A

Thesis report

On

"PAPR reduction in OFDM System Using Partial Transmit Sequence (PTS) and Precoding Techniques"

A thesis report submitted in partial fulfilment of
requirement for the award of degree of

MASTER OF ENGINEERING
In
Wireless Communication

Submitted By
Anil Khatiwada
(Roll No—801263003)

Under the guidance of
Dr. Hem Dutt Joshi
Assistant Professor
ECE Department
Thapar University, Patiala

DEPARTMENT OF ELECTRONICS & COMM.
ENGINEERING
THAPAR UNIVERSITY
(Established under section 3 of UGC Act, 1956)
PATIALA – 147004, INDIA

Declaration

I hereby declare that the work, which is being presented in the report, entitled "**PAPR reduction in OFDM System Using Partial Transmit Sequence (PTS) and Precoding Techniques**" in partial fulfilment of the requirements for the award of Master of Engineering in Wireless Communication at Electronics and Communication Engineering Department of Thapar University, Patiala which is an authentic record of my own work carried out under the guidance of **Dr. Hem Dutt Joshi (Assistant Professor)**, Electronics and Communication Department during the fourth semester, 2014.

The matter presented in this thesis has not been submitted in any other University/Institute for the award of Master of Engineering.

Date: 17-6-2014

Anil.k

Anil Khatiwada

Roll no: 801263003

This is to certify that the above statement made by the student is correct to the best of my knowledge and belief.

Date: 17-6-2014

Joshi

Dr. Hem Dutt Joshi

Supervisor

Dr. Sanjay Sharma

Head of Department

ECED, Thapar University, Patiala

Dr. S.K. Mohapatra

Dean of Academic Affairs

Thapar University, Patiala

Acknowledgement

I would like to give special thanks to my guide **Dr. Hem Dutt Joshi** (Assistant Professor) ECED, Thapar University, Patiala, for his advice, kind assistance, and invaluable guidance. It has been a great honour to work under him.

I am also thankful to **Dr. Sanjay Sharma**, Prof. & Head, Electronics and communication Engineering Department, for providing us with adequate infrastructure in carrying the work.

I am also thankful to **Dr. Kulbir Singh** P.G. Coordinator, Electronics and communication Engineering Department for the motivation and inspiration that triggered me for the report work.

I am greatly indebted to all of my friends who constantly encouraged me and also would like to thank all the faculty members of ECED for the full support of my work. I am also thankful to the authors whose work have been consulted and quoted in this work.

Anil Khatiwada

Abstract

In recent time, the demand for multimedia data services has grown up rapidly. One of the most promising multi-carrier system, Orthogonal Frequency Division Multiplexing (OFDM) forms basis for all 4G wireless communication systems due to its large capacity to allow the number of subcarriers, high data rate and ubiquitous coverage with high mobility. OFDM is significantly affected by peak-to-average-power ratio (PAPR). Unfortunately, the high PAPR inherent to OFDM signal envelopes will occasionally drive high power amplifiers (HPAs) to operate in the nonlinear region of their characteristic curve. The nonlinearity of the HPA exhibits amplitude and phase distortions, which cause loss of orthogonality among the subcarriers, and hence, inter-carrier interference (ICI) is introduced in the transmitted signal. Not only that, high PAPR also leads to in-band distortion and out-of-band radiation.

This thesis emphasis mainly on the PAPR reduction of OFDM system using partial transmits sequence (PTS) and precoding techniques. Some other techniques such as amplitude clipping have low-complexity; on the other hand, they suffer from various problems such as in-band distortion and out-of-band expansion. Signal companding methods have low-complexity, good distortion and spectral properties; however, they have limited PAPR reduction capabilities. Advanced techniques such as coding, partial transmit sequences (PTS) and selected mapping (SLM), have also been considered for PAPR reduction. Such techniques are efficient and distortionless, nevertheless, their computational complexity is high. Also, the precoding is an attractive technique to the PAPR problem which approaches that of single carrier system. This technique has low complexity as well as it is data independent. So, it does not require new processing and optimization for each transmitted block.

We proposed a combine technique of precoding and PTS to reduce the PAPR. This hybrid combined technique reduces PAPR effectively and also minimizes the complexity of PTS technique which arises due to number of subblocks. In PTS scheme, as the number of subblocks increases, the IFFT operation to be performed for subblocks also increases. Simulation results have shown that the decrement of PAPR of proposed scheme is more than PTS and precoding methods as well as the complexity reduced significantly. The out of band radiation of proposed scheme is less than original OFDM as shown in power spectral density (PSD) simulation result.

