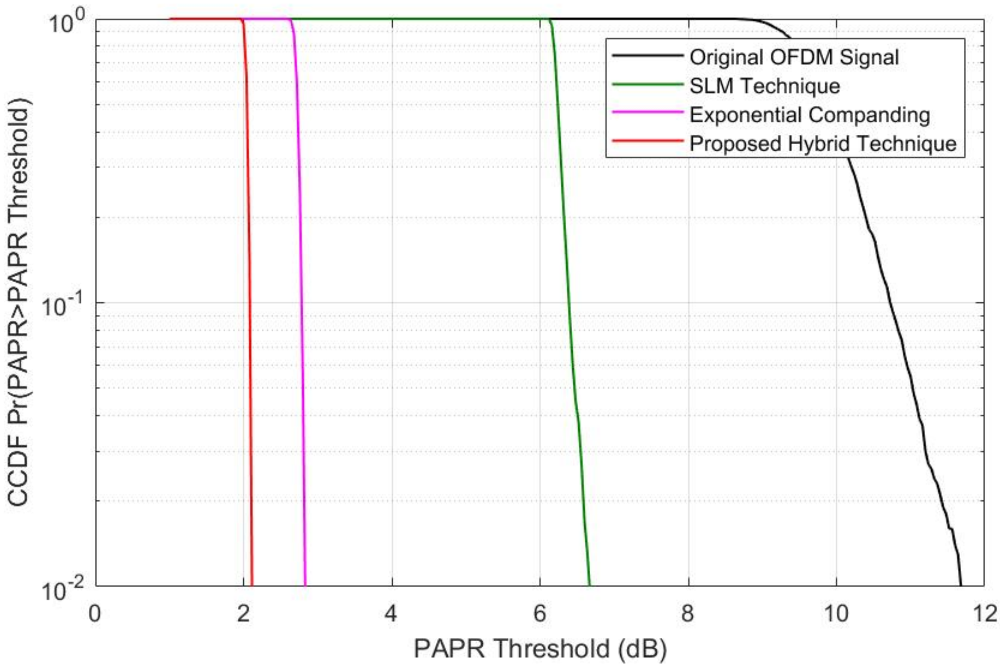

Figure 4.13: CCDF performance comparison among the PAPR reduction techniques for MIMO-OFDM system

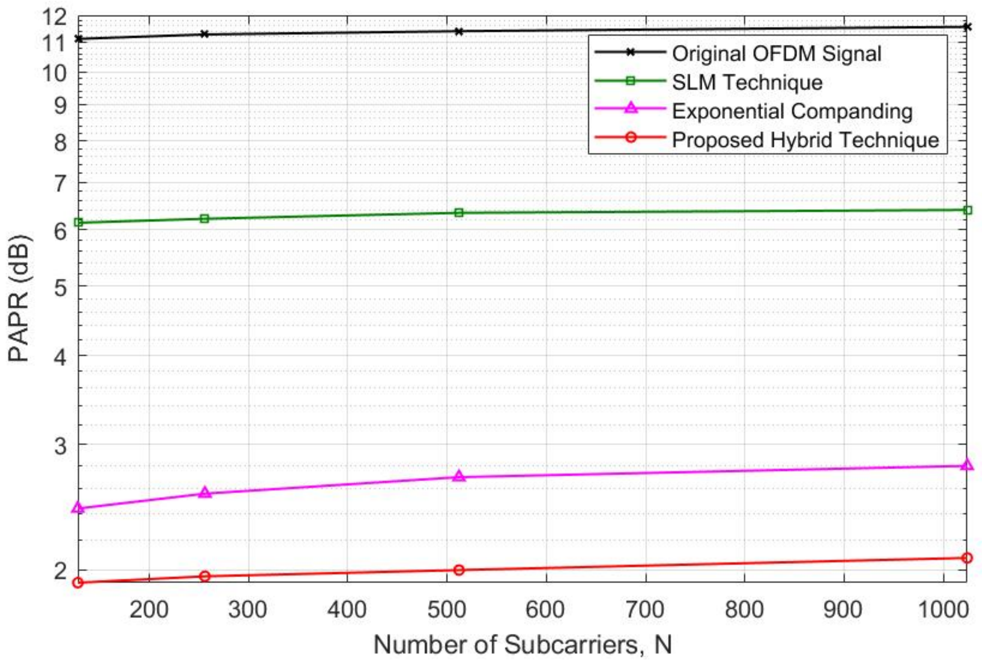

Figure 4.14: CCDF performance comparison among the PAPR reduction techniques for different subcarrier in MIMO-OFDM system

