

Design of Improved Coding Schemes with Low Peak to Average Power Ratio for OFDM System

A THESIS

SUBMITTED IN FULFILLMENT OF THE REQUIREMENT

FOR THE AWARD OF DEGREE OF

DOCTOR OF PHILOSOPHY

IN

ELECTRONICS AND COMMUNICATION ENGINEERING

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2016

CERTIFICATE

I, **Sabhyata Uppal**, hereby declare that the thesis entitled, “**Design of Improved Coding Schemes with Low Peak to Average Power Ratio for OFDM System**” submitted to Thapar University, Patiala, in partial fulfilment of the requirement for the award of the Degree of **Doctor of Philosophy in the Electronics and Communication Engineering** is a record of original, bonafide, and independent research work done by me during 2010-2016. The research work and the thesis have been conducted under the supervision and guidance of **Dr. Sanjay Sharma**, Professor and Head, Electronics and Communication Engineering Department, Thapar University and **Dr. Hardeep Singh**, Assistant Professor, Electronics and Communication Engineering Department, Thapar University. It has not formed the basis for the award of any Degree/Diploma/Associate-ship/Fellowship or other similar title to any candidate of any university.

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ABSTRACT

Orthogonal frequency division multiplexing (OFDM) is an exceptionally attractive practice in the field of wireless communications because of the spectrum efficiency and channel robustness. It is modulation technique in which a high-rate bit stream is split into a large number of parallel low rate data sub-streams and the sub-streams are utilized for modulating the number of orthogonal sub-carriers with the help of Fourier transform processing. OFDM attains robustness against multipath fading due to extended symbol interval for every sub-carrier and against the inter-symbol interference (ISI) due to introduction of a guard interval in each OFDM symbol. Therefore, OFDM has been accepted in many modern communication applications, like wireless local area networks (WLANs) and digital video & audio broadcast. In spite of numerous plus points, a foremost disadvantage of OFDM is the high peak to average power ratio (PAPR). In view of the fact that OFDM signal consists of numerous independently modulated sub-carriers, which results in high PAPR when summed-up coherently. This necessitates the use of power amplifier (linear) with the huge dynamic range. High PAPR increases the dynamic range of analog-to-digital converter (ADC), also it reduces the efficiency of linear power amplifier. Consequently, discovering methods to reduce transmitted signal's PAPR in the OFDM systems is becoming an extremely active field of research in the communication communities.

Numerous procedures have been suggested in the literature for reducing the PAPR. These procedures may be classified into the signal mixing methods & signal distortion methods. Signal mixing methods are the various techniques which suggest how to mix up the codes for reducing the PAPR. Scrambling of signals is achieved by various available coding techniques. Shapiro Rudin series, Golay complementary series, Barker codes, M sequences may be applied proficiently for diminishing the PAPR. On other hand, with

increase in carrier count, operating cost related to comprehensive investigation of best code will increase exponentially. Additional realistic signal scrambling solution methods are partial transmit sequences (PTS), selective level mapping (SLM), and block codes.

In this research, various significant features have been described and mathematical investigation of various techniques has been presented to decrease the PAPR, which are having a potential to offer considerable drop in PAPR at the price of decrease in data rate, amplification in transmit signal power, increase in bit error rate (BER), and computational complexity . Fundamental prerequisite of practical PAPR reducing techniques include compatibility with the family of existing modulation techniques, elevated spectral effectiveness and low complexity. There are lot of aspects to be taken into consideration before a precise PAPR reducing method is selected. These factors consist of PAPR reducing capability, decrease in BER at the receiver end, no loss in data rate, reduction in computational complexity and so on. There is no definite PAPR reducing method which is the appropriate solution. Instead the PAPR reducing method ought to be cautiously selected according to different requirements of system.

OFDM signal obtained using Golay sequences has the advantage of low PAPR values. It has superior error-correcting capability as well. Signals using quadrature-amplitude-modulation (QAM) techniques are normally implemented in OFDM system, 16 QAM OFDM series having very low PAPR is created with 2 quaternary-phase-shift-keying (QPSK) Golay series (complementary). The results are extended to 256 QAM series. In this research, a technique has been proposed to make 16 QAM and 256 QAM series by combining QPSK sequences. If these QPSK series are Golay series resulting from Reed–Muller codes, then the obtained QAM series has low PAPR which is appropriate for OFDM systems. The recommended method reduces the PAPR and the simulation results illustrate that the peak power is reduced by approximately 1dB and by approximately 4dB as

compared to other methods. Simulation results demonstrate that the proposed solution can accomplish the bit-error-rate requirements of WiMAX. In this study, reduction of PAPR in OFDM systems intended for QAM constellation has been considered, particularly for 16-QAM and 256 QAM. The techniques proposed in this investigation can be applied for producing OFDM series having low PAPR for 1024-QAM constellations.

When transmitting signals, one of the most important issues is to keep the transmission errors as low as possible. Or in other words, to obtain a reliable transmission link, the bit-error-rate (BER) should be kept within certain limits. However, the probability of transmission errors strongly depends on the signal-to-noise ratio (SNR) of the transmitted signals. Here, the power amplifier plays a key role in the sender part: the more power, the higher the SNR, the lower the probability of transmission errors. One should take care to keep the peak-to-average power ratio (PAPR) of the transmitted signal low in order not to push the power amplifier into its nonlinear operation region. Classical techniques use clipping or backing-off the input signal to reduce the PAPR of the transmitted signal. However, these techniques have a negative influence on the SNR and hence on the BER. In this work we present a new approach to reduce the BER of transmitted signals in order to reduce the PAPR. The presented technique introduces sequences into the data. The idea behind introducing sequences is to add redundancy in order to obtain a more reliable communication link. Reducing the BER of OFDM signals can not only be a way to reduce the PAPR of a transmission link, but since it prevents the power amplifier to go into compression, it also provides a technique to enhance the efficiency of the power amplifier.

The performance of OFDM is tested for M-QAM using MATLAB/SIMULINK toolbox. It is observed that sequences play an important role to improve the efficiency of the system. After analysis of sequences in M-QAM system we observed that BER is reduced in comparison to a system without sequences. Various sequences were

analyzed to improve the QOS of OFDM system and it can be seen that the system behaves efficiently with Golay sequence as compared to other sequences.

The WiMAX (Worldwide interoperability for microwave access) physical layer is based on OFDM, a method that presents high-quality confrontation to multipath, and permits WiMAX to function in non-line of sight (NLOS) circumstances. The technique proposed may be used to reduce the PAPR of WiMAX OFDM system. IEEE 802.16, which is the standard related to wireless broadband guarantees large bandwidth over transmission in the long range. This standard states the combined interface of medium access control (MAC) and physical layer of broadband wireless access together with the air interface.

BER performance of WiMAX physical layer based wireless communication system using the convolutional coding and various QAM modulation schemes have been analysed. The BER curves are used to evaluate the performance of various modulation and coding scheme used. These results offer a complete indication of the WiMAX systems using OFDM physical layer under different circumstances of modulation and various input sequences. It has been observed that sequences play a significant role to increase the effectiveness of system. After the investigation of sequences in M-QAM system, it has been observed that BER reduces in contrast to system without sequences. A variety of sequences were analysed to enhance the system performance and it may be observed that the system performs better with Golay sequence as compared to any other sequence. Decrease in BER of WiMAX system not only decreases the PAPR, it also improves the efficiency of the system, because it avoids the power amplifier to go into compression.

ACKNOWLEDGEMENT

First and foremost, I am beholden to the Almighty and I bow before Him for his umpteen blessings and bestowing in me the grit and confidence to carry out this research work.

I extend my thanks to **Dr. Prakash Gopalan**, Hon'ble Director and **Dr. O.P Pandey**, Dean (Research and Sponsored Projects) for giving me this opportunity to undertake the PhD.

I would like to put on record my heartfelt and sincere gratitude to my research guide **Dr. Sanjay Sharma**, Professor and Head, Electronics and Communication Engineering Department, Thapar University, Patiala. I feel bound to be grateful to **Dr. Hardeep Singh** my guiding soul for his valuable and constant support, advice, and encouragement.

I am honour bound and profoundly thankful to the doctoral committee members **Dr. Sanjay Sharma**, Professor and Head of Department, Electronics and Communication Engineering Department, Thapar University, Patiala, **Dr. Rajesh Khanna**, Professor, Electronics and Communication Engineering Department, Thapar University, Patiala, and **Dr. Amit Kumar Kohli**, Associate Professor, Electronics and Communication Engineering Department, Thapar University, Patiala, for their consistent help.

It is great privilege to express my profound thankfulness, deep love, and fondness to my husband Arun and my daughter Ishi, who stood like a rock in my difficult times. Their love, patience, persistent encouragement, and good virtuous understanding enabled me to complete the research work successfully.

Finally, I will remain obligated to and filled with appreciation towards my parents for their love, affection, sacrifices, perseverance, and prayers all through my life.

Sabhyata

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ACRONYMS AND ABBREVIATIONS

3G	:	Third Generation
4G	:	Fourth Generation
ACE	:	Adaptive Constellation Extension
ADC	:	Analog to Digital Converters
ALMMSE	:	Approximate LMMSE
AWGN	:	Additive White Gaussian Noise
BCM	:	Block Coded Modulation
BER	:	Bit Error Rate
BLR	:	Block Error Rate
CCDF	:	Complementary Cumulative Distribution Function
CDF	:	Cumulative Distribution Function
CGS	:	Complementary Golay Sequences
CP	:	Cyclic Prefix
CR	:	Clipping Ratio
DAC	:	Digital to Analog Converter
DFT	:	Discrete Fourier Transform
DMT	:	Discrete Multitone
DSI	:	Dummy Sequence Insertion
FEC	:	Forward Error Correcting Codes
FER	:	Frame Error Rate
FFT	:	Fast Fourier Transform
FHT	:	Fast Hadamard Transform
FRFT	:	Fractional Fourier Transformation
GCC	:	Golay Complementary Codes
GDJ	:	Golay–Davis–Jedwab
GSM	:	Global System for Mobile Communications

HPA	:	High Power Amplifier
HPA	:	High Power Amplifier
ICI	:	Inter-Channel-Interference
IFFT	:	Inverse Fast Fourier Transform
ISI	:	Inter-Symbol-Interference
LDPC	:	Low-Density-Parity Check
LOS	:	Line-Of-Sight
LPF	:	Low Pass Filter
LTE	:	Long Term Evolution
MAC	:	Medium Access Control
MBAP	:	Metric Based Amplitude Pre-Distortion
MCM	:	Multi-Chip Module
MCM	:	Multi-Carrier Modulation Microwave Access
MPI	:	Multipath Interference
NLOS	:	Non-Line of Sight
OFDM	:	Orthogonal Frequency Division Multiplexing
OFDMA	:	Orthogonal Frequency Division Multiple Access
PAN	:	Personal Area Networks
PAPR	:	Peak To Average Power Ratio
PDA	:	Personal Digital Assistants
PHY	:	Physical Layer
PMEPR	:	Peak to Mean Envelope Power Ratio
PN	:	Pseudo Noise
PRT	:	Peak Reduction Tones
PSD	:	Power Spectral Density
PSK	:	Phase-Shift Keying
PTS	:	Partial Transmit Sequence Technique

QAM	:	Quadrature Amplitude Modulation
QOS	:	Quality of Service
QPSK	:	quaternary phase shift keying
RMC	:	Reed-Muller Codes
RMS	:	Root Mean Square
SC	:	Single Carrier
SCNR	:	Signal-To-Clipping Noise Quantitative Relation
SLM	:	Selected Mapping
SOCF	:	Second Order Cone Programming
TDM	:	Time Division Multiplexing
TDMA	:	Time Division Multiple Access
TI	:	Tone Injection
TR	:	Tone Reservation
TRA	:	Tone Reservation Approach
Wi-Fi	:	Wireless Fidelity
WiMAX	:	Worldwide Interoperability for Microwave Access
WLAN	:	Wireless Local Area Networks
WMAN	:	Wireless Metropolitan Area Networks

INTRODUCTION BASED ON LITERATURE REVIEW

1. 1 INTRODUCTION

In wireless technology, the focus was much on developing personal area networks (PAN) and wireless local area networks (WLAN), when the new millennium started. These technologies enable the users to use wireless connectivity between the mobile devices that include computer peripherals, personal digital assistants (PDAs), laptop computers, and cordless phones. When compared with wired networks, wireless technology saves cost in deploying cables, and has the advantage of easy and quick installation and portability. Since, both the above said technologies have certain range of coverage, they are used only for indoor applications. When compared with PANs, WLANs cover a wider area and enable a group of portable devices (mostly laptops located in office buildings/private homes) with internet connectivity.

The WLAN products, developed on the basis of IEEE 802.11 family of standards, were mostly successful and there were two amendments introduced in 1999, first being the IEEE 802.11b for the purpose of increasing the data rates upto 11 Mbps which was popularly adopted as Wi-Fi (Wireless Fidelity) and the second being IEEE 802.11g, using OFDM for increasing the data rate upto 54 Mbps. The WLANs, then evolved into wireless metropolitan area networks (WMANs). The primary purpose of the WLANs is to provide internet connectivity through roof-top antennas for residential and corporate buildings, that communicate with central radio based station through wireless link substituting the wired connection.

In 1998, the IEEE 802.16 operational set started its research activities for providing multiple options for WMAN air interface and medium access control (MAC) protocol whose primary goal was to enable the users within the cell radii upto 50 kms, with high speed data rates upto 50 Mbps in the metropolitan cities. This group focused on 10-66 GHz band, since

numerous unlicensed spectrums are available in this bandwidth. In 2002, 802.16 was released focusing on line-of-sight (LOS) applications based on the attenuations that were experienced by the short wavelengths while passing from side to side walls or other obstructions. In combination with time division multiple access (TDMA) the above mentioned standard adopted single carrier (SC) modulation. SC transmission was the first air interface followed by OFDM-TDMA. The next one was operated using the orthogonal frequency division multiple access (OFDMA) principle which segregates the users at sub-carrier level. Amongst these, OFDM and OFDMA air interfaces were preferred by the vendors, since they exhibited a high-end performance in the non-line of sight (NLOS) applications.

Worldwide interoperability for microwave access (WiMAX), an industrial consortium has been created for ensuring the interoperability among all the 802.16 based devices and to join the worldwide WMAN standard in a rapid manner. In the upcoming years, the high-rate wireless communications was expected to grow at an enormous speed since the demand was too high. This led to the development of fourth generation (4G) wireless broadband systems leaving the third generation (3G) products in order to offer uncompromised quality service with increased data rates. Multicarrier techniques appear to be an efficient contender to provide future generation broadband wireless systems as compared to single carrier, since they possess several benefits for instance robustness against channel impairments, improved spectral efficiency, narrowband interference, greater suppleness in supply management plus capability to hold adaptive modulation scheme. Additional sub-standards popularly known as WiMAX is currently being developed [1].

In this thesis, the simulation performance of WiMAX OFDM physical layer (PHY) under different modulation schemes has been investigated. The performance of complementary Golay sequences (CGS) has been examined in terms of both forward error correction and PAPR reduction. The probability analysis in the simulations is a clear demonstration providing the

improvement work for peak to average power ratio (PAPR) reduction. In this thesis, PAPR of OFDM has been analysed and it has been shown that by adding Golay sequence in data, the PAPR of the system can be reduced significantly.

1.2 MOTIVATION FOR RESEARCH

OFDM is seen as an attractive technology in wireless communications as it offers immunity against frequency-selective fading channels, tolerance to multipath delay spread, high spectral efficiency and power efficiency. OFDM is one such multi-carrier modulation technique which has been selected to transfer high data rate communications and deployed at many places which require high speed wireless communications. OFDM based systems seem to be promising and preferred one amongst wireless applications, because it eliminates the need of the equalizers, and at the same time proficient hard-ware realization may be apprehended through fast Fourier transform (FFT) techniques [2].

In spite of the above merits, OFDM systems still exhibit some unresolved complexities such as high PAPR of transmitted OFDM signals. Large signal peaks occur because of the addition of signals in various sub-channels in phase, in the transmitted signal. To keep away from inter-modulation distortion, it is common to cut the transmitted signal's power for operating the power amplifier at the source in the operating range. Due to the above discussed power reduction, the communication system functions inefficiently. Thus, the detection efficiency of OFDM receiver may degrade the performance of the system (due to its high sensitivity for non-linear devices and induced spectral regrowth). Therefore, it becomes critical to research on PAPR characteristics along with its distribution and reduction in OFDM systems for the better utilization of OFDM technicalities.

In order to attain adequate transmission power, high power amplifier (HPA) is employed in the transmitter in most radio systems, which is generally operated near or at the saturation region so that highest output power efficiency can be achieved. In addition, the HPA's non-

linear characteristic is sensitive to the signal amplitude variations. So, between the different sub-carriers, inter-modulation and interference is introduced by HPA because of high PAPR. This results in increase in bit error rate (BER). In order to have low BER and significantly lesser signal deformation, power amplifier needs to be activated in the range which is linear. Power efficiency is an important parameter in wireless communication as it has to cover a vast area and allow small-sized terminals. Therefore, this interference problem can be prevented from occurring through the reduction of PAPR in transmit side by some manipulations in OFDM signal. If the PAPR is large, it demands digital to analog converter (DAC) for accommodating large peaks of OFDM signals. The above scenario is vice-versa where the DAC is less precise at affordable cost, and then quantization noise is high which reduces the signal to noise ratio (SNR) after increasing dynamic range of DAC for supporting high PAPR.

Further, Gaussian distribution is shown by the OFDM signals for many of sub-carriers which implies that the peak in signal reaches rather seldom and it is not desired for uniform quantization by analog to digital converters (ADCs). Various techniques were proposed which were broadly categorized as signal distortion techniques to reduce the PAPR such as tone injection (TI), tone reservation (TR), phase optimization, coding schemes, clipping, selective mapping (SLM), partial transmission sequences (PTS), constellation shaping, nonlinear companding transforms, and other techniques including pre-scrambles. The above schemes mentioned usually reduce the peak amplitudes by simple nonlinear distortion of OFDM signal at the peak or around the peaks. Peak cancellation, peak windowing, and clipping are some of the distortion techniques. Coding techniques are the ones which exclude OFDM symbols with large peak-to-average power relation. Best effective technique in reducing PAPR should provide high transmission power and data speed, and low BER [3].

1.3 LITERATURE REVIEW

There is a high demand for OFDM-based wireless systems which is increasing on daily basis for high mobility and high data rates due to a number of multimedia-based applications. High PAPR is the result of increase in number of sub-carriers to support high mobility and data rates. Due to the rise in OFDM-based systems that provoke the number of sub-carriers which in turn increases the PAPR, the research activities also get boost up to for meeting the demand of highermobility and data rates. A significant shortcoming of OFDM is elevated PAPR. Several methods to reduce this have been proposed and reviewed. Few of them such as amplitude clipping, selected mapping, coding, tone injection, transmit sequence, and tone reservation have been described in [4]. The criteria for selection of a particular technique are also discussed. Peak windowing is one such method which can be used to achieve a PAPR of around 4 dB for a random number of sub-carriers. Nevertheless this process results in a slight increase in BER. The performance of clipping and filtering in OFDM has been analysed in [5], [6] which is further extended in several other literatures discussed subsequently.

1.3.1 PAPR definition and distribution

Scores of research activities have been done on PAPR particularly in the context of OFDM in the past few years and it has been seen that different papers give different definitions of PAPR which leads to confusion. A general expression of PAPR is given by Palicot and Louet [7] in their article by employing the Power Ratio parameter. Various other possible definitions of PAPR can be derived from this. The fundamentals of multi-carrier modulation (MCM) the common method of parallel data transmission on several carriers has been discussed in [8]. Algorithms have been discussed for achieving the desired results and simulation has been done on undistorted channel for getting the required results. Several techniques have been discussed for implementation of MCM and improving upon the performance by coding techniques in addition to methods of dealing with channel impairments. The probable use of duplex MCM

on common switched telephone network is discussed. Another significant factor that has been derived in [9] is the way in which PAPR is distributed in an OFDM signal and it has been shown that large peaks do not occur frequently. Therefore, a very small portion of OFDM signal gets distorted & PAPR reduction methods, can be used effectively.

Based on meaning of PAPR in the OFDM systems, Lin CHEN and Xuelong have described methods on PAPR reduction including block coding, signal scrambling, and signal distortion. The interrelated optimization problems and the pros and cons of the methods have been discussed and a few results have been achieved using Monte Carlo simulations [10]. A design of whole OFDM baseband processing system is proposed based on IEEE 802.16 standard. Algorithms such as PAPR reduction and synchronization are illustrated in detail [11]. Suma and Kanmani have worked on implementation of different features of OFDM and region of its use. Additionally, it offers amendments that are apparent in the channel equalization [12].

The OFDM representation as time organization has been proposed along with inter-channel-interference (ICI) and the inter-symbol-interference (ISI) mitigation with details of OFDM spectral effectiveness & impact of sub-channelization, which predicts the prospects of OFDM. Heftiness beside simple equalization, simple receiver, sub-carrier rate adaptation, narrowband interference, low cost transmitter, and confrontation alongside selective fading are the various the benefits of OFDM [13], [14].

1.3.2 Existing PAPR reduction Techniques

A research survey was conducted by Yasir Rahmatallah discussing about the difficulty of high PAPR in OFDM systems. He also formulated a taxonomy which comprised the available solutions for mitigating the problems. The survey detailed about the OFDM systems' problem i.e., nonlinear distortion provided by the power amplifiers due to the high PAPR. This study was useful in defining the performance metrics for evaluating PAPR reduction schemes [15]. An overview on PAPR reduction techniques in the multi-carrier transmission that included

partial transmit sequence, amplitude clipping and filtering, tone reservation, selecting mapping, active constellation extension, coding and interleaving has been provided in [16], [17].

1.3.3 Amplitude Clipping and Filtering

Ochiai and Imai performed the clipping technique on base-band OFDM signal using oversampling & also without the use of oversampling. After that, the signal should be passed through an idyllic low pass filter (LPF) and thereafter performance of the envelope clipping was analysed by keeping in mind the reduction in PAPR and channel de-gradation. The instantaneous power is also calculated and channel capacity is discussed after oversampling and clipping of OFDM signal by adding white Gaussian noise over Rayleigh fading channel. The distortion terms caused by the clipping are also assumed to be Gaussian. It has been shown that the SNR, because of the clipping, is significantly increased by the use of optimal coding and dropping the information data rate. Simulation is performed using turbo codes and the results are justified. Further research on the above method has been proposed in [9]. The result of filtering after clipping technique upon performance of OFDM, in terms of crest factor, power spectral density, & bit error rate have been examined. From these results it has been shown that filtering and clipping is a capable method for transmitting OFDM signals with the help of linear amplifiers. Firstly, to evaluate upper limit for corresponding growing allocation function of PAPR statistical analysis has been used. It has moreover been proved that solitary single redundant bit is needed to bound peak to mean envelope power ratio (PMEPR) within range of 10% of its highest value for the subcarriers. Secondly, the PMEPR evaluation by means of over-sampling & FFT is evaluated. A new method for measuring the error by OFDM (oversampled) signal is also introduced.

Armstrong in his work has given that it is quite likely to considerably decrease the PAPR of an OFDM signal by repeated clipping and filtering of transmitted signal in frequency

domain. Moreover this method causes no raise in out-of-band power. Major PAPR reduction can be obtained with only reasonable levels of clipping noise [18], [19].

Further research has been done in [20] and the performance of strictly band limited OFDM signal has been evaluated by deliberate clipping. The PAPR and the resultant BER have been evaluated. Here clipping has been performed upon OFDM signals which have been sampled at Nyquist rate, and then passed through an ideal LPF. The LPF may however significantly increase the PAPR. Therefore, PAPR reduction capability is reduced to considerable extent. Hence, to further improve the performance of this scheme, adaptive symbol selection technique is used. By combining adaptive symbol with clipping a considerable reduction in PAPR can be obtained with reasonable complexity. However performance degradation is the price paid for PAPR reduction by this method. BER of the OFDM signal with Nyquist rate clipping in combination with adaptive symbol selection has been evaluated and then forward error correction is considered for compensating the degradation.

Saeedi et al. [21] have shown that to lower the peak factor clipping the OFDM signal in the transmitter side is one of the most convenient methods. Nevertheless, after DAC, further clipping distortion and peak regrowth is introduced. Clipping the oversampled sequence is one of the methods to decrease the peak regrowth. A method is proposed for recreating clipped samples at receiver end in an organized manner and to reduce the consequence of distortion caused by clipping due to channel noise at the cost of expansion in bandwidth. It has been shown in [22] by means of extensive simulations that the system performance may be considerably improved by expanding bandwidth by a small amount regardless of the truth that the maximum amplitude of the analog signal is a limiting factor.

1.3.4 Selected Mapping (SLM) Technique

SLM technique has been introduced in [23] for reducing the PAPR of multi-carrier modulation systems. This method can also be used for other applications and has the advantage

of reducing the complexity and providing considerable gains. SLM being a distortion less technique identifies the actual transmitted signal from a set of other signals, all of which have the same information. The information of signal generated, needs to be transmitted and cautiously protected from bit errors.

SLM is considered to be a better distortion-less technique for reduction in PAPR in OFDM. But SLM exhibits high complexity as the inverse fast Fourier transform (IFFT) and phase search complexity increases which remains as its disadvantage. Based on the random phase sequence selection, the PAPR reduction performance can be decided [24]. In order to reduce high PAPR, Wen et al. [25] proposed two coding schemes in which the former used parity checking coding scheme and the latter employed SLM method. In the former, parity information is utilized for expanding the signal space. It is possible to lower the PAPR of transmitted signal through mapping from unique source of knowledge to the matching message sequence with a low peak power. The simulation results prove that when SLM applied coding scheme is tested in OFDM system, the PAPR can be drastically reduced.

An extension of SLM is projected in [26]. This technique does not use additional side information at the receiver, instead makes use of the scrambling technique. To improve upon the statistics of the transmitted signal, some added complexity and practically negligible redundancy is introduced.

1.3.5 Golay Codes for PAPR Reduction

In the research conducted by Rezgui et al. [27], a more reliable PAPR reduction method was proposed in which Golay coder (with low complexity) was used followed by fractional Fourier transmission (FRFT) block. The low order Golay sequences coded modulation provided by the input data encoder is transmitted through the FRFT block. These FRFT angles are designed in order to exhibit a de-correlation with optimal performance between the signal

and noise. The above discussed method exhibited competitive performance compared with the previous methods and at a relatively low complexity.

Bai et al. [28] applied a coding scheme which relies on the Reed-Muller Codes (RMC) and Golay complementary sequences (GCS) into the system to decrease PAPR. The analysis of simulation results depicts significant reduction in PAPR using the projected technique. Masoud Olfat and Ray Liu proposed the usage of cyclic shifts in low PAPR codes that were used in transmission of OFDM signals. These cyclic shifts contain a super class of Golay complementary codes (GCC) at a similar PAPR value as looked into from the distinct OFDM code. The GCC attain increase in output at the expense of decreased error correction capabilities. Based on the GCC, a framework was proposed to construct which may be simplified to get the cyclic transfer of any code that was mentioned by Boolean algebraic functions. A well-organized communication scheme in which both the Golay and the cyclic Golay codes can be switched in the same coding scheme is proposed with the feedback received from the receiver for a better trade-off performance among the BER and the coding rate [29]. Chong et al. [30] have examined the creation of 16-QAM Golay sequences. This building results in two codes with PMEPR limits of 2 and 3.6 dB. Then they compute the length of codes and provide another set of 16-QAM Golay sequences. The two codes have $\text{PMEPR} \leq 2$ and ≤ 2.8 respectively. In the study conducted by Davis and Jedwab [31], a authoritative theory was developed to yield Golay sequences as combinations of cosets of the classical Reed-Muller codes. The Golay sequences-based codes [32], [33] constructed can be used in the coding approach of PAPR control in multi-carrier communications. These sequences have the benefit of PMEPR of as low as 2. A comprehensive survey of Golay sequences is given in [34], [35] using phase-shift keying (PSK) signal constellations. Another set of sequences which are representatives of family of binary Golay complementary sequences are the Shapiro-Rudin

sequences which have been proposed. The crest factor obtained by numerical analysis on these, show a reduction of almost 5 to 6 dB irrespective of the number of tones.

Lee and Golomb [36] projected a 64-QAM Golay complementary sequences, where 3 standard Golay sequences or QPSK Golay-Davis-Jedwab complementary (GDJ) sequences, linked with a couple of offset were pooled to shape every 64-QAM Golay sequence.

Davis and Jedwab have established a relation among 2nd order RMC with Golay complementary sequences for coding in OFDM transmission. This method reduces the peak power to almost 3 dB and also allows easier coding and decoding. High code rates and better error correction is also achieved [37]. The theory of relation between RMC and polyphase sequences was further extended in [38]. Results show that it is possible to obtain Golay complementary sets from 2nd order co-set of 1st order RMC, the size of which depends on only one parameter that is obtained from the graph related to the co-set. Another significant shortcoming of OFDM transmission system is that of reducing the PMEPR for practical and low cost applications. Golay complementary sequences have been identified for solving this problem for quite some time. These codes have been shown to have efficient error correction ability and increase the range of coding option in OFDM applications having small number of carrier [39], [40]. A new family of methods for reducing the value of PAPR in discrete multitone (DMT) and OFDM systems is proposed in [41], [42]. This new family of algorithms can be applied with different levels of complexity and performance depending on our application constraints. One of the most significant factors while transmitting signals is to keep the BER as low as possible. Popovic in [43] has shown that any polyphase sequence which belongs to a pair of complementary sequences can be used to give a crest factor less than or equivalent to 6 dB.