List of Tables

List of figures

Figure No Description Page No

List of Abbreviations

S. No.	**Abbreviation**	**Description**
1	3GPP	3rd Generation Partnership Project
2	4G	Fourth Generation
3	ABC	Artificial Bee Colony
4	ADC	Analog to Digital Converters
5	ADSL	Asymmetric Digital Subscriber Lines
6	ATM	Asynchronous Transfer Mode
7	AWGN	Additive White Gaussian Noise
8	BER	Bit Error Rate
9	BTRC	Better Than Raised Cosine
10	BWAS	Broadband Wireless Access System
11	CCD	Complementary Cumulative Distribution
12	CCDF	Complementary Cumulative Distribution Function
13	CDMA	Code Division Multiple Access
14	CE	Cross Entropy
15	CP	Cyclic Prefix
16	DAB	Digital Audio Broadcasting
17	DAC	Digital-to-Analog Converter
18	DCT	Discrete Cosine Transform
19	DFT	Discrete Fourier Transform
20	DVB	Digital Video Broadcasting
21	EM	Electromagnetism-like
22	FDM	Frequency Division Multiplexing
23	FDMA	Frequency Division Multiplexing Access
24	FFT	Fast Fourier Transform
25	HDSL	High Bit Rate Digital Subcarriers Lines
26	HDTV	High Definition Television
27	HPA	High Power Amplifier
28	HYPERLAN	High Performance Radio LAN
29	ICI	Inter-Carrier Interference
30	IEEE	Institute of Electrical and Electronics Engineering

31	IFFT	Inverse Fast Fourier Transform
32	IPTS	Iterative Partial Transmit Sequences
33	ISI	Inter-Symbol Interference
34	LDPC	Low Density Parity Check
35	MCM	Multi Carrier Modulation
36	ML	Maximum Likelihood
37	MOCA	Multimedia Over Coax Alliance
38	M-PSK	M-ary Phase Shift Keying
39	MPEG	Moving Picture Experts Group
40	M-QAM	M-ary Quadrature Amplitude Modulation
41	NLOS	Non Line of Sight
42	OFDM	Orthogonal Frequency Division Multiplexing
43	PAPR	Peak-to-Average-Power Ratio
44	PN	Pseudo- Random Noise
45	PTS	Partial Transmit Sequences
46	POTS	Plain old Telephone Services
47	SA	Simulated Annealing
48	SC	Single Carrier
49	SLM	Selective Mapping
50	SNR	Signal to Noise Ratio
51	SQRC	Square Root Raised Cosine
52	TI	Tone Injection
53	QAM	Quadrature Amplitude Modulation
54	QEA	Evolutionary Algorithm
55	QPSK	Quadrature Phase Shift Keying
56	UMTS	Universal Mobile Telecommunications System
57	WiMax	Worldwide Interoperability for Microwave Access

Table of Contents

CHAPTER 1: Introduction

CHAPTER 2: Mathematical analysis of OFDM System

CHAPTER 3: Literature Review

CHAPTER 4: Proposed Technique for PAPR Reduction

CHAPTER 5: Conclusion and Future work

CHAPTER-1

Introduction

Recently, the demand for multimedia data services has grown drastically which drive us in the age of 4th generation wireless communication system. This requirement of multimedia data service where user are in large numbers and with bounded spectrum, modern digital wireless communication system adopted technologies which are bandwidth efficient and robust to multipath channel environment known as multi-carrier communication system. The modern digital multicarrier wireless communication system provide high speed data rate at minimum cost for many users as well as with high reliability. In single carrier system, single carrier occupies the entire communication bandwidth but in multicarrier system the available communication bandwidth is divided by many sub-carriers. So that each sub-carrier has smaller bandwidth as compare to the bandwidth of the single carrier system. These tremendous features of multicarrier technique attract us to study Orthogonal Frequency Division Multiplexing (OFDM). OFDM forms basis for all 4G wireless communication systems due to its huge capacity in terms of number of subcarriers, high data rate in excess of 100 Mbps and ubiquitous coverage with high mobility. The introduction chapter consists of following parts: Overview, Historical Development of OFDM, principle of orthogonality, advantages and disadvantages of OFDM technique, and the applications of OFDM technique.

1.1 Overview

The necessity of high data rate draws the great attention in multi-carrier system. It should be capable to operate smoothly in environment of high carrier frequency, high data transmission rate and mobility. The studied has shown that OFDM fulfil the multi-carrier system necessities. OFDM is a multi-carrier modulation (MCM) technique in which complex data symbols (i.e, BPSK, QPSK, QAM, MPSK etc.) are transmitted in parallel after modulating them over orthogonal sub-carrier. In single carrier (SC) system, one complex data is transmitted using one carrier and in this parallel transmission, N complex data is transmitted over N sub-carrier. Here the effective data rate of the system is same as of SC system. The parallel transmission increases the time period of symbol and the comparative amount of separation in time caused by multipath delay decreases.