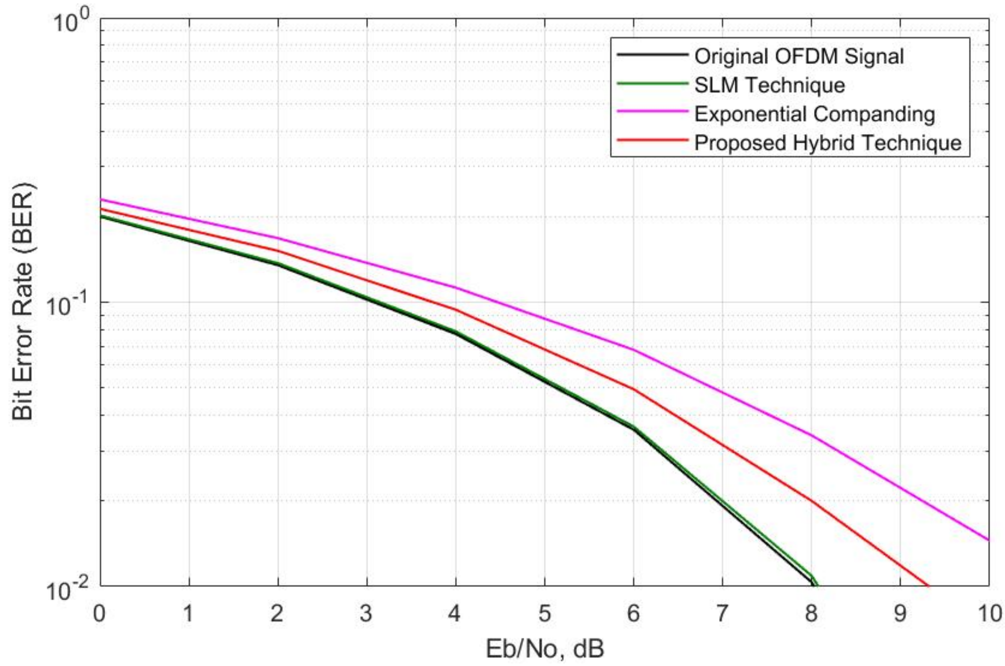

Figure 4.15: BER performance comparison among the PAPR reduction techniques in MIMO-OFDM system

Table 4.2: Performance comparison among PAPR reduction techniques in OFDM and MIMO-OFDM system

Method	OFDM System		MIMO-OFDM System	
	PAPR (dB) at CCDF = 10^{-2}	BER at SNR = 6dB	PAPR (dB) at CCDF=10^{-2}	BER at SNR=6dB
Original OFDM Signal	10.64	0.039	11.68	0.036
SLM Technique	6.4	0.042	6.6	0.037
Exponential Companding	1.92	0.071	2.8	0.068
Proposed Hybrid Method	1.24	0.052	2.08	0.049

According to the simulation results, the proposed hybrid PAPR reduction technique reduces PAPR by more than 5 dB when compared to the SLM technique and more than 0.5 dB when compared to exponential companding technique for both the OFDM and MIMO-OFDM system. Furthermore, the proposed hybrid approach outperforms the exponential companding technique in terms of BER.

4.5 Chapter Summary

In this chapter, a brief description of hybrid PAPR reduction technique is provided. Later, six hybrid PAPR reduction methods are formed from the combination of clipping and filtering, exponential companding, SLM and PTS technique. The performance of these six hybrid PAPR reduction techniques are analyzed in OFDM and MIMO-OFDM system and it is found that, the technique combining exponential companding and SLM technique provide highest PAPR reduction than the other techniques. So, we propose this technique as a potential hybrid PAPR reduction method. The performance of this proposed hybrid PAPR reduction technique is compared with the existing PAPR reduction techniques. From simulation results, it is found that the proposed technique provides better PAPR reduction than the existing techniques and the BER is also improved than exponential companding technique.