1.3.6 Partial Transmit Sequence and Tone Reservation

In case of 4G broadband wireless communications, multi input multi output (MIMO) OFDM seems to be one candidate, which promises high performance. The same disadvantage that exists in OFDM do exists here in MIMO-OFDM also i.e., the probability of high PAPR by transmitting the signals on different antennas. The study conducted by Rihawi et al. [44] extended the PAPR reduction formulation from second order cone programming problem(SOCP) to MIMO-OFDM. This method investigated above is basically a TR method that employs the unused signals. This method neither degrades the BER nor the information or data rate due to which there is no requirement of side information [45]. Emna Hajlaoui et al. [46] proposed a new technique for diminishing PAPR supported by utilizing unused sub-carriers. Consequently, they devised lessening of PAPR difficulty as convex optimization (space-time block codes approach). Lessening technique is initially dependent upon the specific case of tone reservation approach (TRA) which makes use of idle standard carriers.

Han and Lee [47] have introduced partial transmit sequence (PTS) technique which gives improved results for PAPR of OFDM signals. In this method, the chosen transmitted block of data has been splitted in the dislodged sub blocks in order to decrease the PAPR. These sub-blocks are then united by means of phase factors. However, by increasing the number of sub-blocks, the search complexity also increases and a comprehensive search is required over all possible phase factors. It has been shown that the anticipated method achieves major decrease in search complexity with slight reduction in performance. In [48], it has been shown that PTS is capable of improving PAPR performance of OFDM signal. Since, PTS necessitates a comprehensive investigation over every possible permutation of the permissible phase factors, investigation complexity boosts exponentially using number of sub-blocks. Mukunthan & Dananjayan [49] discussed the tailored PTS using interleaving & QPSK technique for reducing PAPR for transmission of OFDM. The authors also explained technique for avoiding

requirement of additional IFFTs, the same as in PAPR lessening with the help of common PTS technique, but as an alternative are dependent upon appropriate choice of various sub-blocks. Through inter-leaving a data frame, peaks with in OFDM signal may be reduced. It is obvious that PAPR of personalized PTS may be enhanced with the use of inter-leaved sub-block separation method. Srinivasarao et al. [50] primarily investigated the PAPR lessening procedure using 2 different PAPR reduction methods. First one is the selective mapping (SLM) & the other one is partial transmit sequence (PTS). These 2 techniques are the sub-entities of a phase revolving method. A procedure known as the sub-optimal procedure which predicts improved PAPR reduction as compared with existing procedures available. Outcomes have been confirmed with the help of MATLAB software. The performance of 2 PAPR lessening techniques namely partial transmit sequence (PTS) & selected mapping (SLM) have been compared by Hassan and El-Tarhuni [51]. The outcomes point that the SLM is having better performance over the PTS in reduction of PAPR for identical sub-carriers, but at cost of elevated computational complexity.

1.3.7 Block Coding

Another method for the reduction of PAPR of multi-carrier modulation transmission scheme, such as OFDM, is block coding, which is proposed in [52], [53]. It has been shown that PAPR can be reduced by approximately 4 dB by using a four carrier signal and $\frac{3}{4}$ block code rate. It has also been analysed by using an eight carrier signal which shows the applications and flexibility of this method.

Torakh and Jafarkhani [54] proved that at any time, the difficulty of finding the code word say C having large value of PAPR for every code C described above an equivalent energy constellation, is associated with the difficulty of minimum distance coding of C in a multi-carrier communication system. So a technique is projected for computing, the PAPR in a multi-carrier modulation system using block codes. Also, a maximum limit on the error between the

true one and computed one is derived. For codes derived over arbitrary signals, constellations analogous results are computed and established. So, the approach of John and Wilkinson [53] is revisited which introduces an explicit move to every coordinate of the entire code words with independent phase-shifts PSK, 8-PSK and 16-PSK [54], [55].

The PAPR of OFDM signal has been diminished with the help of Golay sequences (complementary). In the results obtained by simulations, PAPR is restricted to 3 dB while in physical accomplishment PAPR is restricted to 6 dB. On the other hand, the PAPR lessening is only legitimate for OFDM signals devoid of guard interval [56]. A new PAPR lessening technique for MIMO-OFDM is dependent on second order cone programming (SOCP) [57]. Projected technique is comparatively straightforward and attains noteworthy lessening in PAPR without transmitting the surface message content & also avoids degrading BER & transmission rate of data. The proposed scheme merges inter-leaving method & companding method for reducing PAPR. The proposal has been compared with structure which makes use of the supplementary method, the clipping technique, for reducing the PAPR. By using this scheme, the PAPR of OFDM's PAPR may be diminished by 6.8 dB over novel system by the application of this scheme [58].

1.3.8 Other Methods

The challenge behind cost effectiveness and well-organized beginning of these broadband signalling methods in long term evolution (LTE) is the high PAPR of multi-carrier wireless waveforms (i.e., OFDM). Dick & Tarn [59] projected an overview about the tone condition and adaptive constellation extension (ACE), the two suggested methods of FPGA implementation in PAPR reduction. Dick & Tarn [60] also provided a general idea for FPGA execution of 2 techniques for the reduction of PAPR - adaptive constellation extension (ACE) and tone reservation (TR). The 2 techniques have been projected alongside FPGA resource estimation for realization. It has been concluded that ACE is the dominant method for reducing

the PAPR. Structural design explained in this research article, makes the noteworthy application of time division multiplexing (TDM) functional units.

Xiaong et al. [61] observed out-of-band radiation and BER as a part of PAPR reduction. Daoud et al. [62] employed a low-density-parity check (LDPC) encoder for an effective reduction of PAPR in OFDM technology. Further, MIMO antennas technology was also implemented as a solution to reception problem in parallel with increased system performance. The study concluded that PAPR reduction techniques have been significantly improved during the recent times when a powerful error correcting code is used. Convolutional and LDPC were the two different linear codes which were utilized to evaluate the progress of MIMO-OFDM system. When compared from the previous PAPR reduction techniques such as multiple signal representation, cyclic coding, selective mapping, Golay sequences, and clipping & filtering, the above mentioned technique exhibited good performance. The study also inferred that simulation results were proving that 70% PAPR can be reduced compared to the existing studies which was achieved based on the system type. The power amplifier has an important function in the transmitter system. The SNR increases with increase in power. In order for the power amplifier to function in its linear range, the PAPR should be kept low.

Most of the peak power reduction method has a negative effect on the SNR & therefore on BER. Channel coding, by introducing errors is the method proposed in [63] & [64], which reduced the BER and thereby PAPR. Ryu et al. [65] proposed DSI (dummy sequence insertion) technique for reducing PAPR. Flipping method may be merged in the DSI technique for diminishing PAPR efficiently. Moreover, the PAPR threshold method shoots up processing rate. MAC layer backs up mainly the point-to-multi-point structural design, having a discretionary mesh topology. The MAC layer is pre-arranged for supporting the multiple specifications of physical layer (PHY), all matched for the specific operational environment [66].

Li and Xia [67] developed a software orientation model for OFDM & demonstrated for the functionality which may be accepted in various wireless applications. BER & working of proposed OFDM model has been analyzed for 256 QAM, 64 QAM, and 16 QAM. Faisal et al. [68] depicted that in general the whole system performance assessed in dissimilar channel circumstances. Scatter plots have been produced for validating the proposed representation in form of common trends in the receiving superiority by changing various aspects. The BER curves have been used for comparing performance for various modulations & coding methods used. These techniques projected a complete assessment of performance of physical layer of OFDM for wireless channel's different states.

Seyran Khademi et al. [69] described a valuable optimization method which was based upon sequential quadratic programming for computing common phase shift. The suggested method is having numerous benefits when compared with conventional techniques of PAPR reduction. There is not any requirement of side-information & is having no effect on power & BER whilst giving improved PAPR lessening performance as compared to the many techniques.

Hara and Prasad [70] presented the investigation & assessment of OFDM and CDMA schemes and blend of both techniques. The blend of OFDM & CDMA schemes provides immense improvement which lowers symbol rate in both sub-carriers. The larger symbol duration helps in synchronizing the transmission. Lawrey [71] presented a technique to maximize signal potency within buildings with the help of using transmission repeaters. It is comparable with single frequency networks being used in the digital audio and video broadcasting systems, excluding small scale bi-directional communications.

M. Sharif et al. [72] shows that the peak of the continuous envelope of the OFDM signal can be bounded by the maximum of the corresponding oversampled sequence. The researchers have established that for the huge quantity of sub-carriers, for limiting the PMEPR within 10

% of its maximum value, only single redundant bit is sufficient. The distortion-to-signal power ratio at the output of a memory less nonlinearity is determined by simple calculations. This is done by application of Bussgang's theorem, which may also be obtained as a special case of Price's theorem. Specific results are given for hard and soft instantaneous and envelope limiters [73].

Jayalath and Tellambura [74] presented a method based on interleaver to improve the PAPR of an OFDM. In this method, $K-1$ arbitrary interleavers have been used for producing $(K-1)$ permuted sequences within identical information series. The sequence having least possible PAP is preferred for transmission. Cimini & Sollenberger [75] proposed a new method for reducing PAPR in OFDM signal. Projected scheme was based on the expansion of signal set. Every point in actual signal set is linked with 2 or more points in signal set which is expanded. Every symbol in the OFDM block of data has been mapped among the associated points within expanded signal set for achieving reduction in PAPR.

Popovic projected [76] a particular set of orthogonal GCS for addition in 3G mobile standard as a set of synchronisation preambles for random access channel. Ismail et al. [77] presented an investigational assessment of BER performances and comparisons of single carrier OFDM systems. PAPR in orthogonal frequency and code division multiplexing (OFCDM) system for enhancing spectral efficacy has been presented by Shukla et al. [78]. The model offered by Mohamed et al. [79] may be used for implementing coding & modulations techniques. Simulation results obtained in such a way allow the user for choosing finest alternative to ensemble the desired requirements. Assessment of BER even handedness & Interleaved OFDMA System's PAPR has been examined & the consequence of interleaving upon individual BER performance in OFDMA system has been recognised. Results depicted that for extremely loaded systems, arbitrary and cyclically shifted arbitrary interleavers attain improved BER fairness as compared to the predetermined interleaver [80], [81].

Generally the performance of the proposed techniques is examined in the presence of HPA by assessing the figure of merit with the help of which the PAPR reduction performance due to tone reservation (TR), the average power variation, PAPR reduction of clipping, and active constellation extension (ACE), and in-band distortion. It is clear from the simulation results that TR is the best, followed by ACE and clipping.

1.3.9 PAPR of QAM modulations

Most of the present OFDM systems utilize quadrature amplitude modulation (QAM) constellations. Some analysis of 16-QAM and 64-QAM complementary sequences has been presented sequentially in [82], [83] and [84]. Robing and Tarokh [85] gave an upper bound of PMEPR of a set of 16-QAM sequences generated by 2 quaternary phase-shift keying (QPSK) Golay sequences. Tarokh and Sadjadpour [86] generalized the results in [85] from 16-QAM to 2^{2n} -QAM sequences by using N- QPSK Golay sequences, and determined an upper bound of the PMEPR of this set.

Motivated by these works, it was found that the former construction can be generalized in a new way, such that the family size is significantly enlarged while the upper bound of PMEPR changes insignificantly. Peled and Ruiz [87] highlighted upon the basics of digital data transmission in frequency domain using lesser complex algorithms for implementation of QAM modems using signal processing techniques. The anticipated technique gives much lower computational rate and better bandwidth utilization. This is achieved by allowing optimum signal power distribution depending on channel SNR vs. frequency characteristics. It has been further concluded from experimental results that it could be possible to transmit around 10,000 bps with a BER of 10^{-5} .

Chen and Xeulong have constructed 16- QAM OFDM sequences with little PAPR from 2 QPSK Golay complementary sequences since QAM signals are often accepted in OFDM systems. They have further extended the results to general M-QAM sequences proposed be

Schmidt [88]. Reduction of PAPR of M-QAM signals in OFDM systems is considered in [89], [90]. It has already been established producing 16-QAM / 64-QAM constellation as vectored addition of 2 or 3 QPSK constellations correspondingly.

The GCS can be used over Z_4 for constructing 16-QAM / 64-QAM OFDM sequences having little PAPR. The instigators have further scrutinized squared Euclidean distance of the M-QAM sequences with the deviations. The most important objective is to merge the block coded modulation (BCM) and GCS for trading-off squared Euclidean distance, PAPR, and code rate of M-QAM OFDM signal. The edifice of 2^{2n} -QAM sequences has been provided & upper bound of PMEPR has been dogged [91]. The structure of general QAM Golay complementary sequences based on QPSK Golay–Davis–Jedwab (GDJ) sequences has been described by Li [92]. But still there is a scope of improvement.

1.3.10. PAPR in Worldwide Interoperability for Microwave Access(WiMAX)

OFDM is chosen as the modulation format in WiMAX systems. Islamet et al. [93] have discussed the breakthrough associated with WiMAX. WiMAX can be thought to be the primary engineering in the setup associated with other wireless networks. Acquiring awareness of the WiMAX process could be achieved in an optimum way by simply taking a look at type of the actual WiMAX process. WiMAX physical layer model has been simulated and used for evaluation of BER under various channel conditions and modulation schemes. Simulation results show that BPSK scheme outperforms other techniques to reduce intercarrier and intersymbol interference. It has also been shown that the system's performance reduces with increase in the noise. An overview has been provided in [94] ,[95] for Mobile WiMAX which discusses performance of basic nominal arrangement which is based on system profiles of WiMAX Forum Release-1. It has been shown that mobile WiMAX may offer the capacity of megabits per second per channel from every base station by means of a baseline pattern. A

comprehensive dialogue of how Mobile WiMAX compares to development of 3G technologies has been provided in [96].

The efficacy of various freshly projected techniques has been estimated for WiMAX systems. With the help of distinctive HPA models & spectral masks, these PAPR methods have been estimated in terms of entire system de-gradation [97].

In the previous studies, various authors proposed different solutions to reduce PAPR in which dummy sequence insertion (DSI) seems to be very efficient method for WiMAX systems due to its nature of non-requirement of all the side information being transferred with user data [98]. Workflow of conventional DSI method is that, it finds the dummy sequences through an iterative procedure till it achieves the PAPR in the desired threshold conditions. But, this impacts on the overall performance of WiMAX systems due to the delay in finding the dummy sequence. However, the advanced DSI method performs (PAPR reduction) without delays and side information.

A method has been presented for decreasing the complexity of implementation which can reduce the PAPR effectively in WiMAX system. In this methodology, the WiMAX signals are oversampled, first followed by normalization and finally clipped and filtered.

In the study, conducted in [99], a comparison was performed between Golay and Reed-Muller coded OFDM signal and the results inferred that Golay coded OFDM signal showed better performance in PAPR reduction. Further, for the best results in PAPR reduction, the Golay and Reed-Muller codes configuration were identified.

Several methods have been proposed based on combination of interleaving with peak windowing. It has been analysed that this technique decreases the BER and reduces the PAPR by 3.5 dB in presence of non-linear power amplifier model. Sheila et al. [100] presented a novel PAPR lessening method which is a blend of ideas of selected mapping & tone reservation. The

benefit of this design is that it is having lower intricacy. It has been simulated for a WiMAX system.

PAPR lessening has been attained with the help of selected mapping (SLM) method & without transferring side information (SI) concurrently with OFDM symbol. The PAPR performance with the help of error performance, likelihood of SI detection, and complimentary cumulative distribution function (CCDF) has been assessed as the criteria for WiMAX standard IEEE 802.16e [101]. In the paper [102], it has been shown that choice of appropriate method is having extraordinary consequence on PTS algorithm with SLM method which aims to reduce power peak value which has been believed as most important drawback of WiMAX by means of OFDMA technique. Fan et al. [103] proposed a base station physical-layer self-loop transceiver explanation for WiMAX OFDMA mode. A common simulation proposal for WiMAX base station has been developed submissively with IEEE 802.16e standard. It may be employed as the reference for verifying design of the system & performance of WiMAX BS implementation.

Yu et al. [104] proposed 1st scheme for transmitting concurrently 256-QAM WIMAX signals (IEEE 802.16) and FCC compliant IR-UWB signals over solitary directly modulated fiber-link. Multifunctional blend of WIMAX transmission and optical IR-UWB production formulates this system uncomplicated & cost effectual. Consequently, the projected system finds impending use in the prospect broadband optical wireless access networks having wireless multi services. In recent times, metric based amplitude pre-distortion (MBAP), a type of PAPR reduction scheme was proposed with comparatively low complexity [105].

Maan and Adwany [106] assessed performance of WiMAX downlink scheme by investigating the BER at receiver. Consequences of different channel mutilations such as channel noise & multi-path fading have been examined. For WiMAX, in flat Rayleigh fading channel, physical layer simulator has been proposed [107]. It permits the improved

understanding of signal processing procedure taking place at PHY layer analogous to IEEE 802.16e specifications.

In the unchanging WiMAX standard execution using OFDM, different digital modulation techniques such as QPSK, BPSK, 16 QAM & 64 QAM have been investigated for SUI-1 & SUI-2 channel circumstances [108]. The hypothetical investigation of effect of mutilations on OFDM scheme has been offered [109]. Interactive software has been reported for simulating the spreading codes used in DS/SS uses and is based on application of mathematics & graphics software package, PRO-MATLAB [110].

Rabah et al. [111] presented a novel technique of using multi-carrier CDMA (MC-CDMA) for transmitting the signals rather than OFDM in WiMAX which is based on IEEE 802.16 standard. For understanding the functioning of WiMaX system & role of different parameters on system's performance, simulation model has been developed for WiMaX physical layer with the help of Matlab. Attempts have been made for studying BER performance of proposed model in dissimilar channel circumstances [112].

The comprehensive link level simulation has been examined and investigated physical layer performance of WiMAX IEEE 802.16e over the additive white Gaussian noise (AWGN) & multi-path Rayleigh fading channels, in which ITU-Reference channel models are applied [113].

For transmitting digital data with the help of OFDM over fading channels, inter-channel-interference (ICI) term due to Doppler spread has been correlated with preferred signal term. FPGA execution of the superior channel assessment method for OFDM based WiMAX systems has been projected. This method is the customized edition of well-known MMSE method [114], [115].

Dissimilar algorithms of OFDM and WiMAX physical layer which are based on IEEE 802.16e standard in diverse arrangements of digital modulation techniques & dissimilar

communication channels have been discussed. Simulation results depict that the adaptive modulation attains analogous spectral effectiveness with improved energy efficacy [116].

Model building of WiMAX Physical layer with the help of Simulink of Matlab has been portrayed. The proposed model is helpful means for evaluation of performance in the WiMAX in diverse data rates, channel conditions, and coding schemes [117]. Lastly, performance of IEEE 802.16e physical layer has been attained by link-level simulation using MATLAB [118], [119], [120].

Approximate LMMSE (ALMMSE) channel approximator for OFDM WiMAX has been projected. ALMMSE approximator makes use of natural relationship among channels of adjacent sub-carriers for improving least squares estimate with the help of a spectral smoothing filter. Approximation of performance of the channel estimator is dependent on measurements in the practical WiMAX situation [121], [122].

Our primary aim is to perform PAPR reduction without increase in the bit error rate and input power. WiMAX is considered as the topic of interest among the various target people such as students, researchers, operators, and systems engineers due to its enormous applications in the wireless communication field. WiMAX is also the key player in other technology areas such as wireless sensor networks and it is important to understand it by looking at its model. This work discusses about the WiMAX Physical layer model building using computer simulation. This model is hypothesized as the useful tool for evaluating the performance of BER in the case of WiMAX physical layer.

1.4 PROBLEM FORMULATION

Elevated PAPR is the most important disadvantage for multi-carrier transmission. Numerous techniques have been projected in the literature for reducing PAPR in OFDM systems. Large PAPR can compel amplifier for operating in non-linear region, or for backing

off saturation point which in turn will diminish the lifetime of mobile battery or will degrade quality of signal. A promising means for mitigating this difficulty is the application of hefty power back off which permits amplifier for operating within the linear range. However, it results in a huge reduction in power efficacy of amplifier. Therefore, for finding an efficient method for reducing PAPR of signal applied at input of power amplifier is of utmost importance, to reduce negative effects of non-linear deformations without forfeiting the power efficacy.

In this thesis, a trustworthy PAPR reducing method has been proposed which adds a Golay sequence with the input data. Application of complementary Golay sequences (CGS) for PAPR reduction and correcting errors in an OFDM based WIMAX system has been analysed and performance is examined. The PAPR reduction performance depending on various QAM techniques has been studied. Concerning the error correction potential, Golay sequences have been examined by applying M-QAM constellations with OFDM signal in IEEE 802.16 standard.

The novel technique presents spirited performance in terms of low BER & low PAPR as compared to methods available in literature. The simulation of WIMAX in IEEE 802.16e system demonstrates PAPR development & also BER lessening by contrast to competitive techniques. Furthermore, whole system has been simulated using MATLAB for validating the proposed scheme in the prototype, where the feasibility has been established.

1.5 RESEARCH OBJECTIVES

The research objectives are as follows:

1. To explore the various techniques of PAPR reduction in OFDM systems.
2. To design improved digitally modulated code sequences with low PAPR for OFDM system.
3. To functionally simulate and analyse the proposed technique for performance evaluation.

The major aim of this research work is to study and examine the PAPR reduction methods of the OFDM system and then to propose a novel scheme with low computational complexity as well as one which has less impact on HPA efficiency and BER performance. A promising technique which is being given and proposed is based on using the Golay sequences as PAPR reduction mechanism, which attracts a lot of interest in terms of PAPR reduction for sequences of significant length. In this thesis, we examine the performance of this method and put side by side the theoretical gains as mentioned in the literature with those attained by simulation. The focus of this work is on WiMAX systems based on the OFDM mode of IEEE 802.16e specification. The performance is evaluated in the form of PAPR reduction and BER at the receiver.

1.6 THESIS OUTLINE

This thesis describes the analysis of PAPR problem of OFDM system with their relative evaluation, followed by proposed method for PAPR problem. The thesis is arranged as follows:

Chapter 2 presents an introduction of OFDM and describes its principles, advantages and disadvantages, the basic OFDM transceiver model. It explores the issue of the PAPR in detail starting with a mathematical definition of the PAPR. Theoretical CCDF results are compared to simulated CCDF results identifying the processes which influence large peaks such as the number of subcarriers and oversampling. Chapter 2 further presents the analysis of PAPR

reduction techniques such as clipping and filtering, partial transmit sequences (PTS), selective mapping (SLM), and other methods like, non-linear companding tone reservation (TR) and tone insertion (TI) are examined.

Chapter 3 explains Golay sequences as a PAPR reduction technique. Thereafter, the implementation and the performance of this technique in terms of CCDF and BER is presented and the simulation model and results by using MATLAB have been implemented with QAM 256, QAM 64, and QAM16 modulation schemes.

Chapter 4 deals with the performance analysis of channel coding in a mobile WiMAX system. OFDM-WiMAX physical layer and its implementation with reduced transmission power is discussed. The proposed Golay encoded OFDM-WiMAX system has been simulated in MATLAB.

Finally, **Chapter 5** concludes the research work. Further, a brief description about the future work/scope will be given as a motivational seed for further research work.

1.7 SUMMARY OF THE CHAPTER

This chapter acts as a capsule for the motivation of the thesis. An exhaustive literature survey has been presented. Based on this, the objectives of the thesis have been identified, in which the main focus is on performance enhancement of WiMAX systems based on the OFDM mode of IEEE 802.16e specification. The performance has been calculated in terms of PAPR reduction and BER at the receiver.

Next chapter describes the introduction of OFDM, its principles, advantages, disadvantages, and the basic OFDM transceiver model with mathematical definition of the PAPR.

PEAK-TO-AVERAGE POWER RATIO OF OFDM SYSTEMS

2.1 INTRODUCTION

The wireless networks based on modern applications need to deal with unpredictable high data rates. However, it is very difficult to communicate over a continuously changing and random wireless channel at high data rate. Multi-carrier transmission techniques have been developed to provide wireless communications at very high data rates. OFDM is an efficient and marvellous technique out of various multicarrier modulation (MCM) techniques in which the data is carried on a large number of parallel data streams using several orthogonal sub-carrier signals. A conventional modulation scheme is generally used for modulation of each low data rate sub-carriers to provide high data rate communications. The major benefit of OFDM in comparison to single-carrier techniques is that OFDM provides capability to manage the severe frequency-selective multipath fading channel conditions and attenuation of signals at high frequencies in copper wires without using complex equalization filters. Thus, OFDM provides a solution for high speed data transmission at a competitive accuracy with a manageable complexity.

During the high data rate transmission, significant channel distortion is experienced in the data. Using a simple receiver, it becomes quite impractical to improve the received data. The complex receiver structure utilizes computationally expensive equalization and channel estimation algorithms to approximate the channel correctly for perfect recovery of the data that was originally transmitted. Here, OFDM simplifies the equalization problem drastically by changing the frequency-selective channel to a flat fading channel.

In spite of the above advantages OFDM systems still exhibit some demerits. One of them is the elevated peak-to-average power ratio (PAPR). PAPR is defined as randomly sinusoidal

peaks occurring in OFDM signal when the OFDM travels through the multipath fading channel. In the transmitted signal, large signal peaks occur because of the addition of signals in various sub-channels in phase. To mitigate this problem, it is required to cut the transmitted signal power for operating the power amplifier at the source in the operating range. However, due to decrease in the transmitted signal power, the communication system functions inefficiently. Thus, the detection efficiency of OFDM receiver may degrade the performance of the system. Therefore, it becomes critical to research on PAPR characteristics and methods of reducing the PAPR for the better utilization of OFDM techniques. In other words, optimum and efficient reduction of the PAPR is the most critical requirement for efficient utilization of the OFDM systems. In order to design an efficient PAPR reduction scheme, it was required to perform a detailed analysis of the different existing PAPR reduction techniques.

In this chapter, a brief introduction has been provided for the basic OFDM system model. A comprehensive study and analysis of PAPR has been done. This chapter provides the necessary context for the main work in this thesis.

2.2 SYSTEM MODEL BASED ON OFDM

The basic OFDM system model has been illustrated in figure 2.1. A QAM modulator is used to modulate the input data stream which results in a stream of complex symbols of length N . The modulated stream is denoted as $X[0], X[1], \dots, X[N - 1]$. The modulated stream is converted into a set of N parallel QAM symbols $X[0], \dots, X[N-1]$ using a serial-to-parallel converter. These N symbols represent discrete frequency components of the output $s(t)$ of the OFDM modulator. An inverse DFT is performed using an IFFT algorithm to convert these frequency components into time samples. The IFFT generates a sequence $x[n] = x[0], \dots, x[N - 1]$ of length N for the OFDM symbol in time domain. Being in time domain, the IFFT N output symbols form the baseband signal that carries the data symbol on a set of N orthogonal subcarriers.

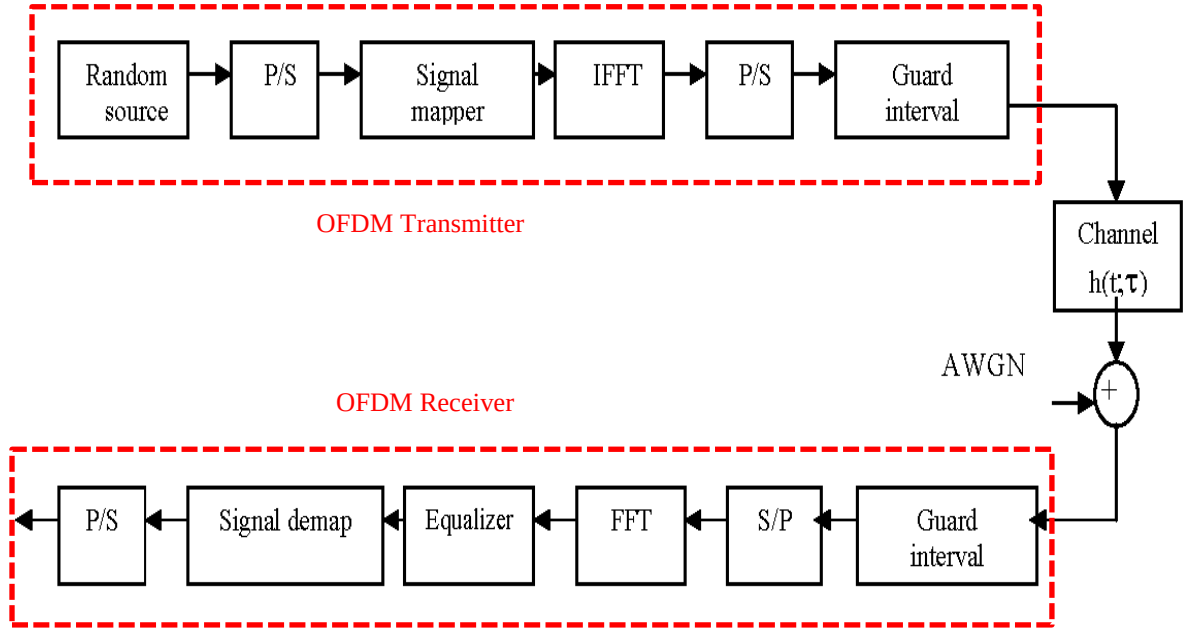


Figure 2.1: An OFDM system model

After IFFT, a cyclic prefix is introduced as a guard interval with the span more than the highest delay of the multipath propagation channel. In order to preserve independence of OFDM symbols and orthogonality of the sub-carriers, guard interval is introduced when OFDM signal is being communicated over the multipath fading channel. The guard interval is basically a cyclic extension of the symbol to be transmitted and transforms the signal into a periodic signal so that the symbol timing is easily recovered at the receiver. After adding the guard interval, a parallel to serial converter is used to convert the symbols in to a serial time waveform which is transmitted over the multipath fading channel.