In OFDM system, the orthogonality among sub-carriers is maintained by using inverse Fast Fourier Transform (IFFT) as shown in figure (2.1). A guard band is inserted between successive OFDM symbols. Insertion of guard band in OFDM symbols can be done by three methods- cyclic prefix, cyclic suffix and zero padding. By adding guard band in OFDM symbols, OFDM convert wideband frequency selective channel into collection of parallel narrowband flat fading channel, one channel across each subcarrier. Thus it removes Inter-Symbol Interference (ISI). Due to features like high immune to multipath fading, high data transmission rate and requirement of less complex equalizer, OFDM has been exploited by many high data rate broadband wireless communication systems of present generation [1], [2].

1.2 Historical Development of OFDM

The concept of multicarrier communication was given by military systems in the late 1950s and mid-1960s, such as KINEPLEX [3-5]. These systems are called multicarrier communication system, which transmit data on non-overlapped band-limited orthogonal signals. These systems require analog oscillator and filter of much wider bandwidth and sharp cut-off. In [6], Saltzberg suggested a MCM system employing time-limited orthogonal signals, which is similar to OFDM was first given in 1960 [7].

“OFDM” was first introduced by U.S in January 1970 [8]. But it becomes popular in 1971, when Weinstein and Ebert proposed a modified OFDM system [9] in which the Discrete Fourier Transform (DFT) was applied to generate the orthogonal sub-carriers waveforms. In their proposed model, baseband signals were modulated by the DFT in the transmitter and then demodulated by inverse DFT (IDFT) in the receiver. So, the implementation complexity is reduced by the use of DFT algorithms (i.e. IFFT/FFT). Therefore, all the sub-carriers overlapped with each other in the frequency domain maintain their orthogonality as shown in figure (1.1).

After 10 years of Weinstein and Ebert proposed paper, Cimini [10] in 1985 provides a analytical and simulation results on the performance of OFDM modems in mobile communications channels. In the late 1980’s the work began on the development of

OFDM for commercial use with the introduction of the Digital Audio Broadcasting (DAB) system [11].

The OFDM systems have some major problems (like high PAPR, timing and frequency synchronization, Inter-Carrier Interference (ICI) etc.) and lot of work has been reported to solve these problems. Most of the work published in the late 1990s and 2000s were related to these problems where main focus was on the analysis and solution of the problems.

1.3 Principle of Orthogonality

In multi-carrier system, occupied bandwidth on the channel is minimized as possible. This minimization is possible by reducing the frequency space between carriers. The narrow space among the carriers is obtained when they are orthogonal to each other. To be orthogonal, the time averaged integral product of two signals should be zero. Mathematically, the orthogonality of two signals can be expressed as-

$$\frac{1}{T}\int_{t_1}^{t_1+T} f_k(t) \times f_l(t)\, dt = 0 \quad if\ k \neq l \qquad (1.1)$$

where, $f_k(t)$ and $f_l(t)$ are any two signals over time interval $[t_1\ ,\ t_1 + T\ ]$, T a is signal time period. For orthonormal, the time averaged integral product of two signals should be one.

Mathematically, ortho-normal of two signals can be expressed as-

$$\frac{1}{T}\int_{t_1}^{t_1+T} f_k(t) \times f_l(t)\, dt = 1\ \ if \quad k = l \qquad (1.2)$$

Using equation (1.1) and (1.2), orthogonality for OFDM system is expressed as-

$$\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} \mathrm{e}^{\mathrm{j}2\pi \mathrm{f_k t}} \times \mathrm{e}^{-\mathrm{j}2\pi \mathrm{f_l t}} \mathrm{dt} = \frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} \mathrm{e}^{\frac{\mathrm{j}2\pi \mathrm{kt}}{\mathrm{T}}} \times \mathrm{e}^{\frac{-\mathrm{j}2\pi \mathrm{lt}}{\mathrm{T}}} \mathrm{dt} = \frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} \mathrm{e}^{\frac{\mathrm{j}2\pi(\mathrm{k}-\mathrm{l})\mathrm{t}}{\mathrm{T}}} \mathrm{dt} \qquad (1.3)$$

Solving equation (1.3), we get-

$$\frac{1}{T}\int_0^{T} e^{j2\pi f_k t} \times e^{-j2\pi f_l t} dt = \begin{cases} 0 & \forall \quad k \neq l \\ 1 & \forall \quad k = l \end{cases} \qquad (1.4)$$