Based on the results obtained from this chapter, the conclusion and future research scopes to enhance the research outcomes has been presented in the next chapter.

CHAPTER 5

CONCLUSIONS AND FUTURE WORKS

In this chapter, the summary and major contributions of the research works are presented. Finally, the future research scopes are outlined that can be conducted to make the outcomes more significant.

5.1 Conclusions

In this thesis a brief description of OFDM system, MIMO-OFDM system, importance of reducing PAPR, performance analysis of four basic PAPR reduction techniques and analysis of six hybrid PAPR reduction techniques are presented. From simulation results, it is observed that among the four existing techniques exponential companding technique provides least PAPR of signal for both OFDM and MIMO-OFDM System. It is also revealed that, for different modulation schemes such as QPSK, BPSK and 16-QAM the performance of these PAPR reduction techniques remains almost unchanged. From BER performance of the existing techniques, it is also observed that, the BER is maximum for exponential companding technique whereas SLM technique provides the minimum BER.

To improve the performance of the existing techniques, six hybrid PAPR reduction techniques are considered from the combination of four basic PAPR reduction techniques and their performance is analyzed in OFDM and MIMO-OFDM system. From simulation results, it is observed that the hybrid PAPR reduction technique combining exponential companding and SLM technique provides the least PAPR than the other hybrid PAPR reduction techniques.

Furthermore, the hybrid PAPR reduction method combining SLM and exponential companding technique is proposed as potential PAPR reduction technique to utilize the advantages of both the techniques. From simulation results, it is observed that the proposed hybrid PAPR reduction method provides the least PAPR than the existing four techniques irrespective of the number of subcarriers. For OFDM system it is almost 88% reduction and for MIMO-OFDM system it is almost 82% reduction from the PAPR of the original signal. Moreover, the BER performance of the proposed hybrid PAPR reduction technique is 26.7% and 27.9% improved than the existing exponential companding technique in OFDM and MIMO-OFDM system, respectively.

5.2 Major Contributions

This research has contributed to the development of new hybrid PAPR reduction technique having promising performance, which have been presented and published in two international conference proceedings. The complete research findings are being also considered for possible publications in reputed journals in the field of wireless communication. The research objectives are thus attained with the following contributions:

a. The prominent PAPR reduction techniques in OFDM and MIMO-OFDM system are thoroughly analyzed and compared to learn their relative effectiveness and efficiency, which could be a reference for the researchers in the related field.

b. Effect of modulation schemes, number of subcarriers and oversampling factor on PAPR are determined for their fine tuning and development of six new hybrid PAPR reduction techniques. The new hybrid PAPR reduction techniques are developed from the combination of the existing four techniques.

c. The CCDF performance of the developed hybrid PAPR reduction techniques is analyzed to demonstrate the most effective hybrid PAPR reduction technique for the OFDM and MIMO-OFDM system.

d. The CCDF and BER performance of the proposed hybrid PAPR reduction technique is compared with the existing techniques for both OFDM and MIMO-OFDM system. The number of subcarrier is also varied to examine the validity of the comparison. The proposed hybrid PAPR reduction technique provides almost 88% PAPR reduction in OFDM and 82% PAPR reduction in MIMO-OFDM system, which is much improved than the existing PAPR reduction techniques.

5.3 Future Works

For the widespread use of OFDM system in wireless communication, the PAPR problem must be resolved while maintaining a significant BER performance. A few areas may further be addressed in future research to explore the possible methods to make the OFDM system more appropriate for the next generation wireless communication system , are noted below:

a. The performance of the described PAPR reduction techniques can be investigated for different communication channels, more number of antennas and receivers, and higher order modulation schemes like 32-QAM or 64-QAM.

b. Furher analysis may also be carried out to learn the performance of new methods combining more than two existing techniques and associated hardware complexity can be determined.

c. The relationship between PAPR and BER can be determined. Similarly, the relationship between PAPR and SNR can be analyzed.