The signal transmitted from the OFDM transmitter travels through a multipath channel. The data symbols which were transmitted on single or multiple sub-carriers may be severely attenuated by the frequency-selective radio channel that leads to bit errors. The attenuation is majorly caused due to addition of white noise and delay spread. Therefore, the forward error coding (FEC) and interleaving may be used to alleviate consequences of multi-path fading channel. This is achieved by using an efficient coding scheme by scattering the coded bits

throughout of bandwidth of the transmitted system. For example, digital signal processing at the transmitter may be used to generate the complex and equivalent baseband signals with different phases for transmission over the multipath fading channel.

The operation of the receiver is reverse in comparison to the transmitter. The receiver removes the guard interval and performs fast Fourier transform (FFT) of each symbol to calculate the original transmitted spectrum. After removing the guard interval, the time dispersive characteristics of the multipath channel changes to cyclic convolution characteristics. Owing to its cyclic convolution characteristics, the multipath channel's effects are restricted and orthogonality of the sub-carriers is maintained. Since the redundant guard interval must be transmitted, there is some loss in the effective transmit power which remains the single drawback of this technique. The signal to noise ratio (SNR) loss of 0.5 to 1 is contributed by the selection of the guard interval with a length of $1/10^{\text{th}}$ to $1/4^{\text{th}}$ of the symbol. The equalization required for detecting the received data symbols is provided by multiplying output of discrete Fourier transform (DFT) with the channel estimations.

2.3 PAPR IN OFDM SYSTEMS

In OFDM system, transmitted signals possess enormous peak values in time domain as a number of sub-carrier components are joined through the inverse fast Fourier transform (IFFT) operation. Comparing with single-carrier systems, OFDM possess large value of PAPR. High PAPR of the OFDM system remains the most detrimental aspect since the SNR of digital to analog converter (DAC) gets reduced by OFDM. This degrades power amplifier efficiency of the transmitter.

PAPR is derived by a relation of the average power and maximum power of the complex pass-band signal $s(t)$ as

$$PAPR\{\tilde{s}(t)\} = \frac{\max|\text{Re}(\tilde{s}(t)e^{j2\pi f_c t})|^2}{E\{|\text{Re}(\tilde{s}(t)e^{j2\pi f_c t})|^2\}} = \frac{\max|s(t)|^2}{E\{|s(t)|^2\}} \quad (2.1)$$

When all N subcarrier components in the OFDM system are having identical phases then all the N sub-carrier components get added constructively to provide the maximum power. There are a number of factors which effect PAPR. If $E\{|s(t)|^2\} = 1$, then $PAPR = N$, which is utmost power that is equal to N . The probability of reaching the maximum power signal increases with increase in number of sub-carrier components. Therefore, PAPR increases by increasing the number of sub-carrier components. Modulation order is another factor that affects the PAPR. When the sub-carrier's modulation is a higher-order QAM type, the PAPR of the summed OFDM signal is increased by PAPR of the QAM constellation used.

2.3.1 Complementary cumulative distribution function (CCDF) for PAPR

OFDM system combines multiple sub carriers which causes increase in PAPR. The increase in PAPR is related to number of sub carriers and their order of modulation. The PAPR performance of OFDM systems is demonstrated by using the CCDF of PAPR. The graph of the signal's relative power levels versus the probability of their occurrence is called as CCDF curve. This curve illustrates the amount of time the signal remains over or higher than a specified power level.

Complementary cumulative distribution function curves provide imperative data related to the OFDM signal being transmitted. The Complementary cumulative distribution function curves have been in practice for numerous additional design applications like for combining numerous signals with the help of system components, estimate spread-spectrum systems, and to devise and examine radio frequency components. In addition, these graphs also present PAPR data as required by designers. Most significant application of CCDF curves is to recognize signals' power characteristics which are to be amplified, mixed, and de-coded. Considering a reference level $PAPR_o > 0$, CCDF is defined as a probability of the PAPR greater than the reference value i.e. CCDF can be expressed as $CCDF(PAPR_o) = Pr(PAPR > PAPR_o)$.

The amplitude of the OFDM signal $s(t)$ tracks a Rayleigh distribution. Assuming that $\{Z_n\}$ represents the magnitudes of complex samples $\{|s(nT_s/N)|\}$ and $E\{|s(t)|^2\} = 1$ represents the average power of $s(t)$, then $\{Z_n\}$ is an identically distributed random variable having the probability density function given as

$$f_{Z_n}(z) = \frac{z}{\sigma^2} e^{-\frac{z^2}{2\sigma^2}} = 2ze^{-z^2}, n=0,1,2,\dots,N-1 \quad (2.2)$$

where $E\{Z_n^2\} = 2\sigma^2 = 1$. Suppose $Z_{\max}$ represents a crest factor, then the cumulative distribution function (CDF) of $Z_{\max}$ is written as

$$F_{Z_{\max}}(z) = P(Z_{\max} < z) = P(Z_0 < z) \cdot P(Z_1 < z) \dots P(Z_{N-1} < z) = (1 - e^{-z^2})^N \quad (2.3)$$

where $P(Z_n < z) = \int_0^z f_{Z_n}(x) dx, n=0,1,2,\dots,N-1$. To verify that probability of crest factor is more than z , a complementary CDF (CCDF) is assumed as:

$$\tilde{F}_{Z_{\max}}(z) = P(Z_{\max} > z) = 1 - P(Z_{\max} \leq z) = 1 - F_{Z_{\max}}(z) = 1 - (1 - e^{-z^2})^N \quad (2.4)$$

The above equations (2.3) and (2.4) are derived based on the assumptions that N samples are independent and are quite large. The calculation of the exact CDF is very complicated, so a simple form of CDF is given as

$$F_Z(z) \approx (1 - e^{-z^2})^{\alpha N} \quad (2.5)$$

It has been found that for sufficiently large value of N , an appropriate value of α is 2.8. Figure 2.2 illustrates hypothetical & simulated OFDM signals' CCDFs with $N = 64, 128, 256, 512, 1024$. It can be noted from the figure 2.2 that there is a deviation between the simulated and theoretical results. The deviation increases as the value of N decreases. Therefore, it can be inferred that the equation 2.5 is accurate only in the case of N being sufficiently large.

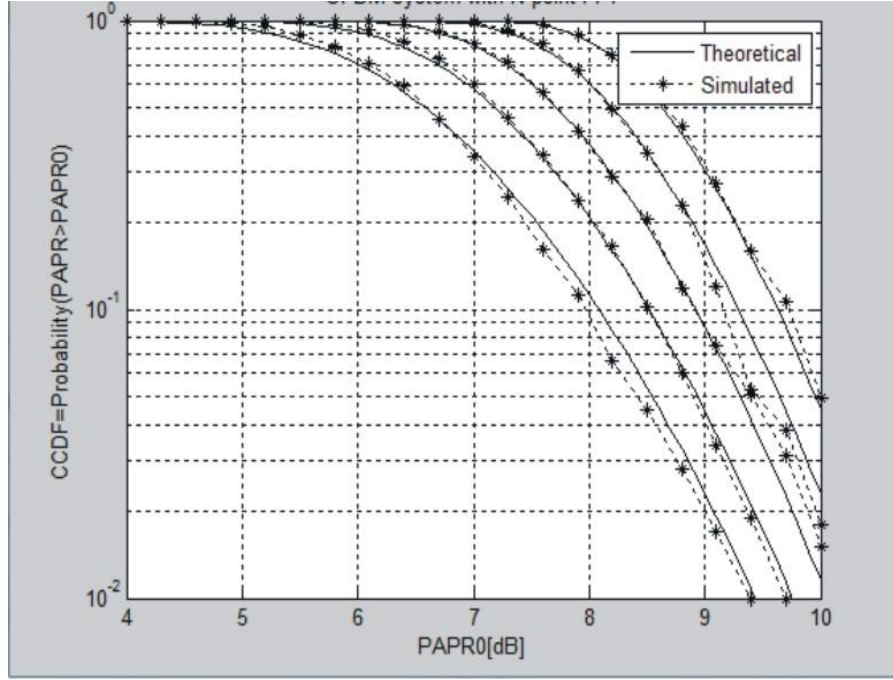


**Figure 2.2: Comparison of theoretical & simulated OFDM signals' CCDFs for
N = 64, 128, 256, 512, and 1024**

2.3.2 PAPR of QAM modulations

Figure 2.3 shows the 16-QAM constellation. The PAPR for 16-QAM is calculated by the equation given below

$$\text{PAPR}_{16\text{-QAM}} = \frac{(9A^2 + 9A^2)}{1} = 1.8 = 2.55 \text{ dB} \quad (2.6)$$

i.e. PAPR of 2.55 dB is obtained for 16-QAM by using 4 symbols (edge constellation points) from a 16 QAM symbols. Similarly, the PAPR for the 4 internal constellation points is calculated as

$$\text{PAPR}_{16\text{-QAM}} = \frac{A^2 + A^2}{1} = 0.2 = -7 \text{ dB} \quad (2.7)$$

The PAPR for 8 constellation points is given by

$$\text{PAPR}_{16\text{-QAM}} = \frac{(A^2 + 9A^2)}{1} = 1.0 = 0.0 \text{ dB} \quad (2.8)$$

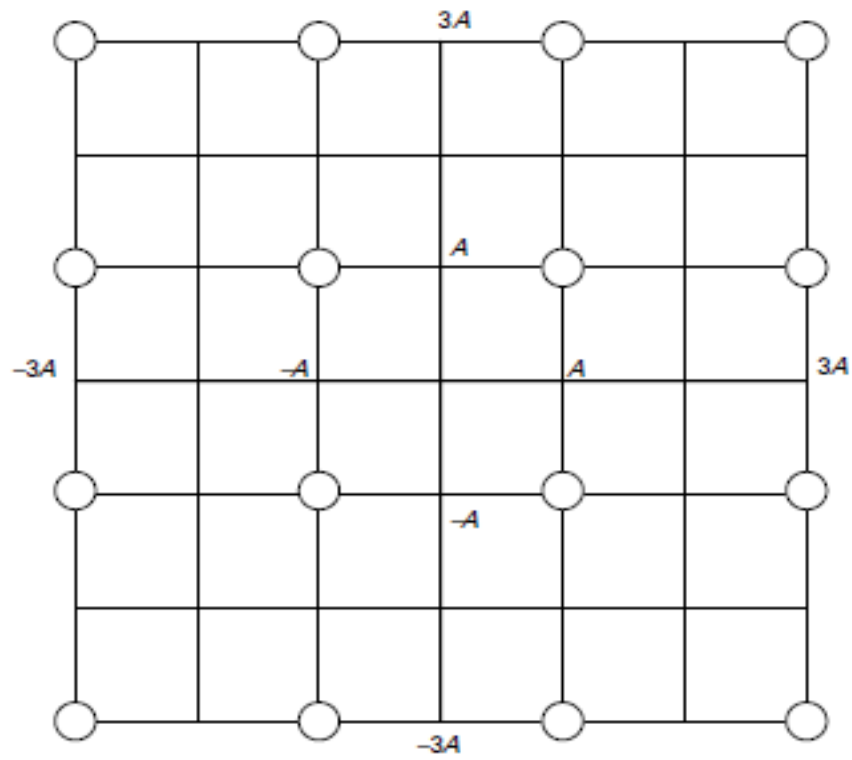


Figure 2.3: 16-QAM constellation

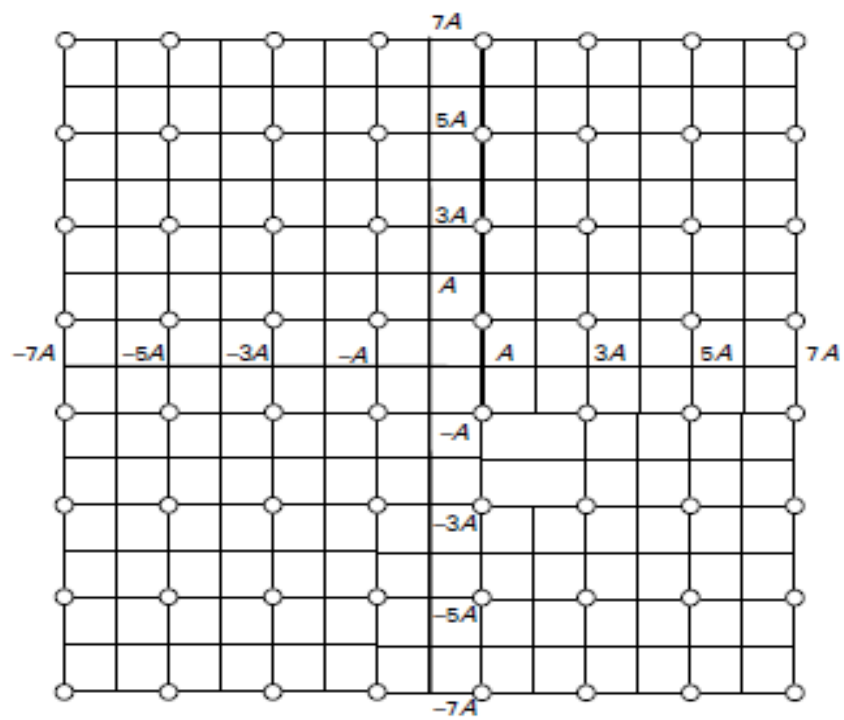


Figure 2.4: 64-QAM constellation

Figure 2.4 illustrates constellation points of the 64-QAM constellation. The real and imaginary parts take A, 3A, 5A, 7A, -A, -3A, -5A and -7A amplitude values where A is equal to $\frac{1}{\sqrt{42}}$ for 64 QAM.

For 64 QAM the maximum PAPR can be found as

$$\text{PAPR}_{64\text{-QAM}} = \frac{(49A^2 + 49A^2)}{1} = \frac{98}{42} = 3.68\text{dB} \quad (2.9)$$

The result indicates that PAPR of 3.68 dB is obtained by 64-QAM with 6.25% (1/16) chance i.e. out of a sum of 64 symbols, four symbols are at PAPR of 3.68dB. It can be noted that for only one sub-channel (OFDM sub-carrier) transmission, maximum PAPR of 0.0, 2.55 and 3.68 dB is obtained by QPSK, 16-QAM and 64-QAM [89] respectively.

2.4 REDUCTION OF PAPR IN THE OFDM SYSTEMS

In OFDM technique, total bandwidth is distributed among a number of thin sub-channels and the information is sent in parallel. This technique possesses many advantages like immunity to impulse interference, large spectral efficiency, and the frequency selective fading in the absence of powerful channel equalizer.

In spite of having numerous advantages, foremost shortcoming of OFDM technique is elevated PAPR. Large PAPR leads to in-band deformation & out-band radiation. It also reduces efficiency of RF power amplifier and increases complexity of the analog to digital converters (ADC) and digital to analog converters (DAC).

An intrinsic property of the multi-carrier techniques is that the transmitted signal has high dynamic frequency range. The high dynamic range of the multi-carrier signals leads to distortion in the signal during amplification at the transmitter. Practically, the power amplifiers at the transmitter section amplify different parts of the signal differently due to high dynamic range of the multi-carrier signal. This results in distortion of the multi-carrier signal, reduces its BER, and also introduces spectral regrowth by radiating energy at adjacent and higher

frequencies values than the frequency of the OFDM signal. Therefore, to efficiently utilize the OFDM systems, it is required to diminish PAPR of OFDM systems.

2.5 PAPR REDUCTION TECHNIQUES

As discussed above, elevated PAPR of signal to be transmitted is the main disadvantage in functional implementation of multicarrier systems. OFDM signal is a superposition of N modulated sinusoidal signals. The superposition of the signals increases the maximum power of the OFDM signal. Due to increase in the maximum power, ADC and DAC require additional bits for analog to digital and digital to analog conversion which results in increase in complexity of ADC & DAC. Moreover, increase in the maximum power results in in-band distortion and spectral spreading of the transmitted signal due to inter modulation effects exhibited by the non-linear power amplifier.

To overcome these drawbacks, researchers have utilized power back off strategies so that the circuit operates in its linear space. However, the drawbacks of the power back off strategies are increase in transmitter circuitry and decrease in the user terminal battery timeline. A better solution to overcome these drawbacks has been proposed by diminishing PAPR of signal to be transmitted by manipulating the OFDM signal. Therefore, it was important and necessary for researchers to develop well organized and optimized PAPR reduction techniques that do not give up the power competence and at the same time, which can decrease the great signal peak incidence at the power amplifier input to reduce the harmful effects of non-linear distortions.

A number of techniques have been designed and implemented to reduce PAPR which are categorized such as multiple signalling techniques, signal distortion techniques, probabilistic techniques, and coding techniques. In this chapter, a comprehensive review of few techniques used for PAPR lessening has been carried out.

2.5.1 Amplitude Clipping

One of the easiest methods of PAPR reduction in OFDM system is amplitude clipping which is used to intentionally clip high peaks of OFDM signal before the amplification. With the help of a soft envelope limiter, the clipping is performed at baseband such that the OFDM signal envelope above a certain level is clipped whereas the OFDM signal envelope is not clipped if the OFDM signal envelope is below the certain level.

Figure 2.5 shows amplitude clipping done on the analog signal $a(t)$ after digital to analog conversion. The output $o(t)$ of the soft envelope limiter appears as shown in figure 2.5 such that amplitude above the certain level A is clipped. The mathematical equation expressing the deformation caused by this method is given in equation (2.10) as

$$d(t) = o(t) - a(t) \quad (2.10)$$

Theoretically, the wavelength of the clipped signal is infinite because the derivative of $d(t)$ depicts discontinuities at instants of clipping. This leads to increase in the in-band deformation and out-of-band emission. The consequence of in-band distortion is reduction in BER whereas out of band emission decreases the spectral effectiveness of the system. So, in order to reduce the consequences of out-of band radiation, filtering is done after the process of clipping inspite of the fact that it introduces some spectral regrowth.

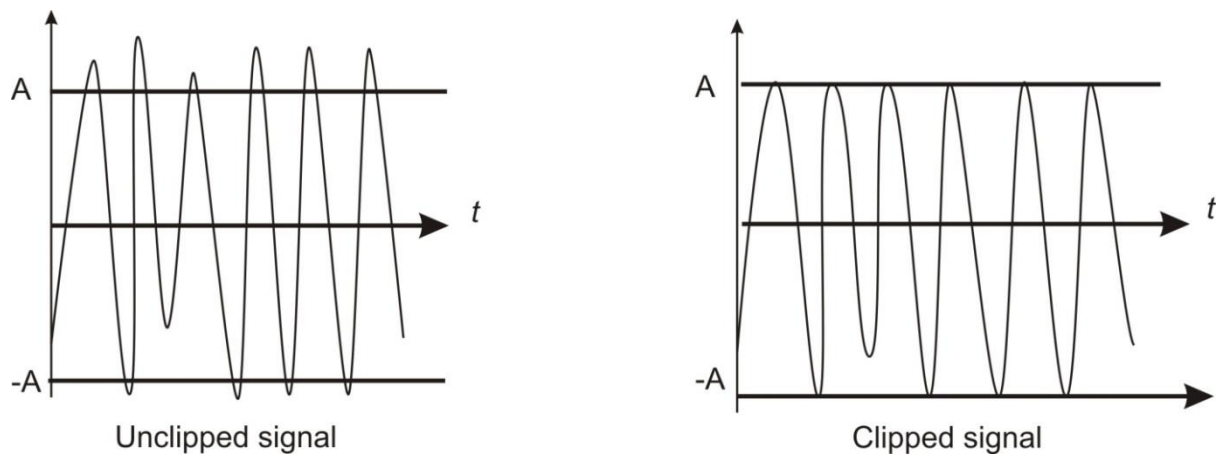


Figure 2.5: Effect of clipping on a signal

2.5.1.1 Filtering after clipping of oversampled signal

In most of the OFDM systems, filtering after clipping process is done prior to D/A converter on an OFDM signal's oversampled adaptation [20]. Considering, the oversampling factor as $J \geq 1$ then

$$s(k) = -\frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x(n) e^{j2\pi nk/JN}, \quad 0 \leq k \leq JN-1 \quad (2.11)$$

are samples of $s(t)$ related with known wedge of data $x = [x(0), x(1), \dots, x(N-1)]^T$

. The oversampling factor J is utilized in the OFDM transmitter to carry out the operations of clipping and filtering.

Figure 2.6 shows generation of a oversampled series $s = [s(0), s(1), \dots, s(JN-1)]$ proficiently as the IDFT of the zero-padded information block $x^{(xP)}$ is extended with $(J-1)N$ zeros as

$$x^{(xP)} = [x(0), x(1), \dots, x(N-1), \underbrace{0, 0, \dots, 0}_{(j-1)N}]^T \quad (2.12)$$

A soft covering limiter clips each sample $s(k)$. Let $\rho_k e^{jqk}$ represent $s(k)$ as the coordinates which are polar, then output of soft covering limiter may be denoted as

$$\tilde{s}(k) = \begin{cases} s(k) & \text{if } \rho_k \leq A \\ Ae^{jqk} & \text{if } \rho_k > A \end{cases} \quad (2.13)$$

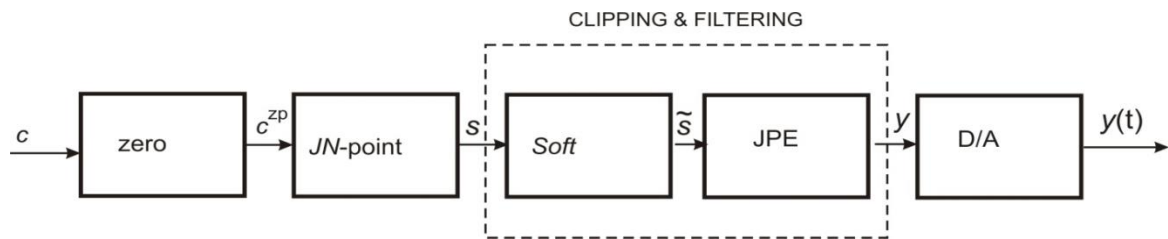


Figure 2.6: Effect of clipping and filtering operations on an oversampled OFDM signal

Normally the clipping level A is normalized to input signals root mean square (RMS) value which gives a value of clipping ratio (CR) as

$$\mu = \frac{A}{\sqrt{P_{in}}} \quad (2.14)$$

The regular power value of the samples unclipped is given as $P_{in} = E\{|s(k)|^2\}$. It is intuitively clear that resultant power is reduced by the clipping procedure. After the clipping, the OFDM signal is considered as a zero-mean circularly symmetric Gaussian process and its amplitude is Rayleigh distributed. The average power of the clipped samples is denoted by

$$P_{out} = (1 - e^{-\mu^2}) P_{in} \quad (2.15)$$

It can be observed from the equation (2.15) that as the value of μ increases, there is a decrease in difference between the P_{out} and P_{in} and at one point, it becomes zero when $\mu = \infty$ which denotes the system is ideal with no clipping.

Aliasing may take place when clipping is performed on the samples $\{s(k)\}$ instead of continuous-time signal $s(t)$. To be exact, if the clipping is performed with Nyquist rate ($J=1$), then range of output signal is folded reverse in signal bandwidth which results in in-band distortion. Moreover, it has been proved that there is no effect of clipping at Nyquist rate on reduction of PAPR. Due to this, clipping is frequently done on an oversampled adaptation of the OFDM ($J>1$). The main advantages of this technique are decrease in in-band radiation and peak re-growth however a drawback of this technique is increase in out-of-band radiation.

The simplest approach for reducing out-of-band radiation is to pass the clipped samples through a low pass filter (LPF) as shown in the figure. 2.7. The LPF outputs a vector samples as $y = [y(0), (1), \dots, y(N-1)]^T$ related to time domain. These vector samples have been appended by the cyclic prefix (CP) and provided for to the DAC. Prior to being launched over the channel, the baseband waveform is first up-converted and then fed to the power amplifier.

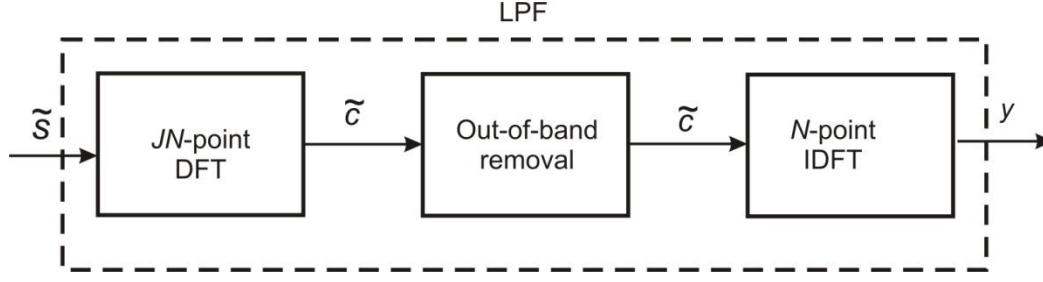


Figure 2.7: Removal of out-of-band radiation by filtering process

By DFT process as shown in figure 2.7, the sequence $\tilde{s}$ gets converted to frequency domain which results in the production of the next vector with the length JN with entries represented as

$$\tilde{x} = [\underbrace{\tilde{x}(0), \tilde{x}(1), \dots, \tilde{x}(N-1)}_{\text{in-band components}}, \underbrace{\tilde{x}(N), \tilde{x}(N+1), \dots, \tilde{x}(JN-1)}_{\text{out-of-band components}}]^T, \quad (2.16)$$

where

$$\tilde{x}(n) = \frac{1}{J\sqrt{N}} \sum_{k=0}^{JN-1} \tilde{s}(k) e^{-j2\pi nk/JN}, \quad 0 \leq n \leq JN-1 \quad (2.17)$$

The next step is without affecting the in-band components and to reduce the ‘out-of-band’ radiation by removing of end $(J-1)N$ terms of x . It gives rise to a new vector of N modified samples $\tilde{x} = [\tilde{x}(0), \tilde{x}(1), \dots, \tilde{x}(N-1)]^T$ in frequency domain. This new vector describes distorted description of data block x . Using an N -point IDFT, vector $\tilde{x}$ is converted back to time-domain which produces a sequence y of N time-domain samples. The analog signal $o(t)$ can be expressed as $\{\tilde{x}(n)\}$ after the DAC such that

$$o(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \tilde{x}(n) e^{j2\pi n f_{cs} t}, \quad 0 \leq t < T \quad (2.18)$$

From figure 2.7, it can be seen that the filtering procedure is analogous to an ideal LPF that permits entire removal of out-of-band radiation irrespective of the value of the over sampling factor J . The clipping process turns out to be useless if the signal is clipped at Nyquist rate because the components of out of band distortion get removed. Therefore, the structure of

figure 2.7 reduces to a simple pair of DFT and IDFT blocks. The method of filtering after clipping gives rise to peak re-growth although it decreases out of band radiation. This results in the actual fact that the analog signal $o(t)$ after the filtering will be more than the clipping level A . However, the peak re-growth after clipping at Nyquist rate is relatively higher when compared with filtering of the oversampled signal.

The results of simulations in figure 2.8 conjointly prove this conclusion through illustration of CCDF of PAPR of a clipped QPSK-OFDM signal with 256 sub-carriers, $\mu = 1$, and $j = 1, 2$, or 4. For the purpose of comparison, un-clipped signal when $\mu = \infty$ has also been shown by curve in figure 2.8. The analog signal $o(t)$ can be denoted by

$$\gamma_d = \frac{\max_{0 \leq k \leq LN-1} |o_k^{(L)}|^2}{\hat{P}} \quad (2.19)$$

where $\{o_k^{(L)}\}$ are samples of $o(t)$ used at L/T_s rate. Once clipping and filtering is done, the power of the OFDM block $\hat{P}$ is denoted by

$$\hat{P} = \frac{1}{N} \sum_{n=0}^{N-1} |\tilde{c}(n)|^2. \quad (2.20)$$

The simulation results have been obtained by considering $L=8$. Figure 2.8 shows that sampling rate clipping decreases the PAPR of the signal significantly in comparison to system while not clipping. Further, better results are obtained by performing the clipping on the oversampled signal. The PAPR reduces up to 2 dB by varying J from 1 to 4. It can be clearly seen that this is obtained when filtering of the signal is done after the clipping. This also leads to a bigger IDFT unit which increases the computational complexity. Comparison of theoretical and simulations results show a good trade-off at oversampling factor of 4.