Taking the discrete samples with the sampling instances at $t = nT_s = nT/N, n = 0,1,2 \dots . N-1$. Equation (1.4) can be written in the discrete time domain as-

$$\frac{1}{N}\sum_{n=0}^{N-1} e^{\frac{j2\pi k}{T}nT_s} \times e^{\frac{-j2\pi k}{T}nT_s} = \frac{1}{N}\sum_{n=0}^{N-1} e^{\frac{j2\pi(k-l)}{N}n} = \begin{cases} 0 & \forall \quad k \neq l \\ 1 & \forall \quad k = l \end{cases} \qquad (1.5)$$

OFDM communication systems are able to effectively utilize the frequency spectrum through overlapping subcarriers. Simulation of figure (1.1) for five sub-carriers shows that sub-carriers are able to partially overlap without interfering with adjacent sub-carriers because the maximum power of each subcarrier corresponds directly with the minimum power of each adjacent channel. In additional, different sub-carriers are orthogonal to each other and they are totally different from one another.

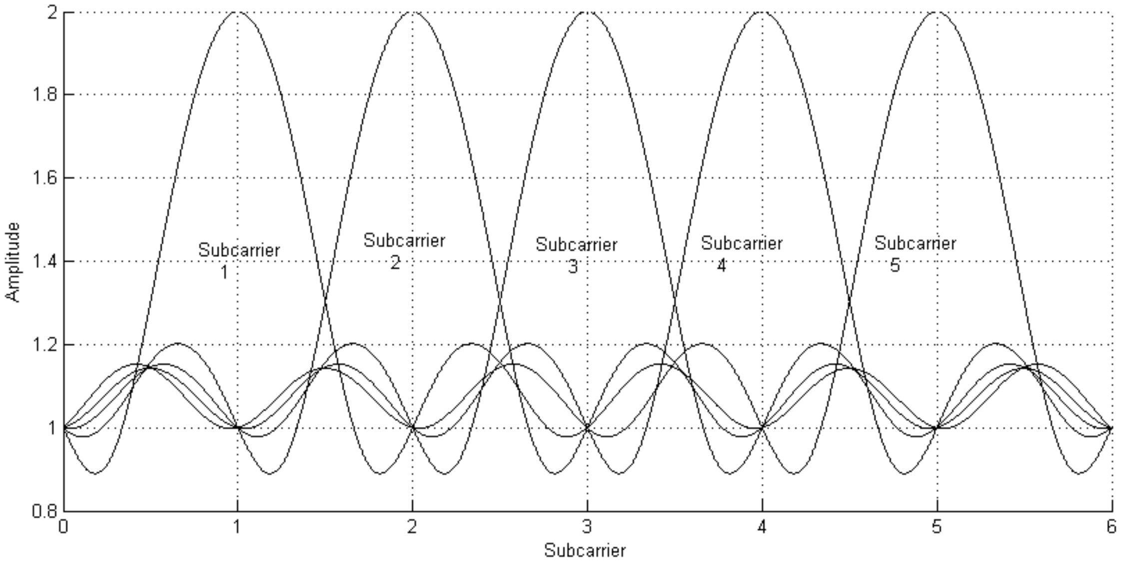


Figure-1.1: Frequency response of 5 sub-carriers of OFDM signal.

1.4 Advantages of OFDM system

The advantages of OFDM system are given as-

- **Saving of Bandwidth-**

  The OFDM system is more bandwidth efficient in comparison to Frequency Division Multiplexing (FDM). As shown in figure 1.2(a), in FDM technique numerous distinct carriers are spaced apart without overlapping where in OFDM system the sub-carrier overlap each other due to orthogonality features. Due to overlapping of sub-carriers the usage of bandwidth reduced drastically and also reduced the guard bands for the separation of sub-carriers.

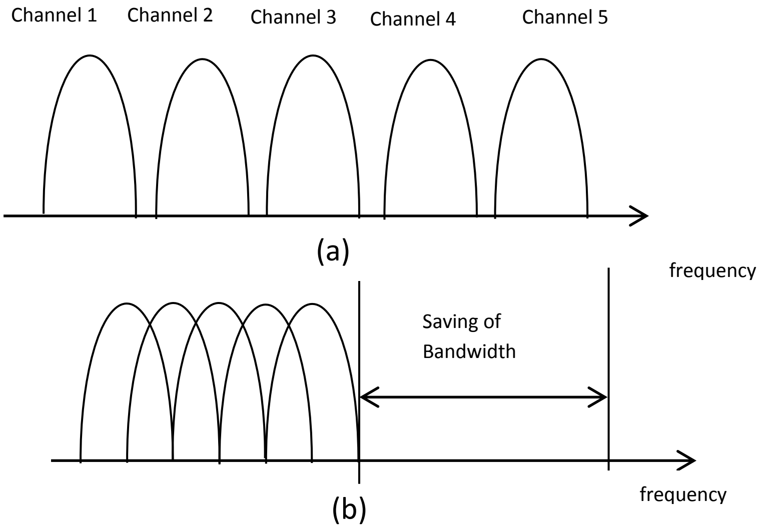


Figure-1.2: Comparison of (a) conventional multi-carrier technique and (b) orthogonal multi-carrier modulation technique.