With these advancements, the outcomes of this research work will be improved even further, allowing them to be used more widely in the future.

LIST OF PUBLICATIONS

Conference Papers:

(i) **T. N. Munni** and M. H. Haider, "Performance Analysis of Peak to Average Power Ratio (PAPR) Reduction Techniques in OFDM System for Different Modulation Schemes", 4^{th} *International Conference on Electrical Engineering and Information & Communication Technology (iCEEiCT)*, pp. 605-610, Sept. 2018.

(ii) **T. N. Munni** and M. H. Haider, "A Hybrid Method Based on SLM and Exponential Companding Technique to Reduce the Peak to Average Power Ratio (PAPR) in an OFDM System", *International Conference on Automation, Control and Mechatronics for Industry 4.0 (ACMI)*, pp. 1-5, Jul. 2021.

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ANNEXURE

MATLAB CODES

Matlab code for performance analysis of existing PAPR reduction techniques:

```
clc;
close all;
N_syms = 1000;
fc = 2e6;
Nsc = 1024;
BW = 1e6;
df = BW/Nsc;
T_sym = 1/df;
fs = 1/(T_sym/Nsc);
L = 4;
ts = (1/fs/L);
M = 4;
K = log2(M);
clip_ratio = 10^ (3/20);
d = 2;
[tx_data, tx_bits, ofdm_sym] = oftm_tx (N_syms, Nsc, L);
% Apply PAPR reduction techniques
%     Clipping and Filtering
tx_clip_1 = icf (tx_data, N_syms, Nsc, L, clip_ratio, 1);
tx_clip_2 = icf (tx_data, N_syms, Nsc, L, clip_ratio, 2);
tx_clip_4 = icf (tx_data, N_syms, Nsc, L, clip_ratio, 4);
```

```
% Exponential Companding
 [tx_comp_exp, sigma_sqr, alpha1] = ec (tx_data, N_syms, Nsc, L, 2);
% PTS
tx_pts = pts (ofdm_sym, N_syms, Nsc, L);
% SLM
[tx_slm, phase_slm] = ofdm_slm (ofdm_sym, N_syms, Nsc, L);
% compute PAPR
papr_dB_orig = compute_papr (tx_data, N_syms, Nsc, L);
papr_dB_icf_1 = compute_papr (tx_clip_1, N_syms, Nsc, L);
papr_dB_icf_2 = compute_papr tx_clip_2, N_syms, Nsc, L);
papr_dB_icf_4 = compute_papr (tx_clip_4, N_syms, Nsc, L);
papr_dB_exp_comp = compute_papr (tx_comp_exp, N_syms, Nsc, L);
papr_dB_pts = compute_papr (tx_pts, N_syms, Nsc, L);
papr_dB_slm = compute_papr (tx_slm, N_syms, Nsc, L);
% Compute ccdf of papr Pr (PAPR > threshold)
for ii = 1: length(papr_thres)
ccdf_papr_orig(ii) = (sum (papr_dB_orig > papr_thres(ii)))/N_syms;
ccdf_papr_1(ii) = (sum (papr_dB_icf_1 > papr_thres(ii)))/N_syms;
ccdf_papr_2(ii) = (sum (papr_dB_icf_2 > papr_thres(ii)))/N_syms;
ccdf_papr_4(ii) = (sum (papr_dB_icf_4 > papr_thres(ii)))/N_syms;
ccdf_papr_comp(ii) = (sum (papr_dB_exp_comp > papr_thres(ii)))/N_syms;
ccdf_papr_pts (ii) = (sum (papr_dB_pts > papr_thres(ii)))/N_syms;
 ccdf_papr_slm(ii) = (sum (papr_dB_slm > papr_thres(ii)))/N_syms;
end
% plot CCDF of PAPR
figure (1);
semilogy (papr_thres (1: end), ccdf_papr_orig (1: end));
hold;
```

```
semilogy (papr_thres (1: end), ccdf_papr_1(1: end));
semilogy (papr_thres (1: end), ccdf_papr_2 (1: end));
semilogy (papr_thres (1: end), ccdf_papr_4 (1: end));
semilogy (papr_thres (1: end), ccdf_papr_comp (1: end));
semilogy (papr_thres (1: end), ccdf_papr_pts (1: end));
semilogy (papr_thres (1: end), ccdf_papr_slm (1: end));
hold off
grid on;
grid on;
xlabel ('PAPR Threshold (dB)')
ylabel ('CCDF Pr (PAPR > PAPR Threshold')
legend ('Original OFDM Signal', 'Clipping 1-Iteration', 'Clipping 2-Iteration', 'Clipping 4-Iteration', 'Exponential Companding', 'PTS Technique', 'SLM Technique');
```