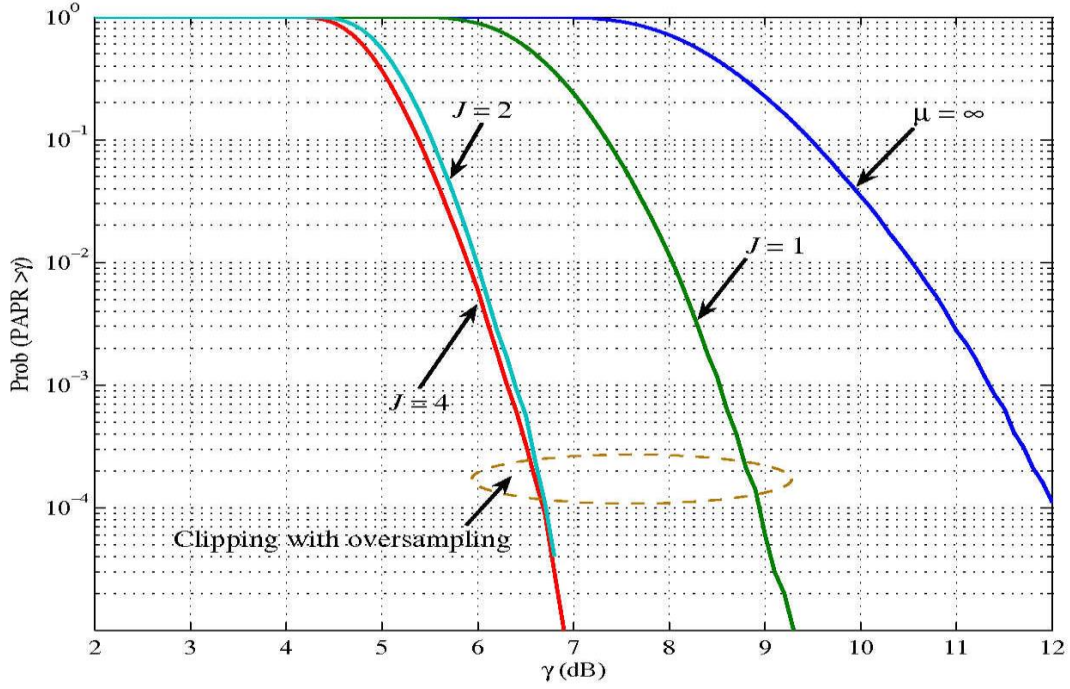


Figure 2.8: CCDF of OFDM signal after clipping and filtering with oversampling

2.5.1.2 Signal-To-Clipping Noise Ratio

The signal-to-clipping noise quantitative relation (SCNR) is a parameter generally used to measure the in-band distortion which affects the clipped signal. SCNR is usually measured as ratio of the average received signal power to power of clipped signal [22].

In order to determine SCNR, a standard OFDM receiver is considered in which the low-pass filtered incoming signal are sampled at the Nyquist sampling rate. N-point DFT units are used to retrieve the original symbols from the remaining samples after removal of CP. Considering perfect synchronization of timing and frequency, the output from DFT is given as

$$R(n) = H(n)\tilde{x}(n) + W(n), \quad 0 \leq n \leq N-1 \quad (2.21)$$

where $H(n)$ denotes the response of the channel over n^{th} sub-carrier, $W(n)$ represents thermal noise & $\tilde{x}(n)$ denotes the distorted form of $x(n)$. Equation (2.17) provides a relation between $\tilde{x}(n)$ and $\{\tilde{s}(k)\}$ and equation (2.13) denotes $\tilde{x}(n)$ in a more significant manner through observing $\tilde{s}(k)$ as the memory-less output of the non-linear unclipped signal $s(k)$.

Using the central limit theorem, it is clear that when number of sub-carriers are large, then

$\{s(k)\}$ can be considered as Guassian distributed with zero-mean. The non-linearity output $\tilde{s}(k)$ [41] is given by

$$\tilde{s}(k) = \eta s(k) + d(k), \quad 0 \leq k \leq JN - 1 \quad (2.22)$$

The zero-mean distortion term $d(k)$ is independent of $s(k)$, whereas an attenuation factor η is given by the following equation as

$$\eta = \frac{E\{\tilde{s}(k)s^*(k)\}}{E\{|s(k)|^2\}}. \quad (2.23)$$

Considering clipping ratio as μ , then the output [26] of the soft envelope limiter is given by

$$\eta = 1 - e^{-\mu^2} + \frac{\sqrt{\pi}\mu}{2} \text{erfc}(\mu) \quad (2.24)$$

with

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt \quad (2.25)$$

Substituting equation (2.22) into equation (2.17)

$$\tilde{x}(n) = \eta x(n) + D(n), \quad 0 \leq n \leq N - 1 \quad (2.26)$$

$$\text{where } D(n) = \frac{1}{J\sqrt{N}} \sum_{k=0}^{JN-1} d(k) e^{-j2\pi nk/JN} \quad (2.27)$$

$D(n)$ denotes in-band deformation over the n^{th} sub-carrier. Although the PDF of $d(k)$ is non Gaussian because of the addition of large peaks still $D(n)$ is approximately Gaussian because of a large quantity of clips taking place in the OFDM blocks. This is because $D(n)$ is addition of number of non-zero values of arbitrary variable $d(k)$. Equation 2.26 shows that additional noise is introduced during the clipping process. The SCNR over the n^{th} sub carrier can be obtained by taking $C_2 = E\{|x(n)|^2\}$

$$SCNR_n = \frac{\eta^2 C_2}{P_{D,n}} \quad (2.28)$$

Where $P_{D,n} = E\{|D(n)|^2\}$ is power spectral density of $d(k)$. Clearly, $SCNR_n$ does not

depend upon the frequency response of the channel as noise due to clipping is being introduced at sender which as a result fades away with the length of the signal.

Substituting equation (2.26) into equation (2.21)

$$R(n) = H(n)[\eta x(n) + D(n)] + W(n), \quad 0 \leq n \leq N - 1 \quad (2.29)$$

Based on equation (2.29), an equivalent model for the clipped OFDM transmission channel is represented in figure 2.9.

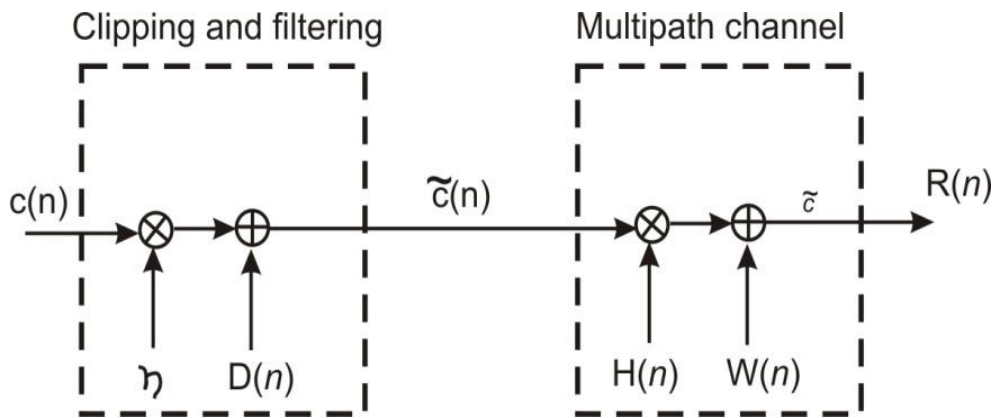


Figure: 2.9 Equivalent model of a clipped OFDM multipath channel

Figure 2.10 shows that SCNR is a function of μ with 256 sub-carriers for an OFDM signal. A unit power QPSK constellation i.e. $C_2=1$ and $J=4$ has been utilized for generating the data symbols. By averaging the equation (2.28), the results are obtained numerically over the given sub-carriers. It may be deduced that SCNR increases by increasing the value of μ and remains quite high even when there is severe clipping.

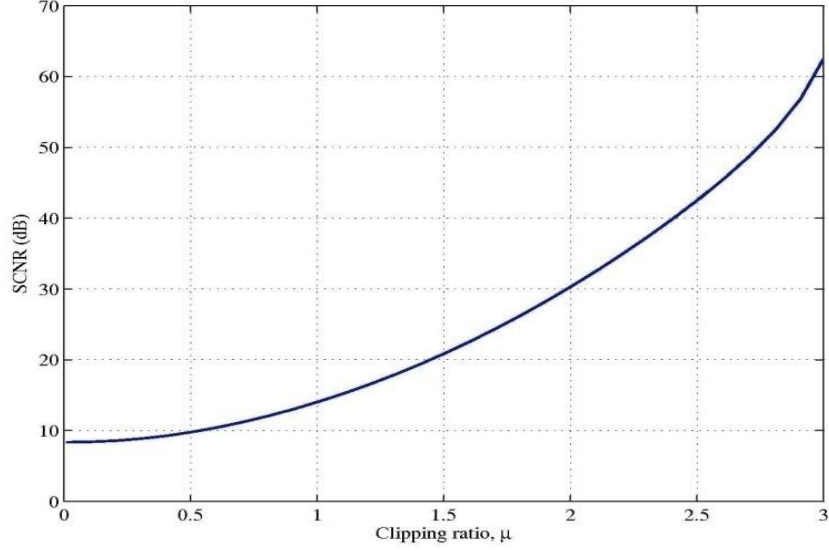


Figure 2.10: SCNR for a QPSK-OFDM signal as a function of μ with 256 sub carriers and oversampling factor $J = 4$

Figure 2.11 illustrates effects of clipping noise on performance of error-rate. BER is calculated as a function of E_b/N_0 . Here $N_0/2$ is the dual-end noise PSD over an additive white Gaussian noise (AWGN) channel using different values of μ and E_b is the average energy per bit post clipping and filtering. The simulation results show that there is decrease in SNR by 3.5 dB at a BER of 10^{-4} as compared to unclipped signal i.e. with $\mu = \infty$ and decreases by 0.5 dB with $\mu \geq 1.5$.

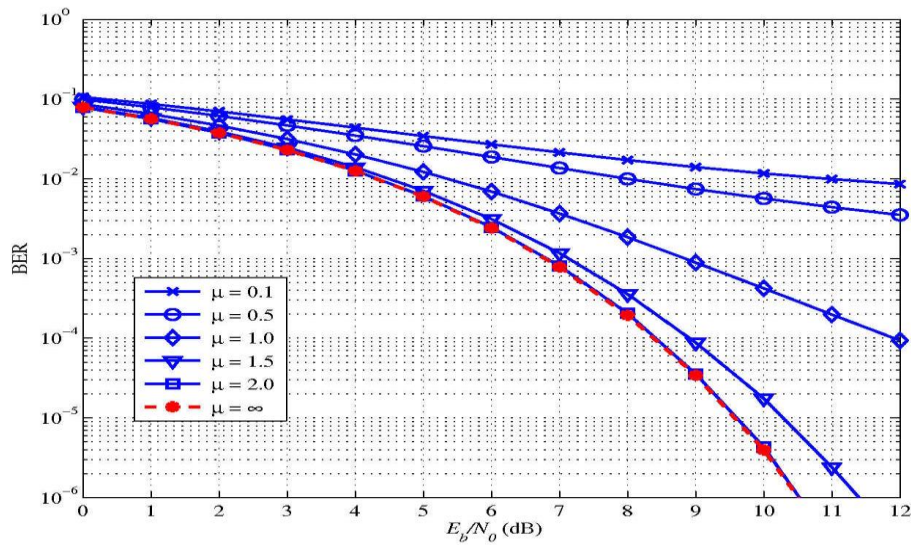


Figure 2.11: The performance analysis of a QPSK-OFDM transmission by varying the clipping noise

2.5.1.3 Reduction in Clipping Noise

Numerous methods have been suggested for reducing disadvantages caused due to noise produced by clipping in OFDM systems. Few of them propose interpolation of the received oversampled samples[21] to recover the original signal from clipped signal. However, this results in decrease in spectral efficiency because of out of band radiation at the transmitter side as a result of exact interpolation. Another technique is the iterative cancellation of clipping noise which does not need any bandwidth expansion. In this technique, the detected data is used to reduce the distortion caused by clipping noise.

This technique works in the frequency domain and it is assumed that frequency response of channel is available at receiver. The output data at j^{th} iteration results in the vector given by $\hat{c}^{(j)} = [\hat{c}^{(j)}(0), \hat{c}^{(j)}(1), \dots, \hat{c}^{(j)}(N-1)]^T$. This is followed by cancellation of clipping noise as follows:

(1) The clipping and filtering operations (shown in figure (2.12) which were performed at the transmitter are also performed on the detected data $\hat{c}^{(j)}(n)$. This results in N sample sequence

$$\tilde{c}^{(j)} = [\tilde{c}^{(j)}(0), \tilde{c}^{(j)}(1), \dots, \tilde{c}^{(j)}(N-1)]^T$$

which is comparable with the equation (2.26) and is given as

$$\tilde{c}^{(j)}(n) = \eta \hat{c}^{(j)}(n) + \hat{D}^{(j)}(n), 0 \leq n \leq N-1 \quad (2.30)$$

where as η is calculated using equation (2.24).

(2) From equation (2.30), the clipping noise conditions $\hat{D}^{(j)}(n)$ may be written as

$$\hat{D}^{(j)}(n) = \tilde{c}^{(j)}(n) - \eta \hat{c}^{(j)}(n) \quad (2.31)$$

Subtracting these conditions from DFT output gives the following modified sequence

$$\hat{R}^{(j)}(n) = R(n) - H(n) \hat{D}^{(j)}(n). \quad (2.32)$$

When the equations (2.29) and (2.31) are substituted into the equation (2.32), the results is given as follows

$$\hat{R}^{(j)}(n) = \eta H(n)c(n) + H(n)[D(n) - \hat{D}^{(j)}(n)] + W(n) \quad (2.33)$$

where $D(n) - \hat{D}^{(j)}(n)$ is the remaining clipping noise over the n th sub-carrier.

The resulting output of DFT $\hat{R}^{(j)}(n) = [\hat{R}^{(j)}(0), \hat{R}^{(j)}(1), \dots, \hat{R}^{(j)}(N-1)]^T$ is passed through channel equalization and detector element. $\hat{c}^{(j+1)}(n)$ ($n=0,1,\dots,N-1$) is the output which is used in the subsequent iteration.[22]

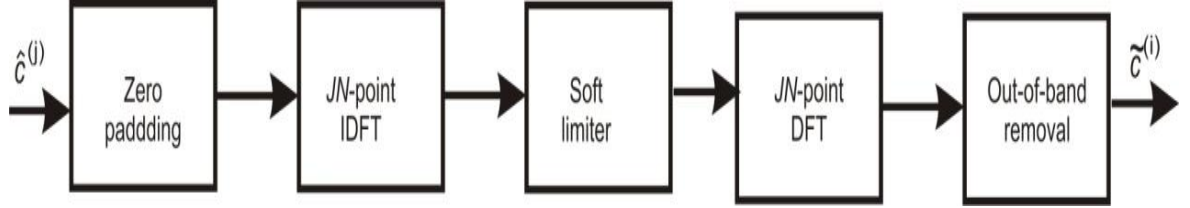


Figure 2.12: Signal regeneration at the receiver (clipped & filtered)

Simulation results have shown that the error rate performance improves by increasing number of iterations. This is because with increase in the number of iterations, the clipping noise component $\hat{D}^{(j)}(n)$ becomes more accurate which directly improves the error rate performance.

2.5.2 Selected Mapping (SLM) Technique

SLM technique has been introduced in [23] for reducing the PAPR of multi-carrier modulation systems. This method can also be used for other applications and has the advantage of reducing the complexity and providing considerable gains. SLM being a distortion less technique identifies the actual transmitted signal from a set of other signals, all of which have the same information. The information of signal generated, needs to be transmitted and cautiously protected from bit errors.

SLM is considered to be a better distortion-less technique for reduction in PAPR in OFDM. But SLM exhibits high complexity as the inverse fast Fourier transform (IFFT) and phase search complexity increases which remains as its disadvantage. Based on the random phase sequence selection, the PAPR reduction performance can be decided [24]. In order to reduce

high PAPR, Wen et al. [25] proposed two coding schemes in which the former used parity checking coding scheme and the latter employed SLM method.

One of the probable approaches of reducing the PAPR in multi-carrier systems is based on mapping the input sequence $x = [x(0), x(1), \dots, x(N-1)]^T$ to a set of different signals. This technique is known as selected mapping because a signal having the best characteristics is chosen from a set of signals for transmission.

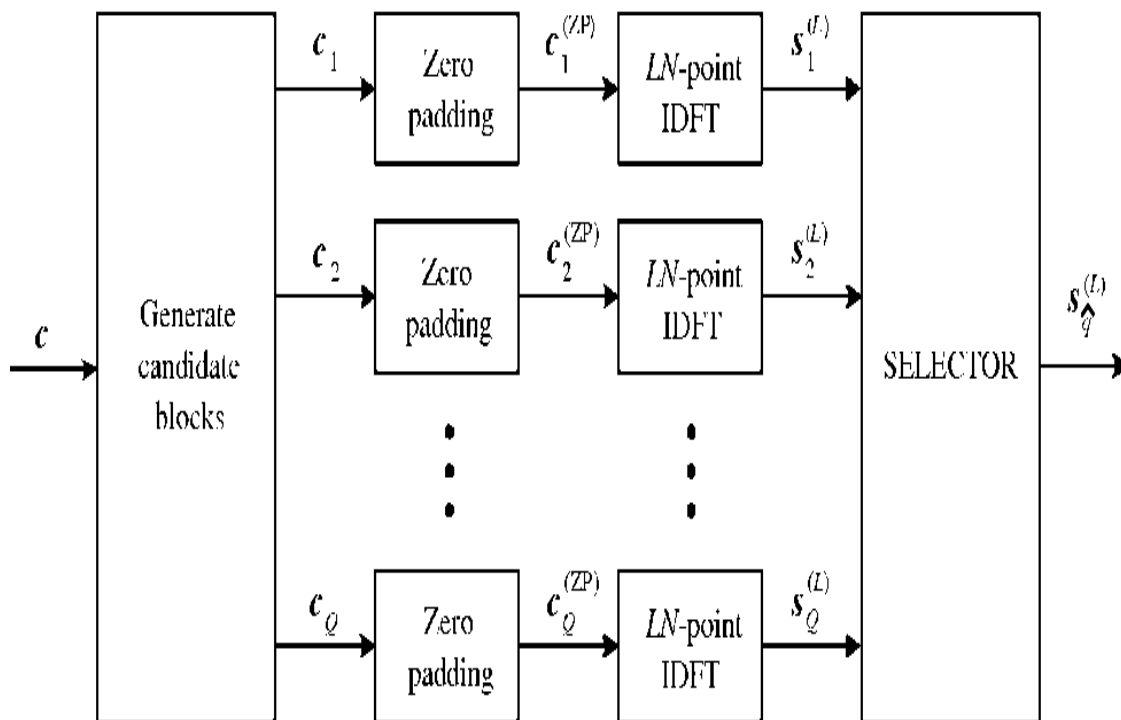


Figure 2.13: PAPR Reduction Using SLM technique

Figure 2.13 illustrates the building block plan of SLM technique. It is clear from the block diagram that by using an appropriate algorithm, the transmitter generates blocks of information $c_q = [c_q(0), c_q(1), \dots, c_q(N-1)]^T$ ($q=1, 2, \dots, Q$). All blocks c_q are transformed into the time domain and a block with least PAPR is transmitted.

As, it is not possible to compute the PAPR of the continuous time signal from its samples taken at Nyquist rate, $(L-1)N$ zeroes are padded in each block before the selected block is

input in a LN point IDFT block. This offers Q oversampled sequences $s_q^{(L)} (q=1,2,\dots,Q)$ having values

$$s_{q,k}^{(L)} = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} c_q(n) e^{j2\pi nk/LN}, \quad 0 \leq k \leq NL-1 \quad (2.34)$$

The discrete-time PAPRs are characterized by

$$\gamma_q = \frac{\max_{0 \leq k \leq LN-1} |s_{q,k}^{(L)}|^2}{P_q}, \quad q=1,2,\dots,Q \quad (2.35)$$

$$\text{where } \hat{P}_q = \frac{1}{N} \sum_{n=0}^{N-1} |c_q(n)|^2 \quad (2.36)$$

$L=4$ has been shown as an optimum value to capture the highest points (peaks) of the continuous signal. Figure 2.13 shows that the selector computes the quantity γ_q and selects the sequence $s_q^{(L)}$ which are given by

$$\hat{q} = \arg \min_{1 \leq q \leq Q} \{\gamma_q\} \quad (2.37)$$

Thereafter, the chosen sequence is passed to the DAC and amplified before transmitting over the channel. For improved illustration of PAPR reduction capability of SLM method, the CCDF of γ_q is given by

$$F_{\hat{q}}(\gamma) = \Pr \left\{ \bigcap_{q=1}^Q (\gamma_q \geq \gamma) \right\} \quad (2.38)$$

where $\gamma_{\hat{q}}$ is the smallest value in the set $\{\gamma_q\}$. Since, the oversampled sequences $s_q^{(L)}$ are dissimilar, the random variables γ_q are considered as independent and the equation (2.38) changes to

$$F_{\hat{q}}(\gamma) = \prod_{q=1}^Q F_q(\gamma) \quad (2.39)$$

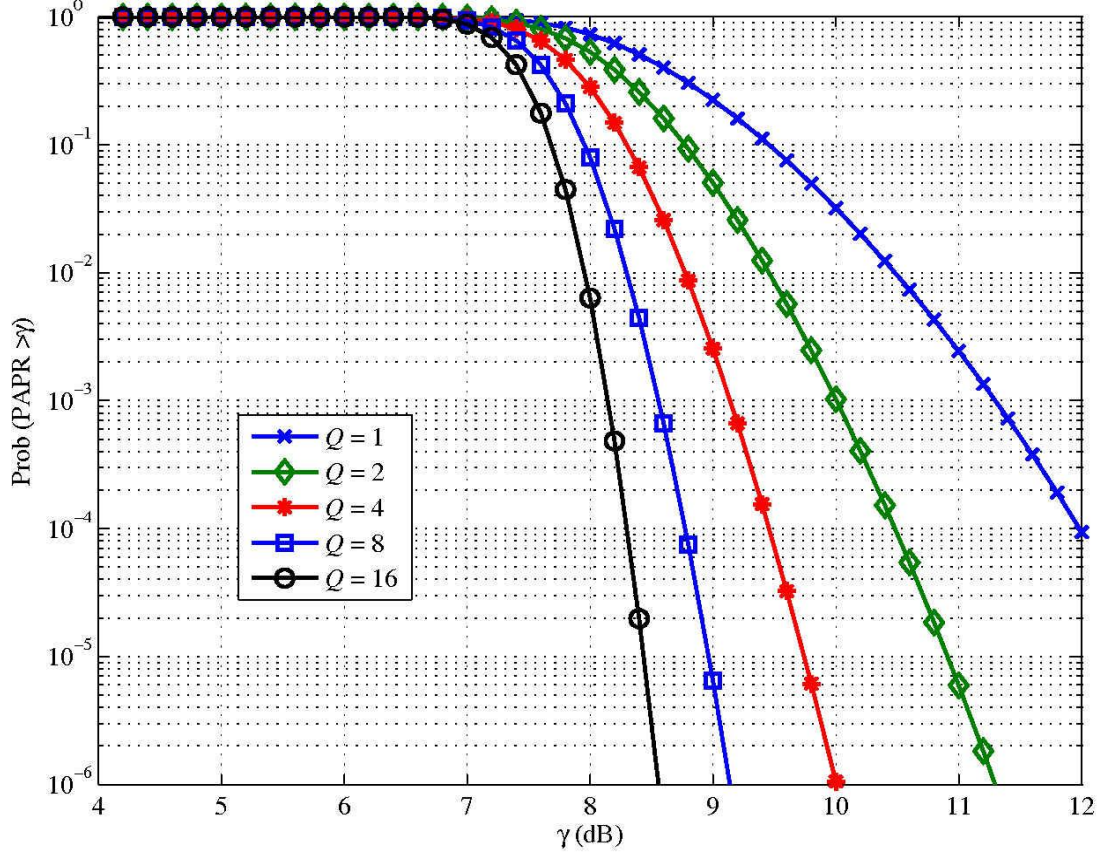


Figure 2.14: Function $F_q(\gamma)$ for various values of Q

Figure 2.14 shows that the PAPR for $N=256$ sub-carriers with different values of Q . Figure 2.14 illustrates that the extent of reduction in PAPR is dependent on value of Q . The PAPR reduces significantly when Q varies from 1 to 4 and there is marginal improvement when the value of Q is more than 4.

The primary concern of this technique is to generate sufficiently different sequences $s_q^{(L)}$ from the candidate blocks. To overcome this, permuted versions of the candidate sequence are generated using pseudo random interleavers.[26]

Figure 2.15 shows another method in which sequences are obtained by multiplying c by different pseudo-random phase sequences $b_q = [e^{j\phi_q(0)}, e^{j\phi_q(1)}, \dots, e^{j\phi_q(N-1)}]^T$. The output of the multiplication provides sequences [74] which are represented as

$$c_q(n) = c(n)e^{j\phi_q(n)}, \quad n = 0, 1, \dots, N-1 \quad (2.40)$$

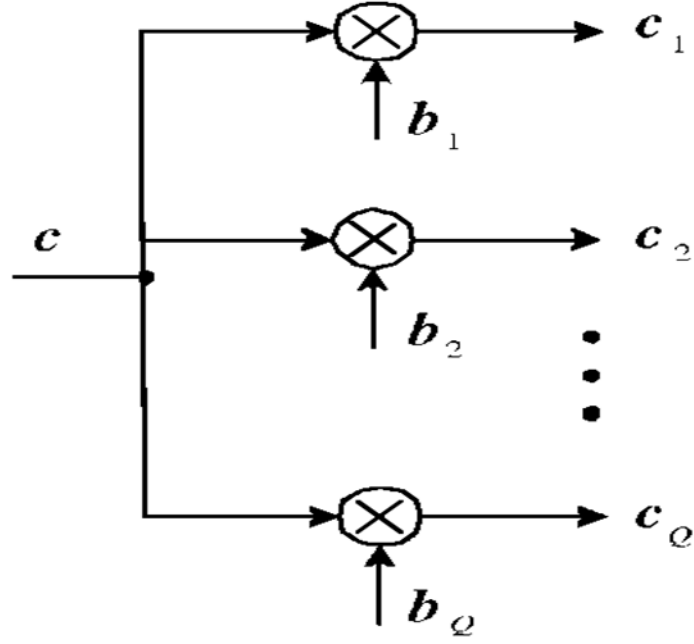


Figure 2.15: Usage of pseudo-random phase shifts for generating candidate sequences

Each phase shift $\varphi_q(n)$ is a multiple of $\pi/2$ for reducing the complexity of the system. Therefore, $c_q(n)$ is calculated from $c(n)$ by sign inversion to eliminate the need for any multiplication.

With additional advantages like reduction in out-of-band emission and elimination of inter-modulation among sub-carriers, SLM possess the potential advantage of distortion-less property as compared to amplitude clipping. Therefore, for exact recovery of data at the receiver, the receiver should have knowledge about the phase sequence and the inter-leaver used at the transmitter for generating the chosen block $c_{\hat{q}}$.

2.5.3 Partial Transmit Sequence Technique (PTS)

The information in SLM technique is mapped to a number of sequences in frequency domain. A separate IDFT operation has to be performed for measuring the PAPR of each sequence which increases the system complexity. Therefore, the major limitation of SLM technique is that a limited number of candidate sequences can be used in SLM technique.

Partial transmit sequence is a technique utilized to overcome this drawback in which

sequences are in time domain rather than in frequency domain as compared to SLM technique.

Therefore, a large number of candidate sequences can be obtained with few IDFT operations.

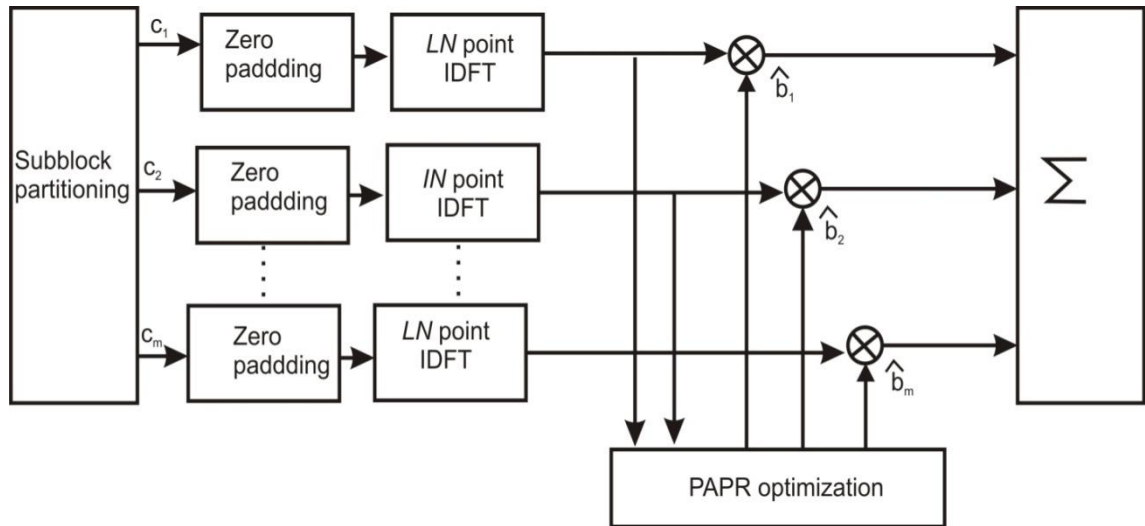


Figure 2.16: System model for the PTS technique

Figure 2.16 illustrates a system model of the PTS technique. The input vector $x = [x(0), x(1), \dots, x(N-1)]^T$ splits into M disjoint associate blocks $x_m = [x_m(0), x_m(1), \dots, x_m(N-1)]^T$ where $(m = 1, 2, \dots, M)$ and $x_m(n)$ is represented by

$$x_m(n) = \begin{cases} x(n), & \text{if } n \in J_m \\ 0 & \text{otherwise.} \end{cases} \quad (2.41)$$

The sets $\{J_m\}$ represent the indices of sub-carriers assigned to different sub-blocks so that

$$\bigcup_{m=1}^M J_m = \{0, 1, \dots, N-1\} \quad (2.42)$$

and

$$J_m \cap J_l = \phi, \quad \text{for } m \neq l \quad (2.43)$$

Hence, the input vector can be derived from equation (2.41) as

$$x = \sum_{m=1}^M x_m. \quad (2.44)$$

From figure 2.16, it can be seen that the vectors x_m are appended with $(L - 1) N$ zeros for converting to time-domain by using M parallel and different IDFT units. The output of IDFT set of oversampled vectors $\{v_m^{(L)}; m = 1, 2, \dots, M\}$ which represent the partial transmit sequences. The rotating factors $\hat{b}_m = e^{j\hat{\varphi}m}$, where $\hat{b} = [\hat{b}_1, \hat{b}_2, \dots, \hat{b}_M]^T$ are then combined with these sequences. The resulting time domain samples are denoted by

$$s^{(L)}(\hat{b}) = \sum_{m=1}^M b_m v_m^{(L)} \quad (2.45)$$

These samples are input into the DAC and then transmitted over the channel. The PAPR reduction block calculates phase shifts $\{\hat{\varphi}m\}$ which reduce PAPR of the sequence $s^{(L)}(\hat{b})$. The phase shifts are divided by using a set of W elements to decrease complexity. The best possible weighting vector $(\hat{b})$ is given by

$$\hat{b} = \arg \min_b \{PAPR[s^{(L)}(b)]\} \quad (2.46)$$

where $b_m = e^{j\varphi_m}$ and $\varphi_n \in \{2\pi l / W, l = 0, 1, \dots, W - 1\}$.