- **Easy to implement modulation and demodulation**

  The challenging problem in a MCM system is to implement bank of modulators at the transmitter side and demodulators at the receiver side. The concept of “Data transmission” can be efficiently implemented using IFFT and FFT instead of bank of modulators at the transmitter side and demodulators at the receiver side respectively.

- **Easy Equalization-**

  In a single carrier system, equalization make frequency channel flat but equalization amplify noise greatly in frequencies domain where channel response is poor. As a result, single carrier performance is affected due to high attenuation in some bands since all used frequencies are given equal importance. In OFDM system, wideband channel are divided into flat fading sub-channels, it reduces the equalization complexity in the receiver. So, it is possible to use maximum likelihood decoding with reasonable complexity.

- **Susceptible to frequency selective fading-**

  Due to capability of parallel transmission (each sub-carrier has narrow bandwidth to overall bandwidth of signal) OFDM is highly susceptible to frequency selective fading. OFDM converts a frequency selective fading channel into several flat fading channels.

- **Protection against Intersymbol interference-**

  The extended symbol time (due to lower data rate) makes the signal less susceptible to effect the channel such as multipath propagation which introduces Inter Symbol Interference (ISI). The use of cyclic prefix between consecutive OFDM symbols makes it immune to ISI. Also, it is less sensitive to sample timing offsets than single carrier system.

1.5 Major problems of OFDM system

Despite of several advantages, the OFDM systems also have some major problems like-

- **High Peak to Average Power Ratio (PAPR) of transmitted signal-**

  Presence of a large number of subcarriers with varying amplitude results in a high peak to average power ratio (PAPR) of the system with large dynamic range, which in turn effects on the efficiency of the RF amplifier.

- **Synchronization (timing and frequency) at the receiver-**

  Symbol Timing Offset (STO) and Carrier Frequency Offset (CFO) affects on the performance of OFDM system. Correct timing between FFT and IFFT is required at the receiver side. OFDM system is highly sensitive to Doppler shifts which affect the carrier frequency offset, resulting in ICI.

This thesis is mainly focused on the PAPR problem in OFDM system.

1.6 Applications

After the use of IFFT/FFT technique, the implementation of OFDM becomes more convenient. The applications of OFDM are divided into two categories-wire-line and wireless application. The wire-line application such as-

- Asymmetric Digital Subscriber Line (ADSL) broadband access through plain old telephone service (POTS) copper wiring [12].

- Multimedia over Coax Alliance (MOCA) home networking [13].

The wireless application such as-

- IEEE 802.11 a/g/n [14-16].
- IEEE 802.15.3a [17].
- IEEE 802.16 d [18].
- IEEE 802.20 [19].
- Digital Audio Broadcast (DAB) systems [20].
- Digital Video Broadcast (DVB) terrestrial TV systems [21].
- HIPERLAN/2 [22]

OFDM is applied for 3rd Generation Partnership Project (3GPP) UMTS and 3GPP@Long-Term Evolution (LTE) and also in 4th Generation (4G). It is also used for the development of Digital Video Broadcasting (DVB) which was widely used in Europe and Australia. At present, many people still work to modify the IEEE 802.16 i.e. WiMax ("Worldwide Interoperability for Microwave Access") standard which may result in higher data rate up to 100 Mbps.

Table-1.1: Applications of OFDM system

OFDM Applications	Features
1. Asymmetric Digital Subscriber Line (ADSL)	• ADSL provides internet access through wires telephone network. • The data bit rate of ADSL ranges from 256kbit/s to over 100 Mbit/s.
2. Multimedia over Coax Alliance (MOCA)	• MOCA is the standard for home entertainment which provides service of data, internet access and HD video. • MOCA was established in 2004. • There are two versions of MOCA, MOCA 1.1 and MOCA 2.0. • This technology is used in applications like gaming, multi-room, digital video recorders (DVRs). • MOCA 1.1 provides data rate of 175 Mbit/s and its frequency range is 500 to 1650 MHz • MOCA 2.0 provides data rate of 400Mbit/s-1Gbit/s and its frequency range is 500 to 1650 MHz
3. IEEE 802.11	• IEEE 802.11 is a collection of media access control (MAC) and physical layer (PHY) specifications. • It uses 2.4, 3.6, 5 and 60 GHz frequencies.