Matlab code for function of computing PAPR:

```
function [papr_dB] = compute_papr (tx_data, N_syms, Nsc, L)
 papr_lin = zeros (1, N_syms);
for ii = 1: N_syms
tx_sym = tx_data((ii-1) *Nsc*L + 1: ii*Nsc*L);
papr_lin(ii) = max(abs(tx_sym). ^2)/mean(abs(tx_sym). ^2);
end
papr_dB = 10*log10 (papr_lin);
end
```

Matlab code for function of clipping and filtering:

```
function [clipped_data] = icf (tx_data, N_syms, Nsc, L, clip_ratio, n_iter)
clipped_data = [];
```

```
for ii = 1: N_syms
tx_sym = tx_data ((ii-1) *Nsc*L + 1: ii*Nsc*L);
for jj = 1: n_iter
clip_symbol = tx_sym;
rms_tx = sqrt ((sum ((abs (clip_symbol)). ^2))/((Nsc)*L));
clip_level = rms_tx* clip_ratio;
ind = find (abs (tx_sym) > clip_level);
clip_symbol (ind) = (tx_sym (ind)/(abs (tx_sym (ind)))) *clip_level;
clip_symbol_freq = sqrt (1/(Nsc*L)) *fft (clip_symbol, Nsc*L);
clip_symbol_freq_filt = [clip_symbol_freq (1: Nsc/2) zeros (1, Nsc*L-Nsc)
clip_symbol_freq (Nsc*L - Nsc/2+1: end)];
clip_symbol_filt = sqrt (Nsc*L) *ifft (clip_symbol_freq_filt, Nsc*L);
tx_sym = clip_symbol_filt;
end
clipped_data = [clipped_data tx_sym];
end
```

Matlab code for function of exponential companding:

```
function [transformed_data, sigma_sqr, alpha1] = ec (tx_data, N_syms, Nsc, L, d)
transformed_data = [];
for ii = 1: N_syms
tx_sym = tx_data ((ii-1) *Nsc*L + 1: ii*Nsc*L);
sigma_sqr = var (real (tx_sym));
tx_mag = abs (tx_sym);
alpha1 = ((mean (tx_mag.^2))/ (mean (((1 – exp ((tx_mag.^2)/(sigma_sqr))). ^2).
^(1/d)))) ^(d/2);
comp_symbol = sign(tx_sym). *((alpha1*((1 – exp (- (tx_mag.^2). /(sigma_sqr))))).
^(1/d));
```

```
transformed_data = [ transformed_data comp_symbol];
end
```

Matlab code for function of exponential decompanding:

```
function [original_data] = decompanding (transformed_data, N_syms, Nsc, L, d,
sigma_sqr, alpha1)
original_data = [];
for ii = 1: N_syms
rx_sym = transformed_data ((ii-1) *Nsc*L + 1: ii*Nsc*L);
rx_mag = abs (rx_sym);
de_comp_symbol = sign (rx_sym). *sqrt ((-sigma_sqr)*log(1-
(rx_mag.^d)/(alpha1)));
original_data = [ original_data de_comp_symbol];
end
```