Practically, the quantity of phase shifts must be $M - 1$ for better optimization as there is exponential increase in the complexity of this technique with the number of partial transmit sequences M .

Equation (2.46) describes the complication of the optimization problem for which various reduction techniques have been given in [74], [4], [48]. The weighting factors $\{\hat{b}_m\}$ are calculated in sequence in steps of $M - 1$, taking $m = 2, 3, \dots, M$ in the case of iterative flipping algorithm. We assume $W = 2$ for the purpose of illustration so that $b_m \in \{\pm 1\}$ and b_1 is arbitrarily set to unity with no performance loss. The first step of the algorithm is that it flips the sign of b_2 after initializing $b_m = 1$ for $m = 1, 2, 3, \dots, M$, and PAPRs of two signals

produced were evaluated through the weighting factors i.e. $[1, 1, 1, \dots, 1]^T$ as well as $[1, -1, 1, \dots, 1]^T$. In the next step, the value of $\hat{b}_2$ which gives the least value of PAPR is then used. Here signals obtained with $[1, \hat{b}_2, 1, \dots, 1]^T$ and $[1, \hat{b}_2, -1, \dots, 1]^T$ are evaluated for finding $\hat{b}_3$. Until all the factors $\{\hat{b}_2, \hat{b}_3, \dots, \hat{b}_M\}$ are found, the iterative procedure continues in the same manner. To obtain any value of W this algorithm can be generalized. From the set $P = \{e^{j2\pi l/W}; l = 0, 1, \dots, W-1\}$ rotating factors are taken. W alternatives are also explored at every step. When compared with the normal PTS method, much more computational saving takes place in search complexity connected with the flipping approach in which it is directly related to $W(M-1)$. But, there is degradation of system performance due to this computational saving in terms of PAPR reduction. By taking the weighting factors, $r > 1$ and by allowing simultaneous flipping at every iteration improved results are obtained. Therefore we can conclude that, a promising design of r enables the investigator to score an optimum compromise between the complexity and efficiency.

It is clearly understood that due to a large number of candidate sequences $s^{(L)}(b)$, the capability of PTS technique for reducing the PAPR enhances with M and W . The value of W is usually set to 4 and the number of partial transmit sequences should not be limited to keep the complexity of the system within tolerable limits.

Another factor that affects the performance of the system is the method of generating the sub-blocks. The sub-band approach is usually preferred because of its simplicity although simulation results show that pseudo-random technique is a better option in terms of PAPR reduction. However, it has been shown that using an interleaved design for partitioning of sub-blocks when most of the elements in each sub-block is zero, with M as a power of 2 results in a implementation of IDFT algorithms which is computationally vary efficient.

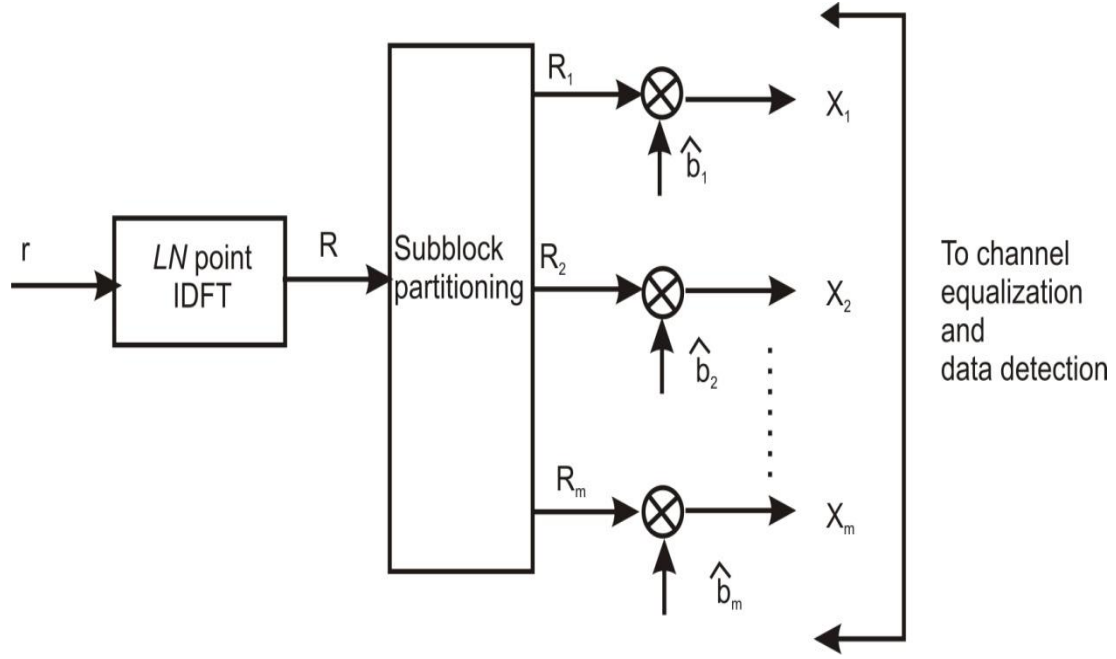


Figure 2.17: An OFDM coherent receiver system employing the PTS technique

Figure 2.17 demonstrates an OFDM receiver which uses the PTS method. Using an N point DFT process, the ‘ r ’ received samples are then converted to frequency-domain. The R resulting vector has been split into M sub blocks $\{\mathbf{R}_1, \mathbf{R}_2, \dots, \mathbf{R}_M\}$ with the same rule that was used in the transmitter. The entries R_m are stated by:

$$R_m(n) = \begin{cases} H(n)c(n)\hat{b}_m + W(n), & \text{if } n \in J_m, \\ 0, & \text{otherwise} \end{cases} \quad (2.47)$$

Where $W(n)$ is thermal noise and $H(n)$ is the frequency response for the n^{th} sub carrier. For generating M vectors $\{\mathbf{X}_1, \mathbf{X}_2, \dots, \mathbf{X}_M\}$, with $X_m = \hat{b}_m^* R_m$ the sub blocks are then rotated.

Recalling that $\hat{b}_m = e^{j\hat{\varphi}_m}$, from Equation. (2.47), it follows that $\mathbf{X}_m$ has entries

$$X_n(n) = \begin{cases} H(n)c(n) + W'(n), & \text{if } n \in J_m, \\ 0, & \text{otherwise.} \end{cases} \quad (2.48)$$

where $W'(n) = \hat{b}_m^* W(n)$.

Data detection and channel equalization block provides the final decision on the information symbols. Therefore, it can be concluded that PTS is called as the distortion less

method for reducing the PAPR because the information about exact set of rotation factors used by the transmitter is available at receiver for generating the time domain samples. Therefore, an exact and definite information of $\hat{b}$ is delivered as side information to the receiver in this technique. Since $\hat{b}$ is derived using a collection of W^{M-1} acceptable vectors, the number of bits required as side information is $(M - 1)\log_2 W$.

Figure 2.17 represents a substitute for the coherent receiver design known as differential decoding approach. However, in this method, there is a limitation for the generation of M sub-blocks. There is no change in the phase relations among sub-carriers in each sub-block because of rotation of the entries in a sub-block by the same angle. Hence, each sub-block can be decoded using the differential decoding without needing information about the rotation vector. A supplementary carrier is required to be interleaved in every sub-block to offer phase reference required for the decoding. Therefore, this technique requires a overall M redundant sub-carriers which is significant overhead for this technique.

Figure 2.18 shows a comparison of PTS and SLM techniques using CCDF of PAPR levels for $N=256$ QPSK modulated sub carriers in the OFDM system obtained by utilizing $Q = 8$ dissimilar phase vectors. In order to evaluate equal number of IDFT units, in PTS system, $M=8$ sub-blocks are generated. A sub-band design plan is used with a group of 32 neighboring sub-carriers assigned to any secondary block. Simulation results with 1024 point IDFT is obtained by using $L=24$ as the oversampling factor.

The probability of decreasing the search complexity in using the flipping algorithm is also investigated in addition to normal PTS method. It can be seen that ordinary PTS technique is efficient than SLM because the number of waveforms are restricted to $Q = 2^3$ whereas in PTS technique the number of candidate sequences is $W^{M-1} = 2^7$ which in turn reduces the PAPR. When comparing the performance of flipping algorithm with ordinary PTS, the former reduces complexity of the system considerably by 1 dB as compared to ordinary PTS. There is

considerable PAPR reduction by both schemes in comparison to the conventional system which do not use techniques for reducing the amplitude variations.

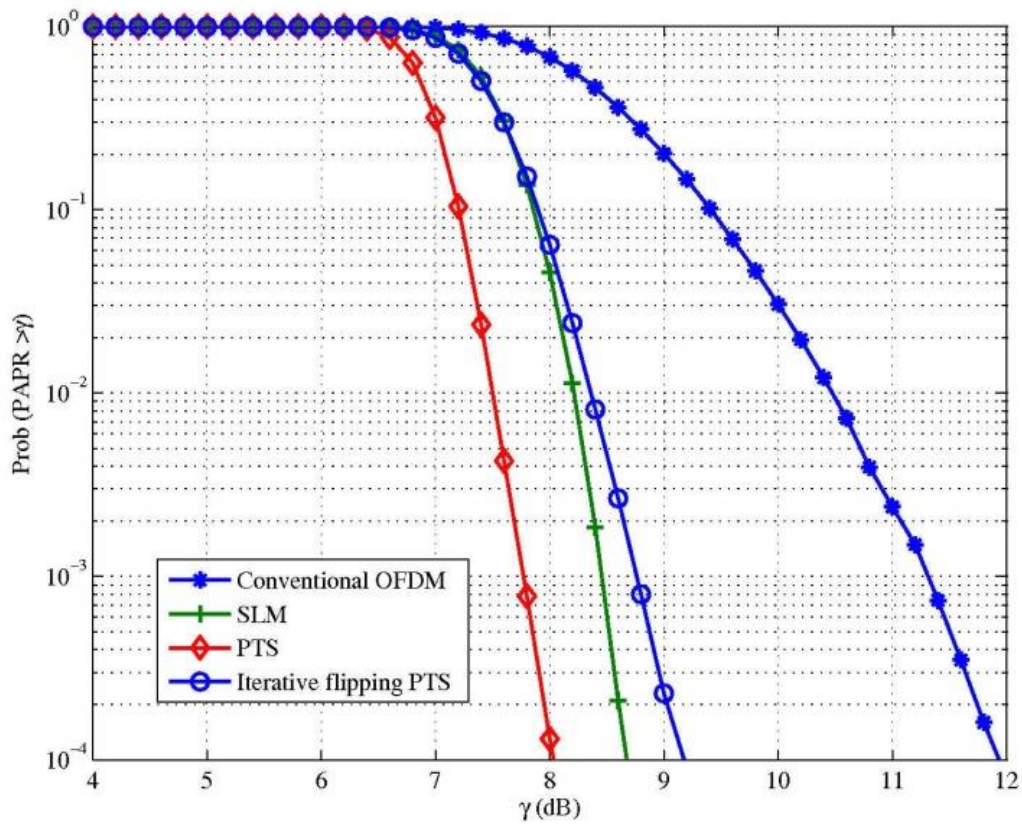


Figure 2.18: Comparison between PTS and SLM techniques in terms of PAPR reduction

2.5.4 Coding Technique

It has been proved that in OFDM systems, it is not possible to fully explore the frequency diversity offered by multipath channel without use of some channel coding techniques. In addition to providing redundancy, the channel coding reduces PAPR of transmitted signal. Technique of employing block codes for reducing PAPR was proposed in [52] in which only those code words were selected and transmitted which showed least PAPR and all others were discarded. The table 2.1 shows an example listing discrete-time PAPR for a BPSK-OFDM system with oversampling factor $L = 4$ and $N = 4$ sub carriers.

Table 2.1: Discrete-time PAPR for a BPSK-OFDM system

Code words				BPSK symbols				PAPR (dB)
$d(0)$	$d(1)$	$d(2)$	$d(3)$	$e(0)$	$e(1)$	$e(2)$	$e(3)$	
0	0	0	0	1	1	1	1	6.02
1	0	0	0	-1	1	1	1	2.32
0	1	0	0	1	-1	1	1	2.32
1	1	0	0	-1	-1	1	1	3.72
0	0	1	0	1	1	-1	1	2.32
1	0	1	0	-1	1	-1	1	6.02
0	1	1	0	1	-1	-1	1	3.72
1	1	1	0	-1	-1	-1	1	2.32
0	0	0	1	1	1	1	-1	2.32
1	0	0	1	-1	1	1	-1	3.72
0	1	0	1	1	-1	1	-1	6.02
1	1	0	1	-1	-1	1	-1	2.32
0	0	1	1	1	1	-1	-1	3.72
1	0	1	1	-1	1	-1	-1	2.32
0	1	1	1	1	-1	-1	-1	2.32
1	1	1	1	-1	-1	-1	-1	6.02

It can be seen from the table that highest PAPR (6.02 dB) is exhibited by four data blocks and an additional set of 4 blocks gives a PAPR of 3.72dB. Therefore, it is evident that an appropriate coding system can avoid the transmission of these sequences which can radically decrease PAPR of the transmitted signal. Table 2.1 shows reduction of PAPR with odd parity check code of rate $\frac{3}{4}$ with first 3 elements as $d(0), d(1), d(2)$. These elements represent the information bits which are followed by a fourth element $d(3) = d(0) \oplus d(1) \oplus d(2) \oplus 1$, where $\oplus$ in binary Galois field denotes mathematics addition. By this approach PAPR turns out to be 2.32dB for all code words. Thus, coding reduces PAPR by 3.70 dB as compared with an un-coded system.

There is a possibility to achieve high gains of 6.02 dB and 4.58 dB when $N = 8$ sub-carriers are used in coding methods with rates $\frac{7}{8}$ and $\frac{3}{4}$ respectively. However, there is some loss in spectral efficiency because of the inherent redundancy introduced in the transmitted signal by the coding. It can be noted that the above method is used only for reducing PAPR and not for shielding against channel imperfections. The best codes are found by searching thorough large look-up tables for coding and decoding procedures. Therefore, this method is not practical for large values of N .

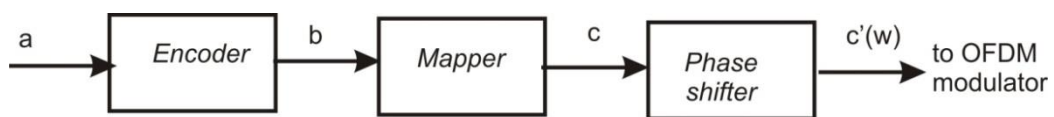


Figure 2.19: PAPR reduction, coding and phase rotation for simultaneous error control

Another refined approach based on a combination of coding techniques for both the error management and reduction in PAPR was proposed in [53]. In this method, the error control is achieved through typical linear block codes and PAPR is reduced through code redundancy.

Figure 2.19 shows a combination of coding and phase revolution for concurrent control of

error control and reduction in PAPR. A $(N\mathcal{G}, k)$ the binary code having $\mathcal{G}$ points in the constellation is chosen for error correction. A vector $\mathbf{b}$ of $N\mathcal{G}$ coded bits is generated from the transformation of a block $\mathbf{a}$ which is made up of k information bits. Then the coded bits are split into N adjoining segments of length $\mathcal{G}$. Every section is mapped with a symbolic (n) separately. It results in a code $x = \{x(0), x(1), \dots, x(N-1)\}$ of length N for every block of k information bits. $x = \{x_m; m=1, 2, 3, \dots, 2^k\}$ indicate a set of all possible code words.

To reduce the PAPR, a revolving vector $\mathbf{w} = [e^{j\psi(0)}, e^{j\psi(1)}, \dots, e^{j\psi(N-1)}]^T$ is multiplied with code words element wise, where phase shift $\{\psi(n)\}$ differ in the set $[0, 2\pi] \times [0, 2\pi] \times \dots \times [0, 2\pi]$. Let the rotated version of x_m be denoted by $x'_m(\mathbf{w})$ which is given by

$$x'_m(\mathbf{w}) = \{x_m(0)e^{j\psi(0)}, x_m(1)e^{j\psi(1)}, \dots, x_m(N)e^{j\psi(N-1)}\}. \quad (2.49)$$

New code $x'(\mathbf{w}) = \{x'_m(\mathbf{w}); m = 1, 2, 3, \dots, 2^k\}$ will have the same distances after rotation. Therefore, the error correction ability remains same as the original one. However, if there is a suitable selection of the phase shifts, then low value of PAPR is obtained.

Therefore, for finding an optimum vector $\mathbf{w} = [e^{j\hat{\psi}(0)}, e^{j\hat{\psi}(1)}, \dots, e^{j\hat{\psi}(N-1)}]^T$ for a given code such that

$$\mathbf{w} = \arg \min_{\mathbf{w}} \{PAPR[x'(\mathbf{w})]\}, \quad (2.50)$$

here $PAPR[x'(\mathbf{w})]$ may be described as

$$PAPR[x'(\mathbf{w})] = \max_{x'_m(\mathbf{w}) \in x'(\mathbf{w})} \{PAPR[x'_m(\mathbf{w})]\}, \quad (2.51)$$

$PAPR[x'_m(\mathbf{w})]$ represents the waveform's PAPR linked with the m^{th} rotated codeword $x'_m(\mathbf{w})$. As mentioned previously, the performance and decoding complexity of x as well as $x'(\mathbf{w})$ are equal. The phase shifts that are introduced by $\hat{\mathbf{w}}$ at the receiver end can be compensated easily at the receiver by suitable rotation of the DFT output. So, it is vital that $\hat{\mathbf{w}}$

must be recognized at the receiver end.

Based on equation (2.51), it is concluded that the major shortcoming of the mentioned technique is the large computational complexity which is needed for solving the problem of optimization. Another approach for finding the optimal rotation vector is given in [53]. Here, it is assumed that the phase shifts are a part of a finite set $\psi = \{2\pi l / W; l = 0, 1, \dots, W - 1\}$. However, it is unfortunate that this technique can be applied solely to smaller codes due to large computational complexity drawn in finding the PAPR of the code words which are shifted. An answer to the above difficulty of computational complexity is given in [54] in which a simplified approach is proposed. According to this method, those code words with highest PAPR are identified and then an iterative based minimization technique is applied to find the rotation vector which is optimum.

Another significant approach intended for PAPR reduction is using Golay complementary pair. If the modulated sequences correspond to a member of Golay complementary pair, then the maximum value of PAPR of the OFDM signal comes out to be 3dB. Between Golay and 1st and 2nd order Reed Muller codes a theoretical relation has been established in [53]. Until then, it was not known that these sequences possess appropriate properties to be used as coding sequences. This property in combination with the error adjustment property of Reed Muller codes gives efficient system performance. Still further improvements to the above method can be done by using binary, quaternary and higher order modulation schemes which gives higher PAPR control in terms of spectral efficiency and error correction. Algorithms having higher computational efficiency have been introduced based on fast Hadamard transform (FHT)[38]. Still further research has been done for designing a wide choice of coding methods which employ higher order modulation techniques. However, these can only be used for multi-carrier communication systems having less quantity of sub-carriers. Increasing the sub-carriers increases the computational complexity of the system. This limits the usefulness of all these

methods. One of the major merits of this technique is that the side information is not required for recovering the transmitted data symbols at the receiver.

2.5.5 Tone Injection and Tone Reservation Techniques

Tone injection and reservation are two more techniques dependent on the principle of addition of data independent vector for reducing the PAPR. In this method, vector $e = [e(0), e(1), \dots, e(N-1)]^T$ in frequency domain is added to unique data block $x = [x(0), x(1), \dots, x(N-1)]^T$ which results in reduction of peaks of the OFDM signal. Since, the added vector can be removed at any time from the receiver end with no impact on the performance. Both the methods show a remarkable benefit of being distortion less.

2.5.5.1 Tone Reservation (TR) Technique

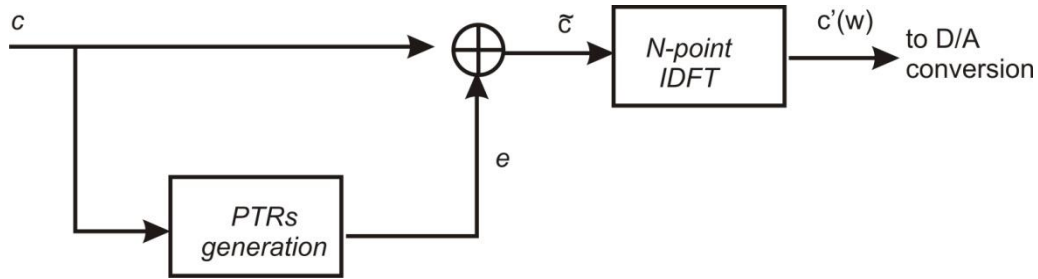


Figure 2.20: Block diagram of the tone reservation method

In this method, a set of Q sub-carriers is reserved and information is sent by the transmitter over this set of Q subcarriers for PAPR control. These sub-carriers are spread across the signal bandwidth in a pseudo random manner. These sub-carriers are known as peak reduction tones. For the purpose of design, $J^c = \{i_1, i_2, \dots, i_Q\}$ is denoted as the set which collects the PRTs indices whereas the indices for data sub channels are in the set $J = \{0, 1, \dots, N-1\} - J^c$.

Figure 2.20 depicts that a block $\tilde{x} = [\tilde{x}(0), \tilde{x}(1), \dots, \tilde{x}(N-1)]^T$ of frequency domain samples is generated by adding the vectors c and e at the transmitter. The entries of the block are represented as

$$\tilde{x}(n) = \begin{cases} x(n) & n \in J, \\ e(n) & n \in J^c \end{cases} \quad (2.52)$$

The sequence $\{\tilde{x}(n)\}$ is then passed through the DAC after converting into time domain by passing through N -point IDFT unit, which gives the signal

$$s(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \tilde{x}(n) e^{j2\pi f_{cs}t}, \quad 0 \leq t \leq T. \quad (2.53)$$

At the receiver, discrete Fourier transform (DFT) having indices in set J are selected to recover the information symbols because e and x are restricted to be disjoint frequency subspaces. Hence, it is required that the receiver must have information about the sub-carriers which reversal has been done for generating the PRTs. In this technique, a Q -dimensional vector $\tilde{e} = [e(i_1), e(i_2), \dots, e(i_Q)]^T$ is formed based on a combination of non-zero entries of e .

To minimize the PAPR of $s(t)$, it is replaced by its samples $s_k^{(L)}$ ($k=0, 1, \dots, NL-1$) by considering that the oversampling factor $L \geq 4$. The TR optimization problem can thus be projected as a constrained quadratic parameter to minimize $\{\gamma\}$ with respect to $\tilde{e} \in \mathcal{E}$ such that

$$|s_k^{(L)}|^2 \leq \gamma, \quad \text{for all } k=0, 1, \dots, NL-1 \quad (2.54)$$

where $\mathcal{E}$ represents multidimensional space of permissible vectors $\tilde{e}$ and $s_k^{(L)}$ is represented as

$$s_k^{(L)} = \frac{1}{\sqrt{N}} \sum_{n \in J} x(n) e^{j2\pi nk / LN} + \frac{1}{\sqrt{N}} \sum_{n \in J^c} e(n) e^{j2\pi nk / LN}, \quad 0 \leq k \leq NL-1 \quad (2.55)$$

It is a tedious task to search out an accurate solution for minimizing a linear function under quadratic constraints. A relatively simple method is to iteratively come up with a best possible $\tilde{e}$ by utilizing the sub-gradient algorithmic program. This optimization method improves the PAPR reducing potential at the expense of throughput loss because of decrease in number of carriers. Therefore, a compromise is required by appropriately choosing the parameter Q . Simulation results depict that using this method, there is 6dB and 3dB reduction in the PAPR with a decrease in data rate of 0.5% and 0.2% respectively [88].

Another issue that has a remarkable impact towards the system performance is the position of peak reduction tones (PRT). A good selection can be obtained by generation of enough number of pseudo random sets and selecting the most effective amongst it.

In the case of wire line digital subscriber line applications, the throughput penalty that is in association with TR technique is mitigated to some extent by the location of PRTs over frequency sub channels which might not be used as a result of its comparatively poor SNRs. However, this approach cannot be employed in the case of wireless systems as in these applications, there is no availability of quick channel state feedback for deciding as to which sub carriers ought to be reserved for PRTs and which must be used for sending the information.

2.5.5.2 Tone Injection (TI) Technique

The TR technique's upgraded version is tone injection that is geared towards PAPR reduction not at the price of spectral efficiency. By utilizing an extended non bijective constellation set, the core idea lies in transmission of information over all subcarriers in which a set of constellation points are used to map the data symbols. The selection of best constellation points from the set results in reduction of signal peaks.

The minimum distance between adjacent points is considered as $2d$ for a usual M -ary QAM constellation A . Each constellation point within set have $\{\pm d, \pm 3d, \dots, \pm(\sqrt{M}-1)d\}$ as real and imaginary parts, where $\sqrt{M}$ denotes various levels per dimension. Within prolonged set $\tilde{A}$, there is a constellation mapping of original symbol x with one of a plurality of equivalent points $\tilde{x} = x + pD + jqD$, where D is a positive real number available at the receiver and p and q are integers values.

Let a subset $S(x) = \{cx + pD + jqD\}$; $p, q \in I \subset \mathbb{Z}$ is associated with c . The additional degrees of freedom which decrease the PAPR are provided by the integers p and q . It is clear

that a mapping of A 's dissimilar points with disjoint subsets of $\tilde{A}$ is essential for recovering original data symbol x from its equivalent point $\tilde{x}$. However, this approach requires that the parameter D should be designed carefully [63]. Moreover, setting $D = 2\rho d\sqrt{M}$ with $\rho \geq 1$ results in disjoint subsets and provides error-rate probability similar to OFDM system which do not use TI.

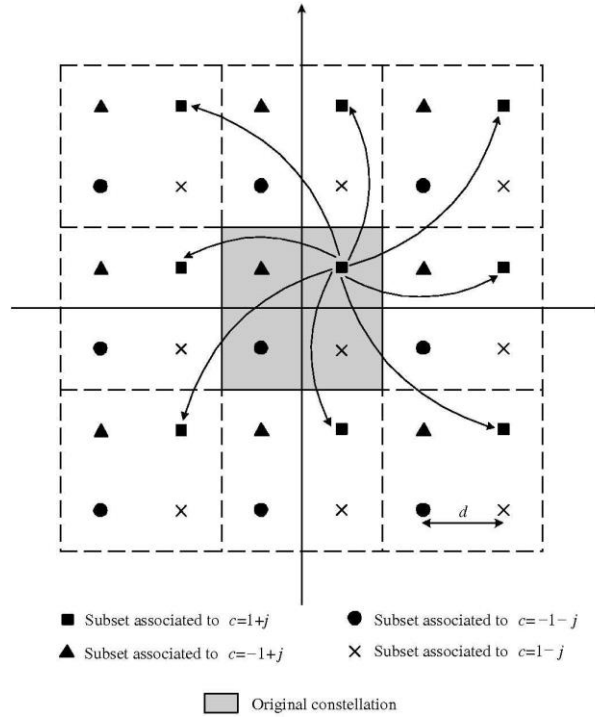


figure 2.21: TI technique using the expanded constellation set

In the case of $\rho = 1$ and QPSK symbols ($M = 4$), the expanded constellation $\tilde{A}$ is depicted in the figure 2.21. The p and q integers remain limited to a set $I = \{-1, 0, 1\}$. It stands clear that $\tilde{A}$ is obtained through known translation vectors by reproducing the original constellation A . With a total of four subsets and nine symbols for each section, each subset is denoted by A with dissimilar symbol. The original symbol x is recovered correctly from $\tilde{x} \in S(x)$ by using the rule

$$MOD(x) = x - 2\rho d\sqrt{M} \left\lfloor \frac{x + \rho d\sqrt{M}}{2\rho d\sqrt{M}} \right\rfloor, \quad (2.56)$$

A complex plane is mapped to the region $\{x_R + jx_I \mid x_R, x_I \in [-\rho d\sqrt{M}, \rho d\sqrt{M}]\}$ with length of side $2\rho d\sqrt{M}$ by $\text{MOD}(x)$. Let $\tilde{x}(n) = x(n) + p_n D + jq_n D$ indicate the chosen point in the subset $S(x(n))$ connected with $x(n)$, then the time domain version of the oversampled sequence is given by

$$s_k^{(L)} = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \tilde{x}(n) e^{j2\pi nk/LN}, \quad 0 \leq k \leq NL - 1 \quad (2.57)$$

Figure 2.21 illustrates the vector $\tilde{x} = [\tilde{x}(0), \tilde{x}(1), \dots, \tilde{x}(N-1)]^T$ obtained in frequency domain after defining $e(n) = p_n D + jq_n D$ for $n = 0, 1, \dots, N-1$. For minimizing the peaks of the transmitted signal, the integers $p = \{p_0, p_1, \dots, p_{N-1}\}$ and $q = \{q_0, q_1, \dots, q_{N-1}\}$ are selected such that they minimize the PAPR of the sequence $s_k^{(L)}$. However, an integer programming problem of exponential growth in complexity is faced with increase in number N of available sub-carriers. This problem can be solved by using the effective iterative methods for analysing the candidate vectors p and q . The complexity can be reduced further by employing an expanded constellation set using a small number of the accessible sub-carriers. Obviously, reduction in number of candidate vectors to be explored results in performance trouncing in the terms of reduction of PAPR.