	• In 1999, 802.11a was established and utilized 5-3.7 GHz frequencies with bandwidth of 20 MHz • In 2003, 802.11g was established and used 2.4 GHz frequency with bandwidth of 20 MHz • In 2009, 802.11n was established and utilized 2.4/5 GHz frequency with bandwidth of 20 to 40 MHz
4. IEEE 802.15.3a	• IEEE 802.15 standard specifies WPAN which was established in 2002. • IEEE 802.15.3a standard provides high speed ultra wideband which was applied for imaging and multimedia.
5. IEEE 802.20	• IEEE 802.20 standard specifies Mobile Broadband Wireless Access (MBWA). • It was established in 2008 and used licensed bands (below 3.5 GHz). • It provides 80Mbit/s data rates.
6. IEEE 802.16 e	• IEEE 802.16e standard specifies WiMAX. • WiMAX established in 2005 has 1.25 MHz, 5MHz and 10MHz or 20MHz bandwidths. • IEEE 802.16.e standard also specifies WiBro developed by South Korea providing data rate of 10Mbit/s. • WiBro utilizes time division duplexing (TDD) for duplexing, OFDMA for multiple access and 10MHz bandwidth.
7. Digital Audio Broadcasting (DAB)	• Digital Audio Broadcasting had started its service in 1996. • It was the oldest system using OFDM technique and it used DQPSK modulation scheme. • It can transmit text, images and sound over a 1.5 MHz system bandwidth. • It has 192-1596 carriers depending on frequency and operates from 0.1-3 GHz. • A digital technology, DAB can be transmitted at lower power than today's FM and AM services without loss of coverage. • Ability to provide CD-quality stereo sound. • Easy to implement DAB receivers. • Single multiplex can carry up to six full quality stereo programs. • DAB is used in EUREKA 147, Digital Radio Mondiale, HD Radio, T-DMB and ISDB-TSB
8. Digital Video Broadcasting (DVB)	• Digital Video Broadcasting started its service in 2001 in Australia.

	• OFDM technique is used. • QPSK, 16 QAM, 64 QAM modulation techniques are used. • It transmits MPEG-2 compress video at about 31Mbps data rate which is sufficient to support High Definition Television. • It is used in DVB-T, DVB-H, T-DMB and ISDB-T.
9. HIPERLAN/2	• High Performance Radio LAN (HIPERLAN) is Wireless LAN standard. • It provides communications at up to 54 Mbps in the 5 GHz band. • It uses OFDM for high data rates. • DES or Triple DES algorithms are used to secure data. • Company like Alvarion (Israel), Mototrola (USA), Panasonic (Japan) manufactures HiperLAN/2.
10. IEEE 802.16 Broadband Wireless Access System (BWAS)	• BWAS is the broadband wireless technology used to deliver voice, data, Internet and video service in the 25-GHz and higher spectrum. • Broad BW: up to 134 Mbps in 28 MHz wide channel (10-66 GHz). • Support simultaneous multiple services with full QOS IPv4, IPv6, ATM, Ethernet, etc. • Band width as demanded by users. • QPSK, 16 QAM, 64 QAM modulation techniques are used. • Support multiple frequency allocation from 2-66 GHz.

1.7 Objective of Thesis

The demand for higher data rate communication always provides the impetus for doing research in the OFDM field. One of the challenging issue of OFDM system is high peak to average power ratio (PAPR). High PAPR force the high power amplifier (HPA) to operate in non-linear region. This operation in non-linear region degrade the power efficiency of the amplifier simultaneously requires large back-off power, introduce ISI in OFDM system and hence, degrade the bit error rate (BER) performance. Numerous techniques have been proposed during the period of 10 years for reducing the PAPR. The main problems regarding these techniques are computational complexity, HPA efficiency and BER performance. The main purpose of this thesis is to study and analyse the PAPR reduction techniques of the OFDM system and then to propose new scheme with low computational complexity as well as less influence on HPA efficiency and BER performance.

1.8 Outline of Thesis

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

Chapter 2 describes the mathematical analysis of OFDM system. This chapter begins with describing OFDM system model including transmitter, channel and receiver. In the transmitter formation of OFDM signal, adding of guard interval mechanisms are described. Different types of modelling of channels are described and are evaluated in channel part and finally in the receiver signal recovering mechanisms are described.

Chapter 3 elaborates in detail literature survey of high PAPR problem and different PAPR reduction techniques in OFDM system. First the definition of PAPR, its effects on systems and PAPR performance parameter are described. After that, classifications of PAPR reduction techniques and description of some PAPR reduction methods like selective mapping (SLM), partial transmit sequence (PTS), precoding is described. Finally literature reviews for PTS and precoding are presented.

Chapter 4 introduces a new hybrid technique (proposed method) of low complexity for PAPR reduction. The proposed method is the combination of precoding and PTS schemes. The PAPR performance of PTS, precoding and proposed methods are compared and evaluated through matlab simulations.