Matlab code for function of PTS technique:

```
function tx_pts = pts (ofdm_sym, N_syms, Nsc,L)
p = [1 -1 1i -1i];
B = [];
for b1=1:4
for b2 =1:4
for b3 =1:4
for b4 =1:4
B = [B; [p(b1) p(b2) p(b3) p(b4)]];
end
end
end
```

```
end
tx_pts = [];
papro = zeros (1, N_syms);
papr_min = zeros (1, N_syms);
for ii = 1: N_syms
xmap = ofdm_sym (1, (ii-1) *Nsc+1: ii*Nsc);
time_domain_signal = abs (ifft ([xmap (1: fix(Nsc/2)) zeros (1, (L-1) *Nsc) xmap
(fix(Nsc/2) +1: end)]));
meano = mean (abs (time_domain_signal). ^2);
peako = (abs (time_domain_signal). ^2);
papro(ii) =10*log10 (peako/meano);
P1= [xmap (1: fix (Nsc/4)) zeros (1, fix (Nsc/4) *3)];
P2 = [zeros (1, fix(Nsc/4)) xmap (fix(Nsc/4) +1: fix(Nsc/2)) zeros (1, fix (Nsc/2))];
P3 = [zeros (1, fix(Nsc/2)) xmap(fix(Nsc/2) +1: fix(Nsc/4) *3) zeros (1, fix(Nsc/4))];
P4 = [zeros (1, fix(Nsc/4) *3) xmap (fix(Nsc/4) *3+1: end)];
Pt1= sqrt ((Nsc*L)) *(ifft ([P1(1: fix(Nsc/2)) zeros (1, (L-1) *Nsc) P1(fix(Nsc/2) +1:
end)], L*Nsc));
Pt2 = sqrt ((Nsc*L)) *(ifft ([P2(1: fix(Nsc/2)) zeros (1, (L-1) *Nsc) P2(fix(Nsc/2) +1:
end)], L*Nsc));
Pt3 = sqrt ((Nsc*L)) *(ifft ([P3(1: fix(Nsc/2)) zeros (1, (L-1) *Nsc) P3(fix(Nsc/2) +1:
end)], L*Nsc));
Pt4 = sqrt ((Nsc*L)) *(ifft ([P4(1: fix(Nsc/2)) zeros (1, (L-1) *Nsc) P4(fix(Nsc/2) +1:
end)], L*Nsc));
papr_min(ii) = papro(ii);
for kk = 1: length(B)
pt_temp = B(kk,1) *Pt1+B(kk,2) *Pt2+B(kk,3) *Pt3+B(kk,4) *Pt4;
meank = mean(abs(pt_temp). ^2);
peak = max(abs(pt_temp). ^2);
```

```
papr = 10*log10(peak/meank);
if papr < papr_min(ii)
papr_min(ii) = papr;
pt_symb = pt_temp;
end
end
tx_pts_normal = [tx_pts_normal pt_symb];
end
end
```

Matlab code for function of SLM technique:

```
function [tx_slm, phase_sequence] = ofdm_slm (ofdm_sym, _syms, Nsc, L)
C = 4;
P = [1 0.866+0.5i -0.5+0.866i -1 -0.5-0.866i 0.5-0.866i];
randn ('state', 12345);
B = randsrc(C, Nsc, p);
tx_slm = [];
phase_sequence = zeros (N_syms, Nsc);
for ii = 1: N_syms
xmap = ofdm_sym (1, (ii-1) *Nsc+1: ii*Nsc);
time_domain_signa l = abs (ifft ([xmap (1: fix(Nsc/2)) zeros (1, (L-1) *Nsc)
xmap(fix(Nsc/2) +1: end)]));
meano = mean(abs(time_domain_signal). ^2);
peako = max(abs(time_domain_signal). ^2);
papr_min =10*log10(peako/meano);
mod_block = zeros (C, Nsc);
for k=1:C
```

```
mod_block (k,:)=B(k,:).*xmap;
end
pt = time_domain_signal;
phase_temp = B (1, :);
for k =1:C
 Pt_temp = ((Nsc*L)) * (ifft ([mod_block (k,1: fix(Nsc/2)) zeros (1, (L-1) *Nsc)
 mod_block (k, fix Nsc/2) +1: end)], L*Nsc));
 papr_temp =10*log10(max(abs(Pt_temp).^2)/mean(abs(Pt_temp).^2));
 if (papr_min > papr_temp)
 papr_min = papr_temp;
 pt = Pt_temp;
 phase_temp = B (k, :);
 end
 end
 tx_slm = [tx_slm pt];
 phase_sequence (ii, :) = phase_temp;
 end
 end
```