Figure 2.21 shows that new $\tilde{x}(n)$ has additional energy than $x(n)$ when $p_n \neq 0$ or $q_n \neq 0$. This concludes that PAPR is reduced with TI technique only with an increase in total transmission power. However, when compared with TR theme, it can be seen that there is no loss of data since all the sub-carriers are used for transmission. Another advantage is that exchanging side information between the receiver and transmitter is not required because the original symbols are obtained from the decoded sequence using the modulo operator [64].

2.6 SUMMARY OF THE CHAPTER

This chapter presents basic system model for OFDM system and effects of large envelope variations are also explained in this chapter. To measure these large envelope variations one of the metric i.e. PAPR is contemplated and its detailed statistical analysis are summarized. Since, high PAPR decreases the quality of signal in the OFDM system, it was required to analyse the effects of high PAR and techniques to reduce the PAPR. A number of methods have been developed for reduction of the PAPR in OFDM system. These methods include amplitude clipping, filtering, coding, tone reservation (TR), tone injection (TI), partial transmit sequence (PTS), and selected mapping (SLM). These methods are different from each other in terms of requirements, and most of them enforce various restrictions to the system. Therefore, a proper technique should be selected carefully for each specific communication system. In this chapter, focus was on analysing the PAPR reduction techniques for multi-carrier transmission. A brief overview of these techniques has been presented to resolve the high PAPR and the essential considerations before choosing any reduction technique for any particular application.

**ANALYTICAL INVESTIGATION ON PAPR REDUCTION IN OFDM
USING GOLAY CODE**

3.1 INTRODUCTION

OFDM is a multicarrier modulation technique accepted widely in modern communication systems because the OFDM signals are extremely immune to multipath fading and use the spectrum efficiently. The orthogonality of the sub-carriers in OFDM signals eliminates cross talk among dissimilar subcarriers. In spite of having many advantages, one of the disadvantages of OFDM systems is the large value of PAPR. The PAPR of an OFDM signal having 128 subcarriers can be as high as 21dB. This can take place at an instance when all the 128 subcarriers are having same phase. This gives rise to a very high value of crest factor of these signals, which results in increase in BER.

The high value of PAPR makes the power amplifier at the transmitter to operate in nonlinear operation. In order to prevent this, the power input to the power amplifier is required to be backed-off for decreasing the SNR of the amplified signal. The errors of the transmitted signal propagating over an AWGN channel depend on the SNR of the signal. Therefore, the BER will increase when the power input to the power amplifier is backed-off. Thus, it is essential to minimize the PAPR of the transmitted signals.

A number of techniques have been proposed and implemented over the past decades, such as amplitude clipping, peak cancellation, tone reservation and coding. There are advantages and disadvantages for each method. The technique presented in this work is an extension of coding technique and can be utilized with other conventional methods.

Channel coding is used to increase the reliability of the communication channel by adding redundant data bits into the transmitted signal. Many algorithms have been developed for channel coding which are being used only for detecting errors. For example, the parity check

method is used to detect a single bit error. However, the algorithm fails to detect an error if more than one bit is wrong. Apart from development of only error detection algorithms, many advanced algorithms have been developed which are used to detect and correct the multiple errors. The forward error correction (FEC) technique is one of the advanced algorithms which works by addition of redundancy to the information symbols. Therefore, the transmitted symbol or code word carries extra redundant bits with the information symbols. The transmitted symbols or code words are designed based on the combinations of information bits and redundant bits. As an example, considering that the information symbols are of 4 bits and 3 redundant parity bits are selected, then there are $2^7=128$ possible code-words. The parity bits are selected such that each codeword is unique and has maximum Hamming distance [63]. However, a trade-off is considered between the PAPR and OFDM code words which are selected such that the PAPR can be minimized at the expense of Hamming distance.

There is always a limitation on the amount of bit errors in all the standard cellular communication protocols. The BER is primarily dependent on SNR of the signal and the modulation method used for modulating the signal. Therefore, depending upon a particular modulation system, the BER can be optimized by improving level of the signal and using the channel coding techniques. Reed Solomon and turbo codes are few amongst the several coding methods found in various literatures for improving the BER. Many coding techniques have been developed for reducing the PAPR and improving the BER performance. It has been shown that 1 dB reduction in the PAPR results in increase in the average signal power by 1 dB which improves the BER before using channel coding.

The current chapter explores the PAPR reduction using the complementary Golay sequences (CGS) and analysis of FEC in an OFDM-based WIMAX system. A novel method has been proposed by combining the Golay sequence with the input sequence prior to channel coding. The analysis is carried based on the various QAM schemes. When compared with the

previous research studies, this methodology resulted in efficient PAPR reduction as well as low bit error rate (BER). There is a considerable decrease in PAPR as well as in bit error rate reduction when computer simulation is performed for standard WIMAX in IEEE 802.16a system. Further, in MATLAB environment, the entire system is simulated for the purpose of validating the prototype proposal and the simulation results show that addition of Golay sequence provides more reduction in PAPR in comparison with addition of any other sequences. The proposed technique is applicable for any arbitrary number of carriers and any modulation technique.

One of the major advantages of the proposed technique is that the necessity of power back-off of the PA is eliminated because of reduction in the PAPR. Therefore, a high power signal can be used to improve the SNR and consequently decrease the BER. Moreover, the proposed technique also reduces the errors introduced due to clipping of the input signal. Thus, it has been shown in this chapter that combining the Golay sequence with the input sequence, the PAPR and hence BER can be reduced significantly.

3.2 GOLAY SEQUENCES FOR PAPR REDUCTION

Let $a = (a_0, a_1, \dots, a_{n-1})$ denote a sequence of length ' n ' and a characteristic H , such that $\xi = \exp(2\pi\sqrt{-1}/H)$ and each entry $a_i \in \mathbb{Z}_H$, then a periodic autocorrelation of a in u is given by

$$C_a(u) = \sum_{i=0}^{n-1-u} \xi^{a_i - a_{i+u}} \quad (3.1)$$

A pair is defined as a Golay complementary sequences (GCS) pair (a, b) if addition of its autocorrelation functions on results in 0 i.e. $C_a(u) + C_b(u) = 0$, $0 < u < n$. Assuming that the instantaneous power of a signal x is represented as

$$P_x(t) = |s(t)|^2 = \sum_{i,j} \xi^{x_i(t) - x_j(t) - H(i-j)\Delta f t} \quad (3.2)$$

Assuming $x_i(t) = x_i$ for $t \leq 1$, $0 \leq \Delta f$, and $j = u + i$, then the instantaneous power of the signal x is given by

$$P_x(t) = n + \sum_{u \neq 0} \sum_i \xi_i^x i^{-x} u^{-H} u^{\Delta f t} \quad (3.3)$$

The instantaneous power formula rewritten using the auto-correlation formula is given by

$$P_x(t) = n + \sum_{u \neq 0} \sum_i C_x(u) \xi_i^{-H} u^{\Delta f t} \quad (3.4)$$

For example, $x = (x_0, x_1, \dots, x_{n-1})$ and $y = (y_0, y_1, \dots, y_{n-1})$ are the two code words and if $C_x(u) + C_y(u) = 0$ for $u \neq 0$, then both the code words are called as a pair of GCS. Based on above, it can be concluded that a Golay sequence has a PAPR equal to 2. Therefore, the summation of instantaneous power is equal to or less than $2n$ and the average power is equal to n . [29] Then PAPR of the signal x is calculated as

$$PAPR(x) = \frac{P_x(t)}{n} \leq 2 = 3\text{dB} \quad (3.5)$$

3.2.1 Golay sequence generation method

Golay sequence generation method was proposed by Davis and Jedwab [31] by using the boolean function which is defined as a function of $Z_2^m = (x_1, x_2, \dots, x_m) \in \{0,1\}^m$, where each variable x_i in Z_2 , is a Boolean function which is given by

$$f_i(x_1, x_2, \dots, x_m) = x_i \quad (3.6)$$

Considering the 2^m monomial $1, x_1, x_2, \dots, x_m, x_1x_2, x_1x_3, \dots, x_{m-1}x_m, \dots, x_1x_2\dots x_m$. A linear combination in Z_2 of these monomials is a Boolean function, such that Z_2 belong to the coefficients of each monomial. Davis and Jedwab have presented a sequence of length 2^m in lexicographic order for each function f values provided by $f(x_1, x_2, \dots, x_m)$ as $(x_1, x_2, \dots, x_m)$. So, if $i = \sum_{j=1}^m i_j 2^{mj}$ represents $(i_1, i_2, \dots, i_m)$, then i^{th} item is $f(i_1, i_2, \dots, i_m)$. An explicit form for the generation of Golay sequence has been established by using these Boolean functions, such that for any $c, c_k \in Z_2^h$ and any permutation π of symbols $1, 2, \dots, m$.

$$a(x_1, x_2, \dots, x_m) = 2^{h-1} \sum_{k=1}^{m-1} x_{\pi(k)} x_{\pi(k+1)} + \sum_{k=1}^m c_k x_k + c \quad (3.7)$$

represents a Golay sequence in Z_2^h of length 2^m . This definition of Golay sequences provides $2^{h(m+1)} \cdot m! / 2$ Golay possible sequences in Z_2^h of length 2^m .

It is now possible to utilize the GCS over Z_4 to construct 16-QAM or 64-QAM OFDM sequences having less value of PAPR. Golay Complementary sequences and the block coded modulation (BCM) can be combined now in order to trade off the squared Euclidean distance of M -QAM, the code rate, and the PAPR of the OFDM signals. Davis and Jedwab [37], [31] have further contributed to a close link between the GCS and Reed Muller codes (RMC). The 2^h -PSK Golay sequences are derived using the cosets of the first order and second order RMC over the integer Z_2^h . Specifically, in a 2^h -PSK OFDM system of 2^m carriers, any vector in the coset $2^{h-1}(x_{\pi(1)}x_{\pi(2)} + \dots + x_{\pi(m-1)}x_{\pi(m)}) + RM_{2^h}(1, m)$ is a Golay sequence, where $RM_{2^h}(1, m)$ is a first order RMC over Z_2^h and π is a permutation of $1, 2, \dots, m$.

Further, the Golay complementary sets were developed from the GCS by developing and generalizing the same as in [82], [83]. Due to this theoretical advance, the Golay sequence based OFDM signals enjoy both less PAPR values as well as efficient error-correcting capabilities. As discussed in the study [85], 16-QAM OFDM sequence with low PAPR can be generated using two QPSK based GCS. This study was further improved by extending the results for M-QAM sequences in [86].

3.2.2 PAPR using the Golay sequence

Consider that n sinusoidal signals form orthogonal subcarriers for an OFDM signal.

$\{\phi_k(t) = e^{j2\pi f_k t}\}$, $0 \leq k \leq n-1$, where $f_k = \frac{k}{T}$ and each subcarrier has bandwidth equal to $\frac{1}{T}$. The

orthogonal property of OFDM signal is represented as

$$(\phi_k(t), \phi_l(t)) = \frac{1}{T} \int_0^T \phi_k(t) \phi_l^*(t) dt = \begin{cases} 1, & \text{if } k = l \\ 0, & \text{if } k \neq l \end{cases} \quad (3.8)$$

Considering that c_i is complex symbol assigned to i^{th} subcarrier of an OFDM signal, where $i = 0, 1, \dots, n-1$, be, then the complex envelope $S_c(t)$ of the OFDM signal is represented as

$$S_c(t) = \sum_{k=0}^{n-1} c_k \phi_k(t), \quad 0 \leq t \leq T \quad (3.9)$$

The power $P_c(t)$ of the complex envelope $S_c(t)$ is given by $P_c(t) = |S_c(t)|^2$. Since the input vector $c = \{c_k\}_{k=0}^{n-1} = (c_0, c_1, \dots, c_{n-1})$ and the complex envelope signal $S_c(t)$ are a Fourier series pair, then S_c^* and c_{-k}^* are also a Fourier Pair using the conjugate property of the Fourier series. Therefore, $P_c(t) = S_c(t) \cdot S_c^*(t)$ and $c_k \otimes c_{-k}^*$ are also a pair of Fourier series, where $\otimes$ denotes the convolutional operation.

Assuming that $c_k = 0$ for $k < 0$ and $k > n-1$, then for sequence c , the aperiodic autocorrelation is defined by

$$A_c(u) = c_u \otimes c_{-u}^* = \sum_{l=-\infty}^{\infty} |c_l|^2$$

Since $A_c(u)$ and $P_c(t)$ are a pair of Fourier series, $P_c(t)$ is obtained by analysing the aperiodic autocorrelation $A_c(u)$ in frequency domain and the GCS are derived for OFDM systems using the PSK modulation. Since, the harmonic of signals in the set $\{\phi_k(t)\}$ are orthogonal, then $||c||^2$, the average power of c is given by

$$||c||^2 = \frac{1}{T} \int_0^T P_c dt = \sum_{k=0}^{n-1} |c_k|^2 \quad (3.10)$$

Assuming C denotes a set of code words transmitted by a system, $P_{av} = \sum_{c \in C} ||c||^2 p(c)$ denotes average power of the transmitted code words of C , where $p(c)$ is the transmission probability of each code word, then PAPR of the transmitted codeword $c \in C$ is given by

$$\text{PAPR}(c) = \frac{\max_{0 \leq t \leq T} P_c(t)}{P_{av}}, \quad 0 \leq t \leq T \quad (3.11)$$

and the PAPR of a code C is defined as $\max \text{PAPR}(C)$. [32]

3.3. 64 QAM OFDM CODES FROM QPSK SEQUENCES AND GOLAY

COMPLEMENTARY SEQUENCE

The 64-QAM OFDM constellation symbols (S_{64QAM}) are denoted as a sum of three QPSK symbols as

$$S_{64QAM} = \frac{1}{\sqrt{2}}S_{QPSK} + \sqrt{2}S_{QPSK} + \sqrt{2}S_{QPSK} \quad (3.12)$$

The constellation points of 64-QAM has $E=1$ as minimum Euclidean distance and 10.5 as the average energy if each signal point is equally probable. If component codes consist of three 4-ary Golay sequences of length 2^m , the resulting 64-QAM codes C of length $n = 2^m$ has PAPR given by $(\frac{1}{\sqrt{2}}\sqrt{2n} + \sqrt{2}\sqrt{2n} + 2\sqrt{2n})^2/10.5n = 14/3 = 4.67$.

Let 64-QAM code Z_1 be decomposed into six BPSK codes which can be represented by $B_1, B_2, B_3, B_4, B_5, B_6$. From the values in table it is conjectured that $B_1 = B_3 = B_5 = RM(1, m)$ and $B_2 = B_4 = B_6 = Q_\pi + RM(1, m)$, where Q_π represents all $\frac{m!}{2}$ second order Boolean polynomials of the form $Q_\pi = x_{\pi(1)}x_{\pi(2)} + \dots + x_{\pi(m-1)}x_{\pi(m)}$ and $Q = x_1x_2 + \dots + x_{m-1}x_m$ as one of them. The size of C is $(m!/2 \cdot 4^{m+1})^3$ and the squared Euclidean distance is $\min(1 \cdot 2^{m-1}, 2 \cdot 2^{m-2}, 4 \cdot 2^{m-1}, 8 \cdot 2^{m-2}, 16 \cdot 2^{m-1}, 32 \cdot 2^{m-2}) = 2^{m-1}$, shown in the first code Z_1 of Table 3.1 [8]. The code rate (R) for BPSK codes associated with the QPSK code Z_1 can be calculated for different values of n as

Code rate $R(C) = \frac{\log_2|C|}{n}$ bits/symbol, where n is the length of code.

$$\text{For } n=16, m=4, \log_2|Z_1| = 40.75, R(Z_1) = \frac{40.75}{16} = 2.54 \quad (3.13)$$

$$\text{For } n=32, m=5, \log_2|Z_1| = 53.72, R(Z_1) = \frac{53.72}{32} = 1.67 \quad (3.14)$$

$$\text{For } n=64, m=6, \log_2|Z_1| = 67.47, R(Z_1) = \frac{67.47}{64} = 1.054 \quad (3.15)$$

$$\text{For } n=128, m=7, \log_2|Z_1| = 81.89, R(Z_1) = \frac{81.89}{128} = 0.64 \quad (3.16)$$

$$\text{For } n=256, m=8, \log_2|Z_1| = 96.89, R(Z_1) = \frac{96.89}{256} = 0.378 \quad (3.17)$$

As with 16-QAM, three Z_4 component codes C_1 , C_2 , and C_3 [6] can be selected appropriately to achieve a trade-off for the squared Euclidean distance, PAPR and size of a 64-QAM OFDM code. For example, the squared Euclidean distance can be increased by considering $B_1 = \text{RM}(0, m)$ and $B_2 = (x_1x_2 + x_2x_3 + \dots + x_{m-1}x_m) + \text{RM}(1, m) = Q + \text{RM}(1, m)$ as a coset consisting of 2^{m+1} Golay sequences. The table 3.1 shows the squared Euclidean distance, PAPR, and size of the resulting OFDM code as second code Z_2 . The size of the 64-QAM OFDM code can be increased by considering $C_3 = (2Q\pi + \text{RM}_4(1, m-1)) (2Q\pi + \text{RM}_4(1, m-1))$. The C_1 , and C_2 has a PAPR of at most 2, while C_3 has at most 4. The resulting OFDM code Z_3 is shown in Table 3.1. Other possible selections of C_1 , C_2 , and C_3 result in a 64-QAM OFDM code Z_4 with different PAPR, squared Euclidean distance, and size of the code, shown in table 3.1.

Table 3.1: 64- QAM OFDM codes with different values of PAPR

	Z_1, PAPR=4.67	Z_2, PAPR=4.67	Z_3, PAPR=7.14	Z_4, PAPR=13.32
B_1	$\text{RM}(1, m)$	$\text{RM}(0, m)$	$\text{RM}(0, m)$	$\text{RM}(1, m)$
B_2	$Q_\pi + \text{RM}(1, m)$	$Q + \text{RM}(1, m)$	$Q + \text{RM}(1, m)$	$Q_\pi + \text{RM}(1, m)$
B_3	$\text{RM}(1, m)$	$\text{RM}(1, m)$	$\text{RM}(1, m)$	$\text{RM}(1, m-1) \oplus \text{RM}(1, m-1)$
B_4	$Q_\pi + \text{RM}(1, m)$	$Q_\pi + \text{RM}(1, m)$	$Q_\pi + \text{RM}(1, m)$	$(Q_\pi + \text{RM}(1, m-1)) \oplus (Q_\pi + \text{RM}(1, m-1))$
B_5	$\text{RM}(1, m)$	$\text{RM}(1, m)$	$\text{RM}(1, m-1) \oplus \text{RM}(1, m-1)$	$\text{RM}(1, m-2) \oplus \text{RM}(1, m-2) \oplus \text{RM}(1, m-2) \oplus \text{RM}(1, m-2)$
B_6	$Q_\pi + \text{RM}(1, m)$	$Q_\pi + \text{RM}(1, m)$	$(Q_\pi + \text{RM}(1, m-1)) \oplus (Q_\pi + \text{RM}(1, m-1))$	$(Q_\pi + \text{RM}(1, m-2)) \oplus (Q_\pi + \text{RM}(1, m-2)) \oplus (Q_\pi + \text{RM}(1, m-2)) \oplus (Q_\pi + \text{RM}(1, m-2))$
size	$\left(\frac{m!}{2}\right)^3 (4^{m+1})^3$	$\left(\frac{m!}{2}\right)^2 2^{m+2} (4^{m+1})^2$	$\left(\frac{m!}{2}\right)! \left(\frac{(m-1)!}{2}\right)^2 2^{m+2} 4^{m+1}$	$\left(\frac{m!}{2}\right)! \left(\frac{(m-1)!}{2}\right)^2 \left(\frac{(m-2)!}{2}\right)^4 2^{m+2} 4^{m+1} (4^m)^2 (4^{m-1})^2$
PAPR	≤ 4.67	≤ 4.67	≤ 7.14	≤ 13.32
D_E^2	2^{m-1}	2^m	2^m	2^{m-1}

From Table 3.1, it is clear the codes Z_2 and Z_3 have large Euclidean distance and therefore these codes provide improved BER performance and error correction capability. Also table 3.2 shows the performance analysis for codes with code rates $Z_4 \geq Z_3 \geq Z_2 \geq Z_1$. However, according to the PAPR analysis, it is found that the codes Z_1 and Z_2 provide maximum PAPR reduction and are best codes for OFDM systems. The code rate of the code

Z_4 is maximum but it provides minimum reduction in PAPR. The code rate of Z_3 has larger Euclidean distance and therefore, the error correction capability Z_3 is better as compared to the code Z_1 . But the PAPR reduction of Z_3 is less than Z_1 . Also, the PAPR level of codes Z_4 is average, has code rate much higher than Z_1 , and has same Euclidean distance or error correction capability as Z_1 . So, the codes are chosen based on a trade-off among the squared Euclidean distance, PAPR, and the code rate.[36]

Table 3.2. Comparison of OFDM codes based on 64-QAM

Code		Z_1	Z_2	Z_3	Z_4
PAPR		4.67	4.67	7.14	13.32
n=16	D_E^2	8	16	16	8
	R	2.54	2.07	2.422	3.797
n=32	D_E^2	16	32	32	16
	R	1.67	1.34	1.627	2.607
n=64	D_E^2	32	64	64	32
	R	1.05	0.83	1.036	1.760
n=128	D_E^2	64	128	128	64
	R	0.64	0.49	0.635	1.124
n=256	D_E^2	128	256	256	128
	R	0.37	0.29	0.378	0.691

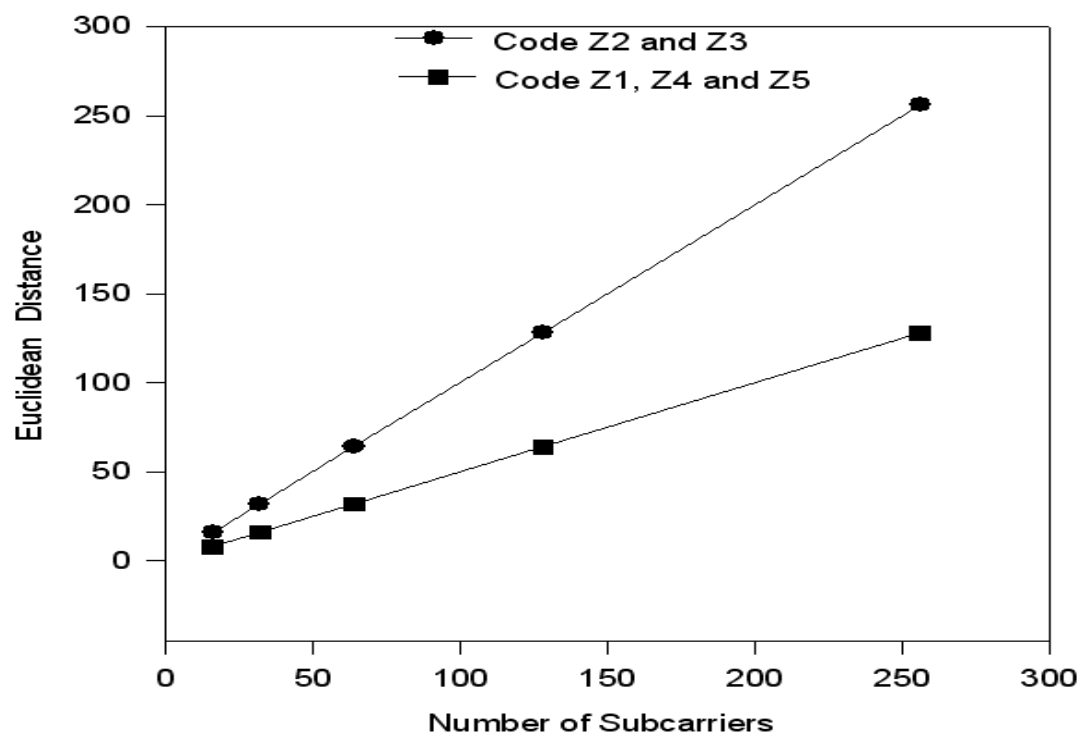


Figure 3.1: Effect of Variations in number of Subcarriers on Euclidean Distance

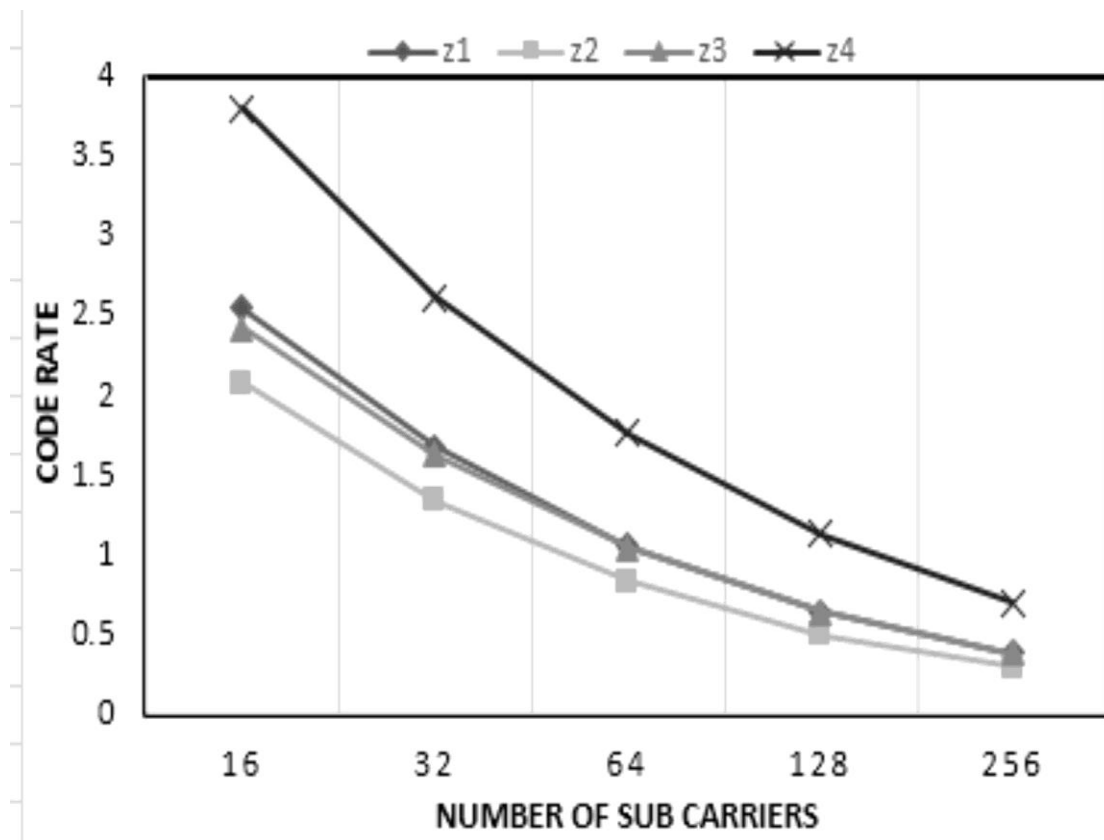


Figure3.2: Effect of Variations in number of Subcarriers on Code Rate

3.4 ADDITION OF DIFFERENT TYPES OF SEQUENCE FOR REDUCTION IN BER OF OFDM SYSTEM

One of the foremost issues during the transmission of signals is to minimize the transmission errors. A reliable transmission link is generally obtained by keeping the BER within certain limits. The SNR determines the probability of transmission errors of the transmitted signals. The SNR depends on the power amplifier employed at the transmitter. Therefore, the power amplifier performs a significant role for determining the probability of transmission errors. Greater the power provided by the power amplifier at the transmitter, higher will be the SNR and lower will be the probability of transmission errors [66].