At last, conclusions are given in chapter 5 along with possible suggestions of future work.

CHAPTER 2

Mathematical analysis of OFDM System

This chapter describes the mathematical analysis of OFDM system. It elaborates the OFDM block diagram with its transmitter, channel and receiver. Simulation results are done to evaluate the performance of OFDM system over multipath environment with inserting cyclic prefix and without inserting cyclic prefix by using different modulation schemes and different subcarriers. At last, the simulation results and conclusion of the chapter are discussed.

2.1 OFDM System Model

The discrete time baseband OFDM system with N subcarriers is shown in figure 2.1. It consists of transmitter, channel and receiver blocks.

2.1.1 Transmitter

In this model, a block of input bits (symbols) are modulated by M-ary data modulators and then, N such symbols are transferred by the serial to parallel converter. Different types of data modulator can be used depending upon system requirement (e.g. M-PSK, M-QAM etc.). The complex parallel data symbols (X_k) obtained by using modulation techniques are given to N point IFFT block as shown in figure 2.1.

The complex envelope of the baseband transmitted OFDM signal can be written as-

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \, e^{j2\pi f_k t}, \qquad 0 \le t \le NT \tag{2.1}$$

where, N is the total number of subcarriers, $X_k,\ k = (0,1,\dots,N-1)$ block of N input bits (symbols), f_k=$k\Delta f$, where Δf=$1/(NT)$, T=original symbol period. Generally, the complex data are uncorrelated as shown in below-

$$E[X_k X_l^*] = \begin{cases} 1, & k = l \\ 0 & k \neq l \end{cases} \tag{2.2}$$

where, X_l^* represents the complex conjugate of X_l.