As discussed previously, each subcarrier is modulated at rate which is lower than the rate of modulation of the original symbol. These subcarriers are made orthogonal and close to each other to minimize the crosstalk between them. Furthermore, the spectrum is used efficiently using this modulation technique. However, one of the drawbacks of this modulation technique is high PAPR and therefore high BER. High value of PAPR and BER are results of higher ISI (inter symbol interference) and ICI (inter carrier interference). The BER should be limited to a certain value for reliable transmission of digital data. Moreover, as discussed previously, the PAPR of the signal transmitted by the OFDM system is kept minimum by operating the PA in its linear region. As discussed in chapter 2, many techniques have been developed for reducing the PAPR and BER in OFDM systems. Addition of sequences with the input data is one of the unexplored methods for decreasing the PAPR and BER of the OFDM systems.

In current wireless communication systems, sequences have played a major role. The sequences are primarily used in spread-spectrum as spreading sequences for majority of the cellular systems. Apart from using the sequences in spread spectrum, the sequences

can be utilized for minimizing the PAPR and BER of the OFDM systems. The idea behind the technique presented in this chapter is to perform an analysis of decrease in the BER of the OFDM system by adding different types of sequences along with input data. The combination of sequence with data reduces the PAPR and BER because of spreading of the signal energy over a wider bandwidth. The spreading of the energy over a wider bandwidth results in low amount of energy per specific frequency which in turn causes decrease in the PAPR [67], [94], [95].

The autocorrelation (AC) properties of the sequences are required to be optimum because different time shifts of the same sequence are used by different mobile users (base stations) in synchronous operation. A sequence of length N is said to have the perfect AC property if the AC of the sequence is zero for the components which are out-of-phase, and the AC is N for in phase components. The AC property of the sequence support low inter carrier interference (ICI), low multipath interference (MPI), and fast symbol synchronization. The cells in the inter cell asynchronous operation are assigned a unique long sequence to obtain good AC property, low ICI, synchronization of symbols at high rate, and low MPI. This results in efficient utilization of bandwidth as compared to conventional systems because of exploitation of complete frequency band all the time. The SNR depending on the system design determines the number of users that a system can accommodate. Traditionally, Gold sequences and binary maximal length (m) sequences were utilized in the cellular systems for providing scrambling functionality whereas Walsh sequences have been used for providing the channelization functionality. The m sequences can be chosen because they possess the desired randomness and are easily generated via linear feedback shift registers. Gold sequences are an important subclass of the m sequences that can provide good periodic (even) cross correlation [9].

Pseudo Noise sequences or PN sequences are generated by using the shift registers

based on generator polynomials. They are periodic and random binary code. The shifting of a PN sequence by any non-zero number of elements results in a sequence which has equal number of agreements and disagreements with respect to the original sequence.

A novel technique has been presented for reducing the BER and overcoming the problem of variations in the envelope of the signal by adding redundant sequence with the input data. The addition of the sequence with the input data reduces peaks and decreases the BER. The proposed technique is favored over other methods due to its lower cost of implementation. Moreover, it can be utilized with coherent demodulation. It also provides a larger capacity apart from the common advantages of the spread spectrum such as improvement in effects of multipath fading, suppression or rejection of interference, and security [96]. The orthogonality of OFDM sub channels can be maintained and it is possible to separate the individual sub channels at the receiver side when impairments of the transmission channel [67] have not introduced any ISI and ICI.

3.5 SOFTWARE REFERENCE MODEL

Figure 3.3 shows an OFDM system modeled designed using MATLAB/SIMULINK. The performance of the system has been tested and verified using MATLAB/SIMULINK. Initially, the system is analyzed without introducing any sequence into data. Thereafter, the system was analyzed by adding various sequences.

Table 3.3: The parameters of the OFDM system considered for the simulation

Parameter Name	Parameter Value
Channel Type	AWGN
SNR	0-30 dB
Input	Frame Based
FFT size	256
Samples per frame	192
Modulation	16 QAM, 64 QAM, 256 QAM

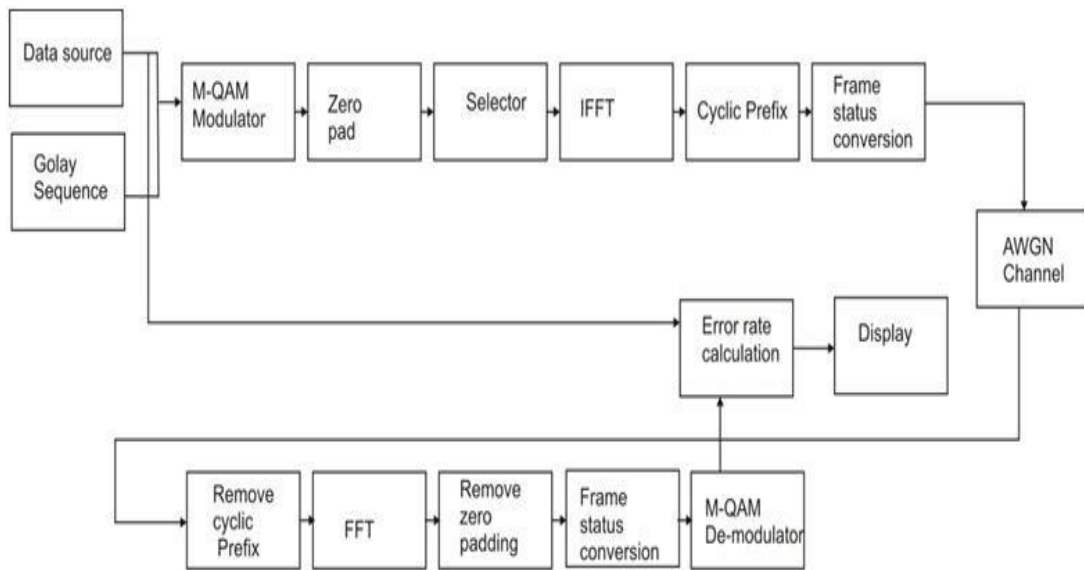


Figure 3.3: System Model of OFDM system considered for simulation

3.6 SIMULATION RESULT

The performance of the OFDM system has been analyzed and measured using BER and SNR. The SNR is varied by changing noise of the channel. The performance of the model has been analyzed by adding the Golay sequence and PN sequence. The BER performance of the system is analyzed for 16 QAM, 64 QAM and 256 QAM.

Figure 3.4 shows simulation results for BER of the system without addition of any sequence into data using for 16 QAM, 64 QAM and 256 QAM. It can be observed that 16 QAM modulation scheme provides better performance in comparison to 64 QAM and 256 QAM.

The addition of a sequence into data reduces the BER considerably. The system has been analyzed by introducing different sequences and it was observed that BER is minimum when Golay sequence is introduced with the data. Figure 3.5 shows simulated results for the BER analysis of the OFDM system using Golay sequence and figure 3.6 shows the BER performance of the OFDM system using PN sequence. It can be seen that there is reduction in BER by adding PN sequence. However, when Golay sequences

are added with the data, there is more reduction in BER as comparison to BER reduction obtained by adding the PN sequence. Figure 3.7 depicts the theoretical results of OFDM system using Golay sequence. Therefore, it can be concluded that QOS of the OFDM system can be improved by adding Golay sequence to the input data. The results of proposed method have been compared with the other methods presented in literatures [31], [65]. The amount of improvement in SNR is around 5 dB at BER of 10^{-3} in comparison to the conventional system. Based on the analysis, it has been concluded that OFDM system has minimum BER by using the Golay sequence.

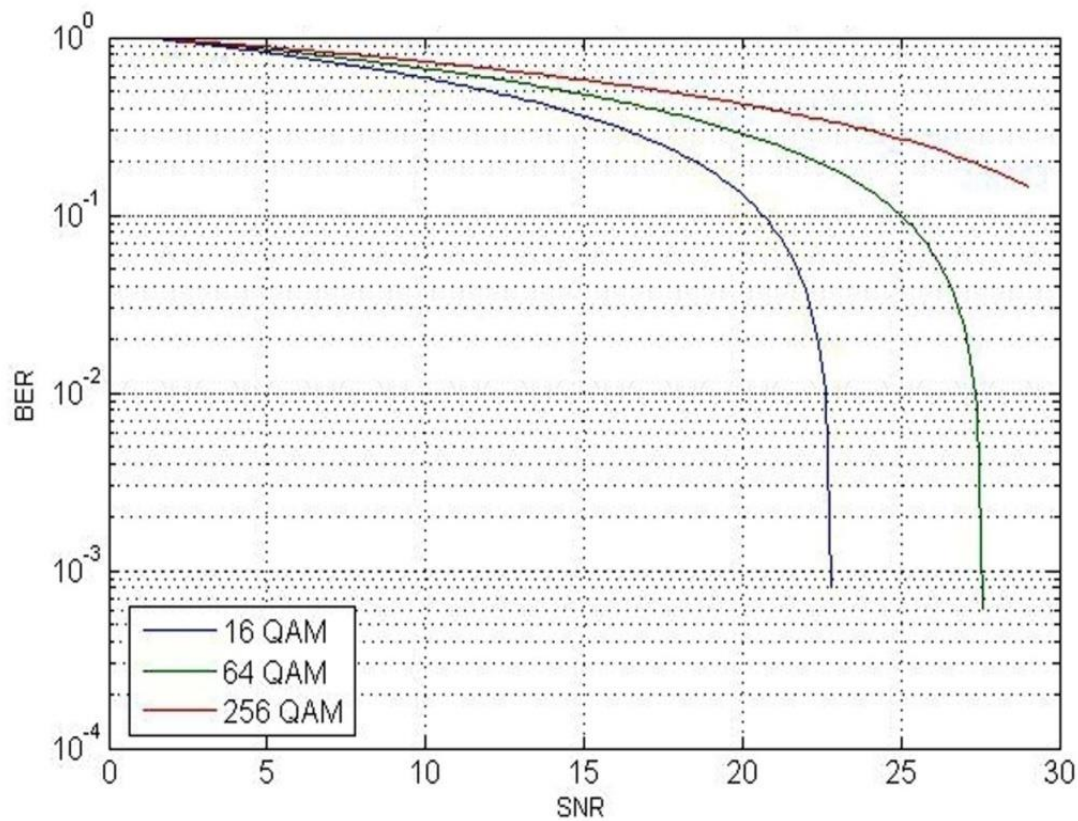


Figure 3.4: BER performance analysis of an OFDM system without adding any sequence using different QAM schemes

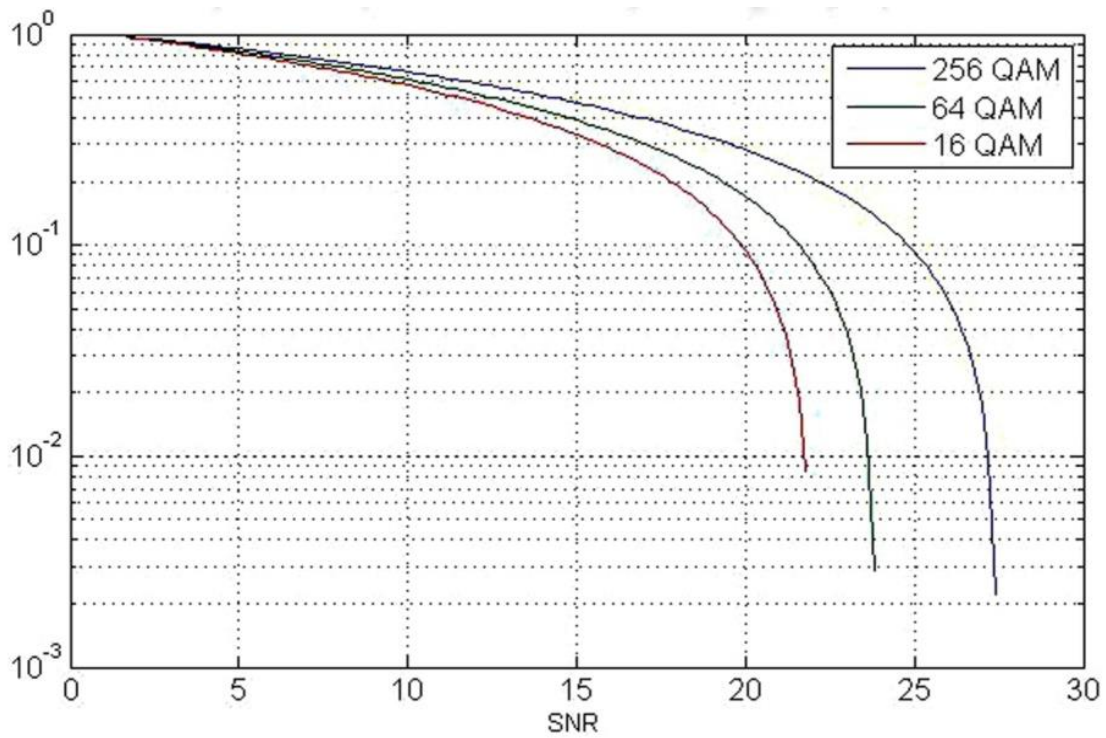


Figure 3.5: BER performance analysis of an OFDM system by adding Golay sequence using different QAM schemes

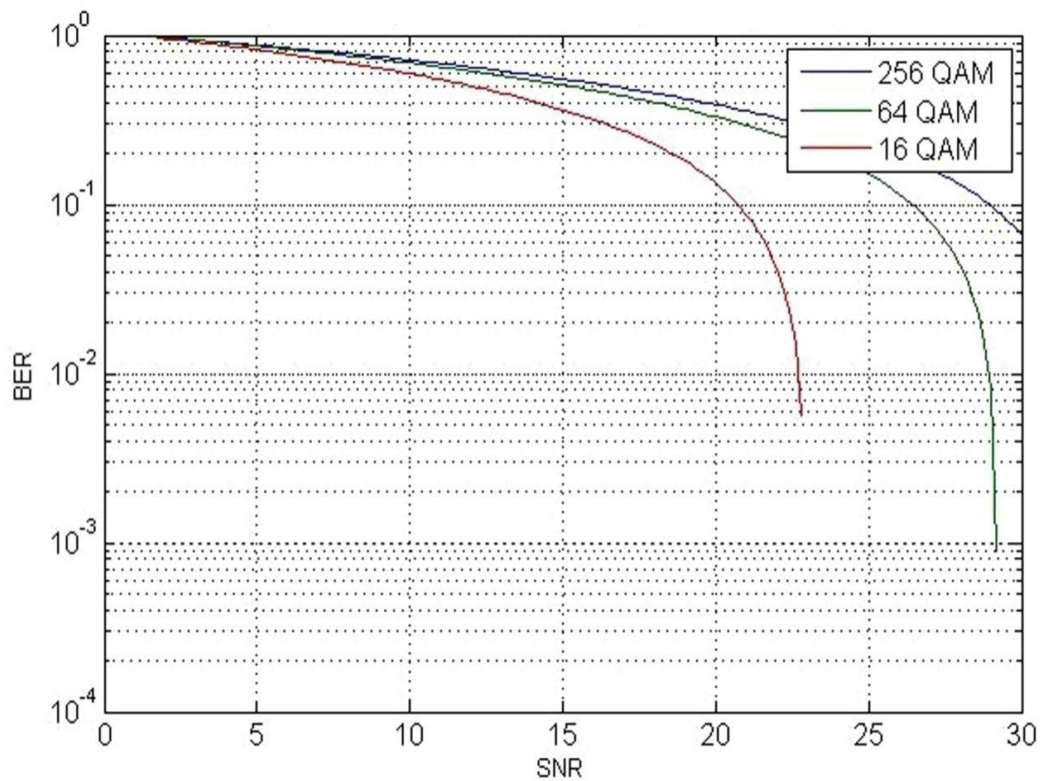


Figure 3.6: BER performance analysis of an OFDM system by adding PN sequence using different QAM schemes

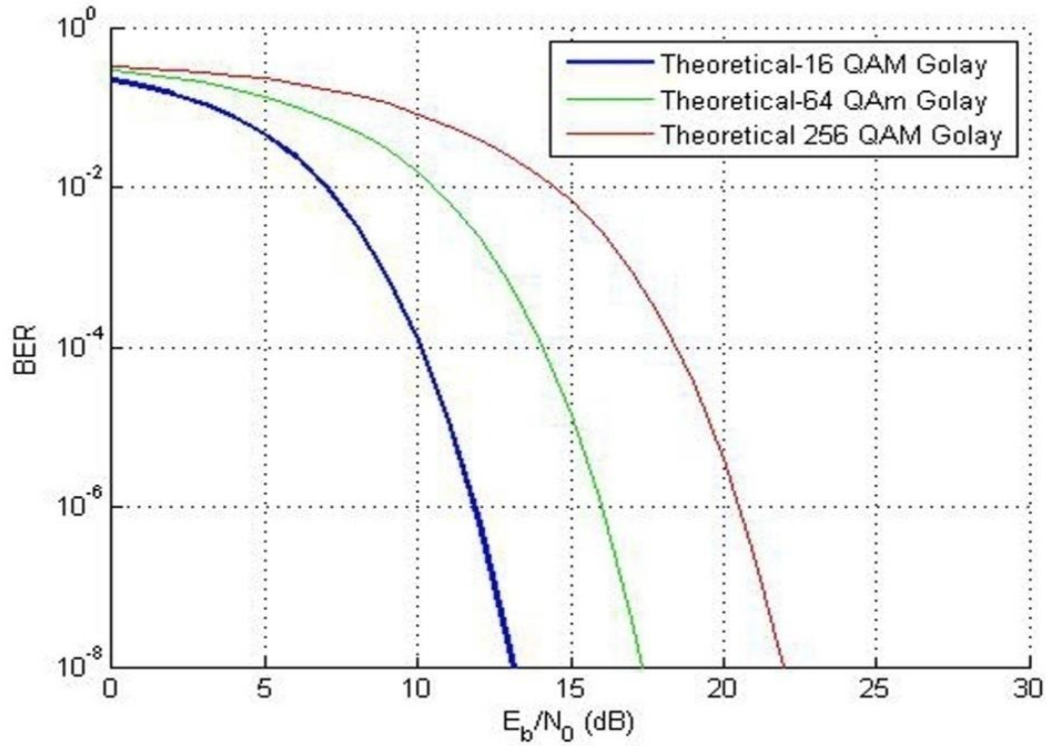


Figure 3.7: Theoretical results of BER for OFDM systems using Golay sequence

3.7 SUMMARY OF THE CHAPTER

In the previous chapter, different techniques have been discussed for decreasing the PAPR of the OFDM system. This chapter presents a novel technique for reduction of the PAPR in the OFDM systems using Golay complementary sequences. A brief introduction of what Golay complementary sequences are and how are they generated has been presented. Effects of adding various sequences along with data were analyzed to improve the QOS of OFDM system. A reference software model has been designed to simulate the OFDM system using the different sequences. The analysis has been carried based on the various QAM methods. The simulation results have shown that the OFDM systems provide optimum performance using Golay sequence in comparison with other sequences. The addition of Golay sequence maximizes BER performance of OFDM system, decreases the PAPR, and avoids the power amplifier to operate in compression. Thus, the efficiency of the OFDM system get enhanced by adding the Golay sequences.

PERFORMANCE ANALYSIS OF CHANNEL CODING IN A MOBILE WIMAX SYSTEM WITH REDUCED TRANSMISSION POWER

4.1 INTRODUCTION

Broadband wireless access (BWA) has now become an efficient solution for supplying high speed internet access in sub-urban and business segments. Presently, DSL and cable technologies are being employed for providing broadband service in sectors mentioned above. However, because of practical difficulties in operation, numerous areas all over the globe at this time might not have broadband services. Also, several localities in urban and sub-urban cannot be provided by DSL connectivity. On the other hand several conventional wired networks are not able to provide internet access in several regions. Although with the help of BWA, these difficulties can easily be removed. Due to the wireless nature, it may be installed in an easier and prompt way, and is more flexible. In this manner, it provides potential for serving clients to best of their satisfaction by their broadband substitutes.

IEEE 802.16 protocol for BWA and WiMAX environment guarantee to provide high data rate over wide areas to huge number of clients wherever broadband is not available. It is a foremost industrial standard which may be used to fix wireless access with considerably higher bandwidth as compared to the majority of the cellular networks [2]. This standard has the specialty in point to multi-point broadband wireless communication. The growth of this protocol results in the reduction of expenditure of equipment and diminishes hazards for operators to guarantee interoperability.

Initial edition of IEEE 802.16 standard functions in 10–66 GHz frequency range and necessitates line of sight (LOS) towers. Afterwards, standard expanded its function throughout dissimilar PHY design to 2-11 GHz frequency range allowing non line of sight (NLOS) connections, which necessitate methods which competently alleviate the mutilation of fading

and multi-path [3]. OFDM has been integrated into WiMAX technique for enabling it to offer high data-rate without selective fading and further concerns of various other type of signals. WiMAX technique uses multipath propagation technique by using multi input multi output (MIMO) technique. By employing multiple signal paths which exist, the utilization of MIMO either facilitates function with lowering the strength of signal, or it permits the elevated data rates. The PHY layer is competent for providing vigorous broadband service in intimidating wireless channel by considering the merits of OFDM technique.

The physical layer of the IEEE 802.16 standard based on OFDM has been standardized in collaboration with High Performance Metropolitan Area Network (Hiper MAN) and European Telecommunications Standards Institute (ETSI). Using WiMax, while operating at a 20MHz wide spectrum, peak PHY data rate transmission rate is elevated up to 74Mbps. Naturally, if 10 MHz spectrum is operated using TDD scheme at a range of 3:1 downlink to up-link ratio, the peak downlink PHY data rate is approximately 25 Mbps and uplink data rate is 6.7 Mbps respectively. When 64 QAM modulation with 5/6 error-correction coding rate is used, the above mentioned peak PHY data rates can be achieved. In the case of favourable signal conditions, it is possible by utilizing multiple antennas and spatial multiplexing to achieve even higher peak rates

With the available channel bandwidth, it is possible for the data rate to scale easily because of scalable physical-layer architecture of WiMAX where the size of the Fast Fourier Transform (FFT) may be leveled with existing channel bandwidth. In OFDMA mode, the characteristics of scalability is maintained, For Instance, 128-bit, 512-bit, or 1,048-bit FFTs may be used by WiMAX system based on the scenario to check whether the channel bandwidth is 1.25 MHz, 5 MHz, or 10 MHz, correspondingly. This scaling is executed vigorously in order to support the users who usually roam across the various networks with varying bandwidth allocations.

Thus, WiMAX has emerged as a revolutionary technique with a numerous advantages. WiMAX is capable for providing high speed data rate for clients and offers data download speeds in surfeit of those which may be presented using the cellular HSPA (high speed packet access). WiMAX may assist service providers convene numerous challenges they countenance because of escalating consumer demands devoid of dumping their existing infrastructure assets since it is having capability for seamlessly interoperating across different networks. WiMAX may offer broad region coverage and quality of service abilities for applications which range from real time delay sensitive voice over internet protocol (VoIP) for real-time video streaming and non real time downloads, making sure that clients attain the performance which is expected from all types of communications. WiMAX, may be incorporated in the 3G mobile and wireless networks which enable it for becoming component of a seamless broadband access resolution. Forward error correction (FEC) and multitude of modulation coding schemes are supported by WiMAX. It also allows system to be modified based on per-frame and per-user for different channel conditions.

In spite of having many benefits, WiMAX suffers with main disadvantage of high PAPR. WiMAX physical layer is based upon OFDM, though fixed and mobile edition of WiMAX are having somewhat dissimilar execution of OFDM. IEEE 802.16 (fixed WiMAX) makes use of 256 IFFT block size and IEEE 802.16e – 2005 (mobile WiMAX) makes use of scalable OFDMA. Hence, hardware equipment related to WiMAX are susceptible to non-linearity because of the high PAPR. With an increase of this PAPR at any time instant the probability of shifting the operating point of the linear power amplifier to the saturation region becomes more. This shifting of operating point directs to in band deformation and out of band radiation, which may be evaded with escalating dynamic range of the power amplifier and again it directs to the growing of size and cost of power amplifier. Also considering power constraint problem it is required to reduce this PAPR in WiMAX. Some researchers have investigated consequence

of non-linear amplifier in WiMAX [17] and apply clipping [27], CORDIC Algorithm [24], and tone reservation [28] for reducing PAPR in the WiMAX system.

Current chapter addresses PAPR problem in WiMAX systems which are used to transmit larger numbers of OFDM sub-carriers. In this chapter, OFDM model-based WiMAX system with IEEE 802.16e specifications has been discussed and a novel method for PAPR reduction has been proposed. A system model has been designed using MATLAB/SIMULINK and its performance of the system has been verified by simulation. Initially, the system was tested without addition of any sequence into data. Thereafter, the system was tested and verified by adding Golay sequence. The simulation results have been presented for evaluating the PAPR and BER at the receiver. It has been investigated for 16 QAM, 64 QAM, and 256 QAM modulations.

4.2 OFDM PARAMETERS IN WiMAX

WiMAX's mobile and fixed versions differ in their OFDM physical layer implementation. A 256 FFT based OFDM physical layer has been used in case of Fixed WiMAX that is based on IEEE 802.16-2004, whereas with variable FFT sizes such as 128-2048 bits, Mobile WiMAX makes use of a scalable OFDMA based physical layer on basis of IEEE 802.16e-2005. The parameters related to OFDM for both OFDM physical layer and OFDMA physical layer have been shown in table 4.1. As per the study, for a restricted set of profiles the parameters have been shown that are likely to be organized. This does not represent the comprehensive set of potential values.

With a predetermined FFT size of 256 in which 192 sub-carriers are allocated to carry data, 8 act like pilot sub-carriers for synchronization and channel estimation. The balance sub-carriers function as the guard band sub-carriers. Due to fixed FFT size, sub-carrier spacing differs in terms of channel bandwidth. In the case of employing large bandwidths, there is an increase in sub-carrier space and decrease in symbol time. But this decreasing symbol time

infers that for overcoming delay increase, a bigger fraction is to be assigned as the guard time. As shown in the table 4.1, a broad range of guard interval has been allowed in WiMAX which enables the system designers for making suitable substitutions among delay spread sturdiness and spectral efficiency. 25 % of the guard interval may be used for achieving the maximum delay spread robustness. This maximum level may contain delay intervals upto the range of 16 μ s when functioning in the channel of 3.5MHz. It can go up to 8 μ s in the case of being operated at 7 MHz channel.

Table 4.1 OFDM Parameters Used in WiMAX

Parameter	Fixed WiMAX OFDM-PHY		Mobile WIMAX Scalable OFDMA-PHY		
FFT size	256	128	512	1024	2048
Number and used data subcarriers	192	72	360	720	1440
Number of pilot subcarriers	8	12	60	120	240
Number of null/guardband subcarriers	56	44	92	184	368
Cyclic prefix or guard time		44	92	184	368
Oversampling rate (Fs/BW)	Depends on bandwidth:7/6 for 256 OFDM, 8/7 for multiples of 1.75 MHz, and 28/25 for multiples of 1,25 MHz, 1.5 MHz, 2MHz, or 2.75 MHz				
Channel bandwidth(MHz)	3.5	1.25	5	10	20

The size of FFT may vary from 128 to 2,048 in Mobile WiMAX. At this point, a proportionate increase is felt i.e., increase in offered bandwidth augments the size of FFT which results in spacing of sub-carrier which is constantly 10.94 KHz. The above scenario maintains OFDM symbol interval as fixed one. This symbol interval is fundamental unit which ensures that scaling exhibits negligible impact on top layers. A scalable plan maintains small

costs. 10.94 KHz sub-carrier spacing is a good choice for balancing among delay interval and Doppler spread requisites for functioning in different atmosphere i.e., fixed and mobile.

Sub-carrier spacing results in delay-spread assessments up to 20 μ s and mobility (vehicular) up to the range of 125 Km/h, when being operated in 3.5 GHz. Whilst channel bandwidth is 1.25MHz, 5MHz, 10MHz, and 20MHz, sub-carrier spacing of 10.94 KHz entails that 128, 512, 1,024, and 2,048 FFT respectively can be used. However, it must be noted down that mobile WiMAX can include supplementary bandwidth as well [70].

4.3 REDUCING HIGH PAPR IN WIMAX

OFDM has high PAPR. A recent analysis of its waveform showed a large fluctuation in its amplitude which leads to a huge challenge to design a power amplifier with adequate power back-off. To do so, it has to focus on different situations like, good sensitivity when the power is low, tolerability to high power level and tracking ability to track down changes. Clipping and coding have been used to fight these effects but still research is needed to make it a good wireless communication system.

Many techniques have been developed for solving the difficulty of elevated PAPR e.g. clipping method. Shortcoming of this technique is that it provides poor performance of BER. Selective Mapping (SLM) technique multiplies numerous phase sequences in the data of OFDM following IFFT operation and chooses series of least PAPR for transmitting. However, this technique essentially necessitates side data in phase rotation for transmitting the consumer data to receiver and provides poor data rate. PTS technique is comparable with SLM technique although its divergence is on multiplying phase factor following IFFT manoeuvre.

The proposed method of Golay sequence insertion makes use of addition of sequences to data for reduction in PAPR. This technique is easier as compared to PTS and SLM techniques as it does not require any side information. For WiMAX scheme, this is further realistic to adopt this method. Because PTS and SLM entail alteration in interface protocols, which are

not required in the proposed technique. Furthermore, WiMAX data frame supports simplicity of applying Golay sequence insertion technique without deprivation of user data.

4.4 SOFTWARE REFERENCE MODEL

The basic simulation model of the WiMAX physical layer is shown the Figure 4.1. The system model has been designed using MATLAB/SIMULINK. The performance of the system has been tested and verified using MATLAB/SIMULINK. Initially, the system was tested without addition of any sequence into data. Thereafter, the system was tested and verified by adding various sequences.

In the reference model, AWGN channel has been considered for transmitting the symbols and range of SNR is taken as 0-30 dB. The FFT size considered is 256 and number of samples take per frame are 256. The simulation has been performed for 16 QAM, 64 QAM, 256 QAM modulations. The table 4.2 list various parameter considered for simulation of the reference model.

Table 4.2: The parameters of the OFDM system considered for the simulation

Parameter Name	Parameter Value
Channel Type	AWGN
SNR	0-30 dB
Input	Frame Based
FFT size	256
Samples per frame	192
Modulation	16 QAM, 64 QAM, 256 QAM

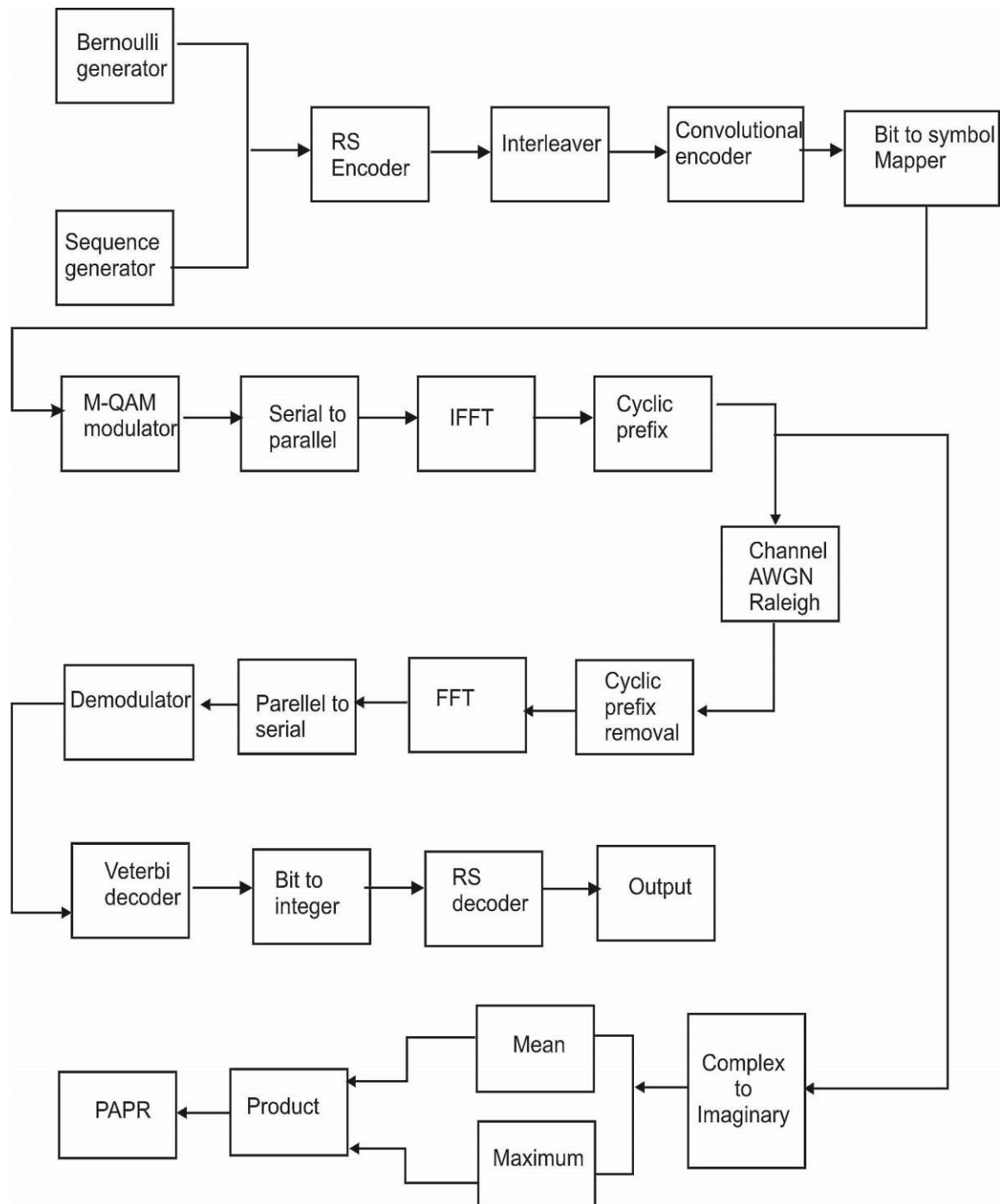


Figure4.1: WiMAX Performance Simulation Block Diagram

Based on OFDM, Wi-MAX physical layer is presented which is mostly preferred among its counterparts for high-speed data rate, multimedia communications, video, business broadband systems that include Wi-Fi, DSL as well as digital video broadcast handheld. The transmitter, receiver and the channel are the three important components in this model where

the first two modules made up of channel coding, modulation sub-components while the latter modelled as AWGN and fading channels.

4.5 SIMULATION AND RESULTS

Simulations have been carried out keeping in mind the WiMAX data frame, This data frame usually utilizes OFDM arrangement with a total of 256 subcarriers. IEEE 802.16 actually describes the WiMAX data frame. Based on the bit rate and SNR error probabilities , the data transmission system's performance is assessed. The model is tested for Golay sequence and has been investigate for 16 QAM, 64 QAM and 256 QAM and the results have been shown in figures below.

The simulations are conducted for $N=16$, 64 and 256 subcarriers. Under the WiMAX environment, the encoded OFDM system's performance is studied using complementary Golay sequences (CGS) in terms of PAPR reduction and BER. Due to correlation of above mentioned sequences with the Reed Muller codes, CGS provides both FEC as well as PAPR bounding characteristics. Based on this, it can be inferred that a combination of FEC capabilities and PAPR reduction can actually increase the overall performance of the system.

Figure 4.3 shows the comparative analysis of BER for WiMAX system using Golay sequence. Figure 4.2 shows the same without addition of sequence. It can be seen that BER is reduced by addition of Golay sequence. The two are compared and shown in the Figure 4.4. The comparison of the two systems is depicted by the simulation that corresponds to various QAM modulation schemes. The outcomes of projected technique have been contrasted with earlier studies [93], [65]. When compared to the convention system (Refer Figure 4.5) the SNR improvement amount is nearly 5 dB at BER of 10^{-4} .

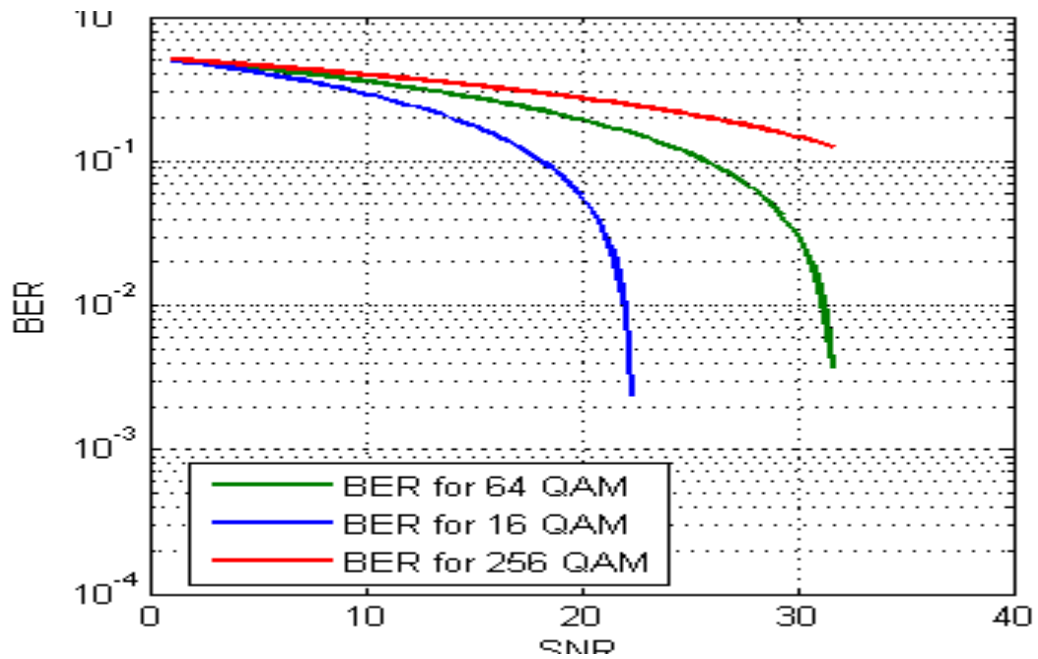


Figure 4.2: BER vs. SNR (dB) without Error Correction in 16-QAM 1/2, 64-QAM 3/4, 256-QAM 3/4 with Guard width ratio (G): 1/4, No of Sub carriers and FFT size 256 on AWGN WiMAX model.

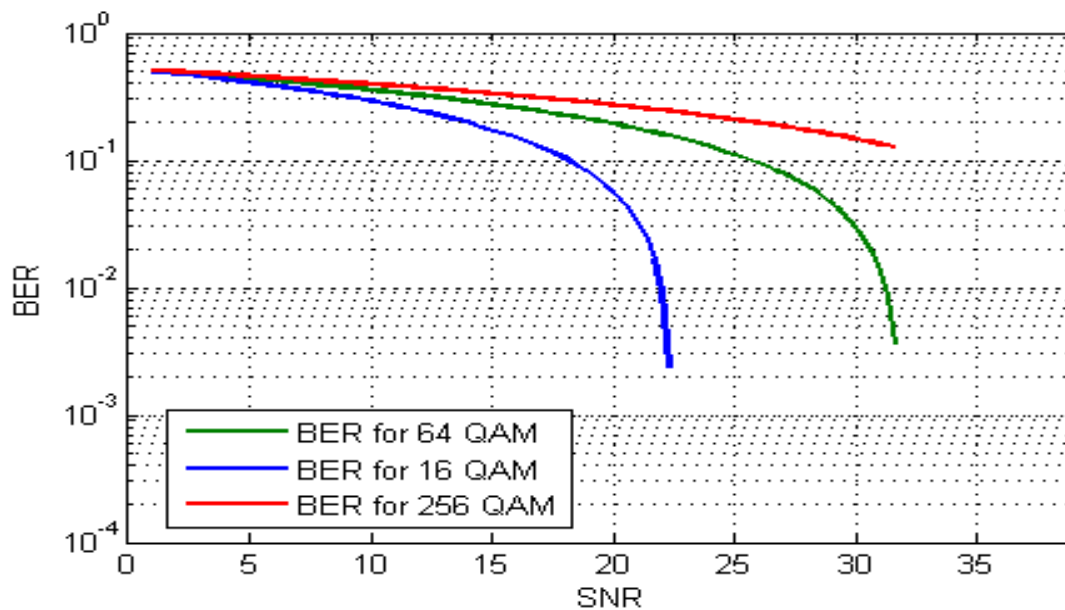


Figure 4.3: BER vs. SNR (dB) for Effect of Error Correction in 16-QAM 1/2, 64-QAM 3/4, 256-QAM 3/4 with Guard width ratio (G): 1/4, No of Sub carriers and FFT size 256 on AWGN WiMAX model.

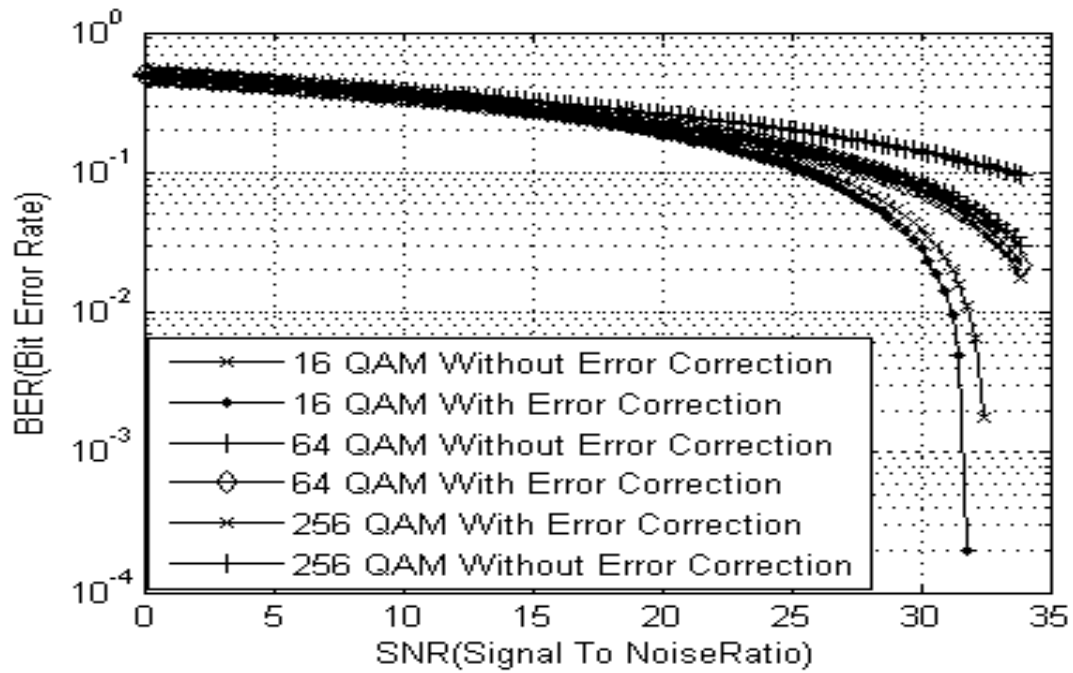


Figure 4.4: Comparison of BER vs. SNR (dB) with and without Error Correction in 16-QAM 1/2, 64-QAM 3/4, 256-QAM 3/4 with Guard width ratio (G): 1/4, No of Sub carriers and FFT size 256 on AWGN WiMAX model

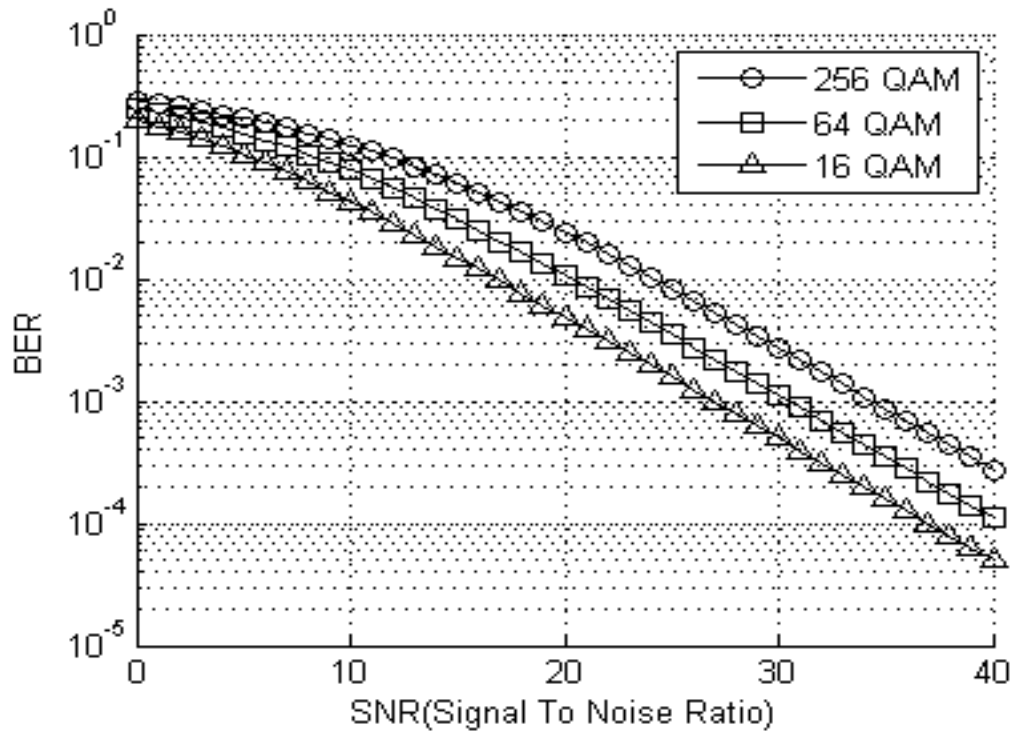


Figure 4.5: Theoretical BER Vs SNR (dB)

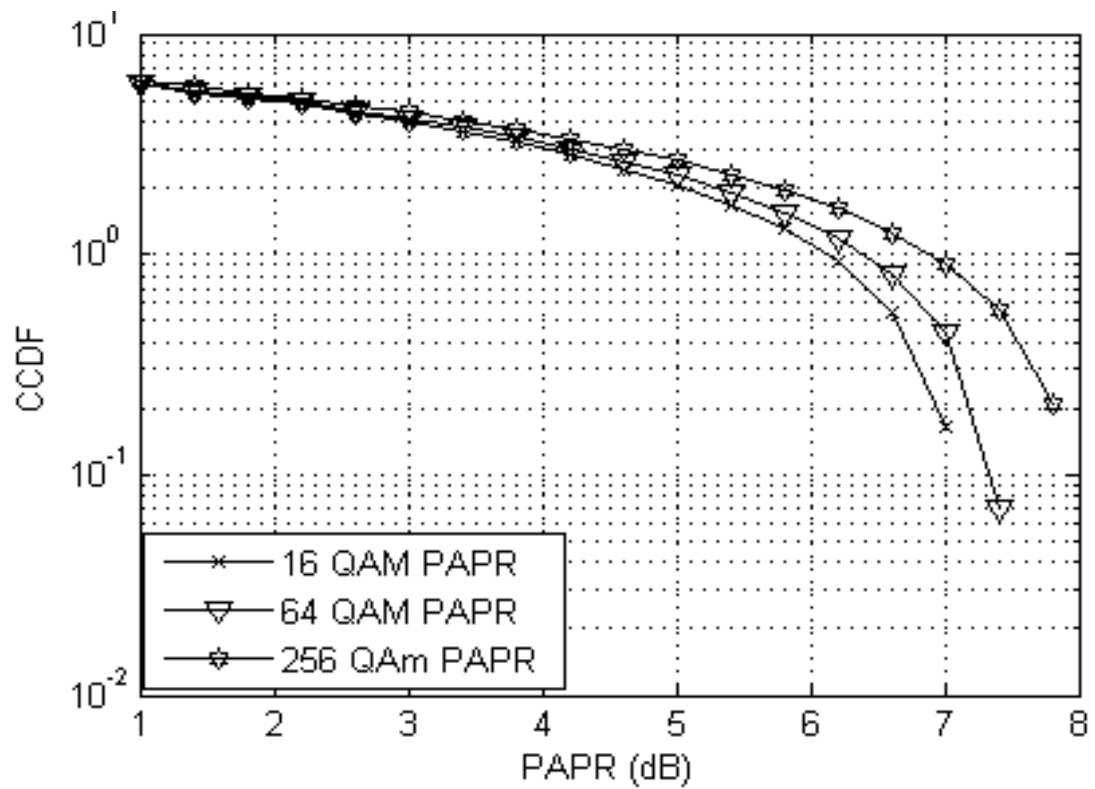


Figure 4.6: CCDF for the PAPR obtained without error correction technique for data subcarriers of WIMAX.

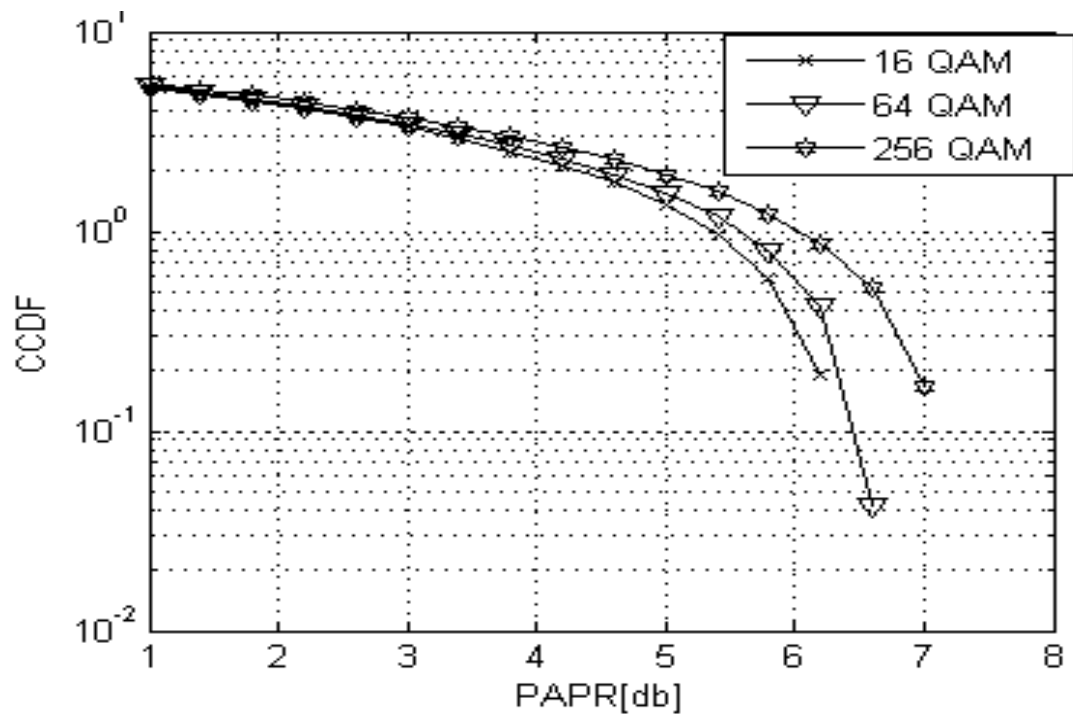


Figure 4.7: CCDF for the PAPR obtained with error correction technique for data subcarriers of WIMAX

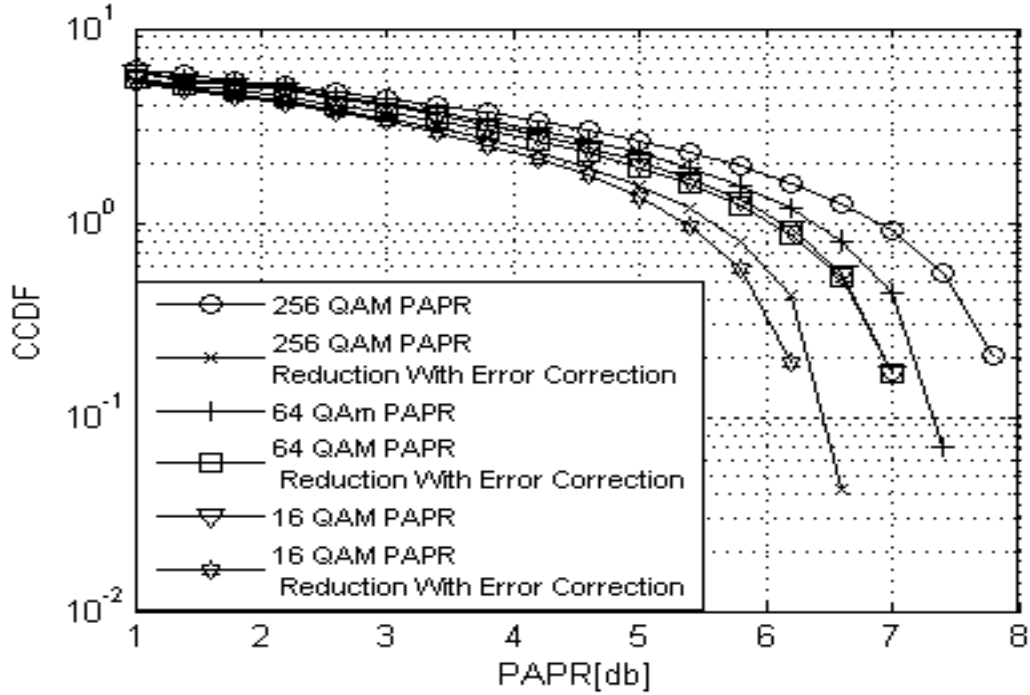


Figure 4.8: CCDF Comparison for PAPR obtained without and with Error correction technique for the data subcarriers of WIMAX.

The CCDF analysis of the proposed system which utilizes the 16, 64 and 256 QAM is shown in the Figures 4.6 and 4.7. The PAPR of the uncoded signal is 8 dB whereas 7 dB is the Golay encoded signal PAPR. From Figure 4.8, which shows the comparison of uncoded and coded systems, it can be concluded that reduction of 1dB in the PAPR is obtained by using the proposed method. A theoretical justification may be that result of insertion of sequence at frequency domain is for rotating a phase shift in the corresponding waveform of time domain.

During phase-shift, it is possible for the waveforms of OFDM to evade coherent summing up for variable components of frequency which actually can lead to PAPR reduction. The implementation of the proposed Golay encoded OFDM-WIMAX system has been done in MATLAB. In almost every case, the encoded OFDM system exhibited the results of low PAPR than its counterpart i.e., un-coded system. The proposed method's results can be compared with the theoretical results [71].

4.6 SUMMARY OF THE CHAPTER

In the previous chapter, a novel technique for reduction in the PAPR of the OFDM systems using Golay complementary sequences was presented and it was shown that the OFDM system provides optimum performance by adding Golay sequence in comparison with other sequences. In this chapter PAPR problem in WiMAX systems has been addressed. A novel method for PAPR reduction in WiMAX systems has been presented by adding Golay sequence. The simulation results have been presented for evaluating the PAPR reduction and BER at the WiMAX receiver using 16 QAM, 64 QAM and 256 QAM modulations. The simulation results have revealed 1dB reduction in PAPR using the proposed method. For WiMAX system, the proposed method is more realistic in execution as compared to the PTS or SLM technique, because PTS and SLM necessitate alteration in air-interface standards, which is not required for the proposed technique. Additionally, data-frame of WiMAX supports simplicity of applying Golay sequence insertion technique without degradation of user data.

CONCLUDING REMARKS AND FUTURE SCOPE

5.1 CONCLUDING REMARKS

OFDM is an excellent aspirant to put up next generation very high bit-rate WiMAX. To evade the high power amplifiers' loss in efficiency some performance impairments such as PAPR should be resolved. In this thesis, the simulation performance of WiMAX OFDM PHY Layer under different modulation schemes has been investigated. Here, the performance of Complementary Golay Sequences (CGS) has been examined in terms of both forward error correction and PAPR reduction. The method recommended reduces the PAPR and the simulation results illustrate that the peak power is reduced by approximately 1dB and approximately 4dB as compared to other methods. Simulation results demonstrate that the proposed solution can accomplish the bit-error-rate requirements of WiMAX. The probability analysis in the simulations is a clear demonstration providing the improved work for PAPR reduction.

Firstly, the effect of various sequences on BER of a basic OFDM model is analyzed and then PAPR is evaluated using MATLAB with different modulation schemes. The system is then analyzed for PAPR using Golay sequence. Simulation results show that Golay sequences give the best results. It is clear that QOS of the system can be enhanced when Golay sequence is added to the input data. When BER of OFDM system is reduced, it reduces the PAPR and also prevents the power amplifier to go into compression. As a result efficiency of the system also gets improved. The investigation has been carried based on the different QAM techniques. The simulation results depict that OFDM systems offer most favorable performance using Golay sequence as compared to other sequences. The addition of Golay sequence maximizes BER performance of OFDM system, decreases the

PAPR, and prevents the power amplifier to go into compression. Thus, the efficiency of the OFDM system gets enhanced by adding the Golay sequences.

In the subsequent part of the thesis PAPR and BER reduction has been examined. Performance of OFDM system (encoded) has been analyzed using CGS for a WiMAX system. Because of correlation of CGS with Reed Muller codes, which also provide FEC in addition to the PAPR reduction capabilities of the CGS. Hence, overall system performance can be augmented by combining FEC capabilities and the PAPR reduction. The efficiency of an encoded OFDM system has been evaluated with respect to reduction in BER and PAPR for WiMAX system. The suggested method decreases the PAPR and simulation results show that peak power is reduced by roughly 4dB. Simulation results show that this method can achieve the bit-error-rate requirements of WiMAX. In this thesis, the reduction of PAPR resulted into the OFDM systems intended for QAM constellation has been considered, in meticulous for 16-QAM and 256 QAM. The techniques proposed in this investigation can be applied for producing OFDM series having less PAPR for 1024-QAM constellations.

The main purpose of this thesis was realization of OFDM PHY layer (IEEE 802.16) for estimating the PHY layer performance by using numerous modulation schemes in MATLAB. The implemented PHY layer very well supports CP lengths defined in the specification and each and every one of modulation and coding designs as well.

For investigating PHY layer performance, the simulation method was used. The main method for performance assessment is contemplated on effect of adding sequences into input data. BER is a primary performance factor of a system (wireless communication). PAPR and BER graphs have been used for comparing the efficiency of various modulation and coding schemes used. These have been presented with a complete and inclusive assessment of efficiency of OFDM PHY layer for various states of the wireless channel.

5.2 Future Works

There is still scope of improvements in the implemented PHY layer model. The channel estimator can be implemented to attain a representation of the channel state to reduce the effects of the channel using an equalizer.

To still further develop the performance, the IEEE 802.16 standard has numerous optional PHY layer features. To enhance the performance of FEC, the optional Block Turbo Coding (BTC) can be implemented.

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