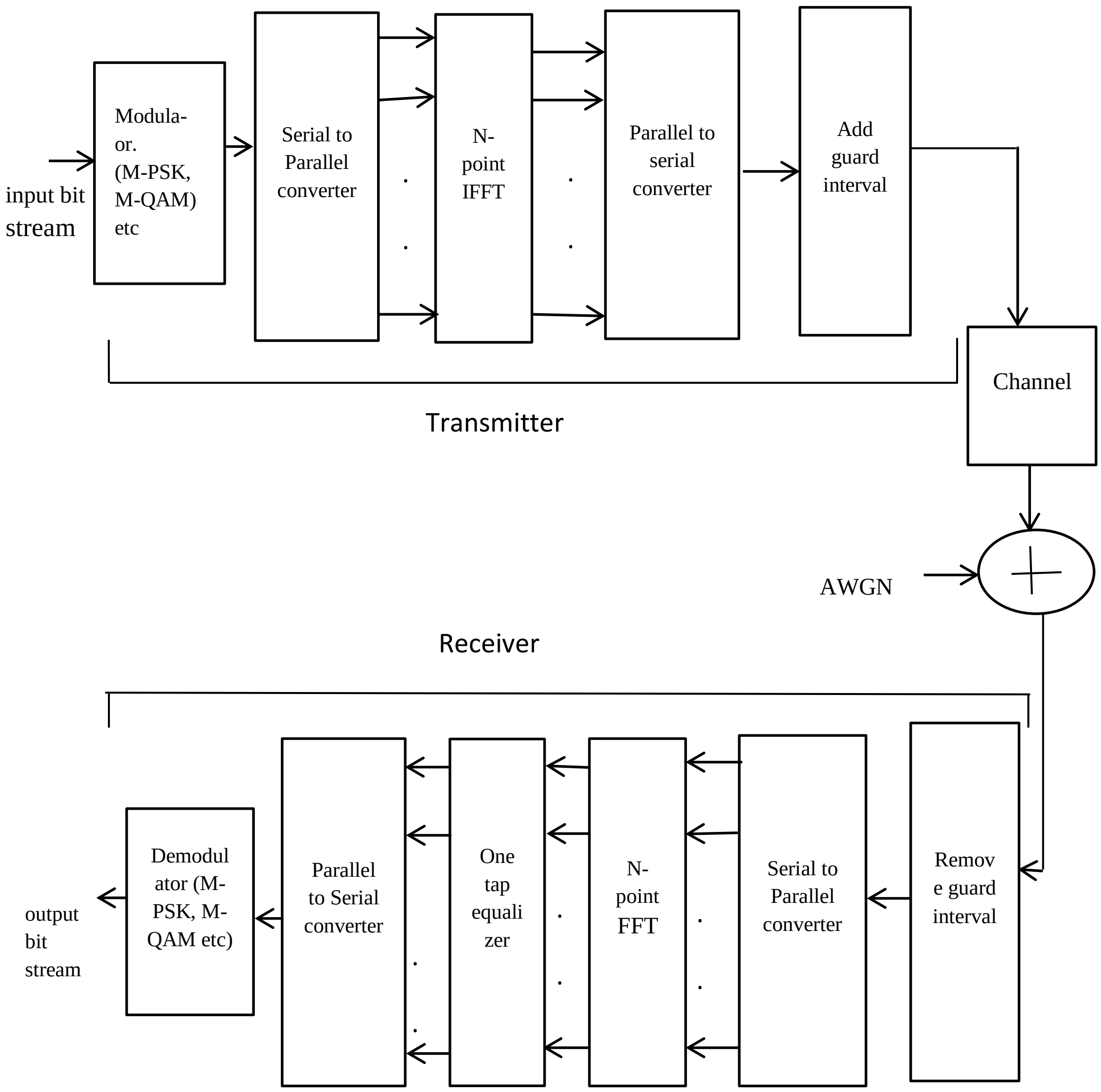


Figure-2.1: Block diagram of OFDM system

The discrete form of OFDM signal $x(n)$ is given by-

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \, e^{\frac{j2\pi kn}{N}}, \qquad for\; n = 0, 1, 2, 3 \ldots N-1 \tag{2.3}$$

Equation (2.3) shows that transmitted signal $x(n)$ is obtained by taking the inverse discrete fourier transform (IDFT) of modulated input data symbols X_k. As shown in figure 2.1, practically IDFT can be comfortably and thoroughly obtained by using inverse fast fourier transform (IFFT).

2.1.1.1 Addition of Guard band

Guard interval in OFDM system is used to remove ISI which is generally introduced between consecutive OFDM symbols. The delay spread of multipath channel caused ISI in OFDM symbols. To remove ISI entirely a guard band interval with no signal transmission can be used but it can produce ICI because of higher spectral components which occurred due to quickly change of waveform.

The guard interval can be used in two ways- zero padding (ZP) and cyclic extension. Cyclic extension can be extended in two ways- cyclic prefix (CP) or cyclic suffix (CS).

2.1.1.1.1 Cyclic prefix

In cyclic prefix, small part or portion of transmitted symbols are taken and repeat that small portion as the prefix of transmitted symbol [2].

By prefixing of OFDM symbol ISI is removed. The CP insertion is shown in figure 2.2.

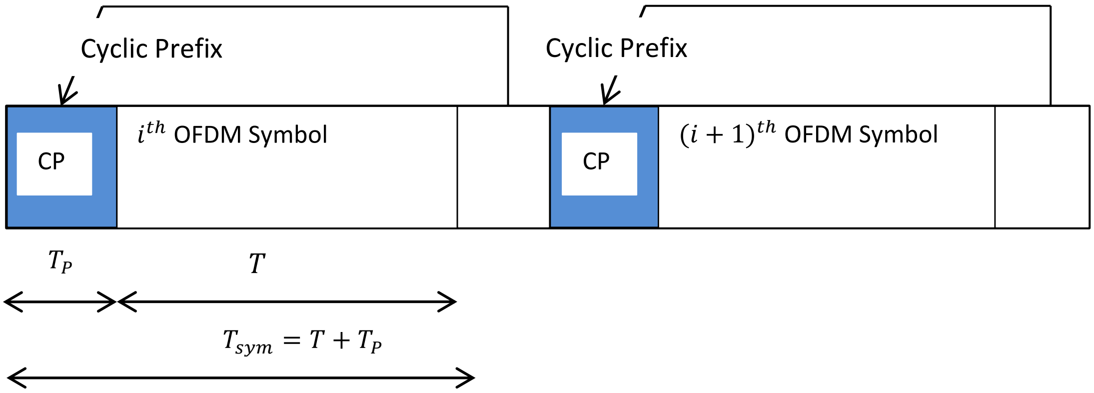


Figure 2.2 OFDM symbols with cyclic prefix

Addition of cyclic prefix extends OFDM symbols to $T_{sym} = T + T_P$ and mathematically it can be expressed as-

$$x(t)_{ext} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \, e^{j2\pi f_k t}, \qquad -T_P \le t \le T \tag{2.4}$$

where, $x(t)_{ext} = x(t+T), \; for \; -T_P \le t \le 0$.

The discrete form of the prefixed OFDM symbols can be expressed as-

$$x(n)_{ext} = \begin{cases} x(n+N), & for\ n = 0,1,\dots\dots,P-1 \\ \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} X_k\, e^{\frac{j2\pi k(n-P)}{N}}, & for\ n = P, P+1 \dots P+N-1 \end{cases} \tag{2.5}$$

where, N is the total number of sub-carriers and P is total number of CP symbols added in the OFDM symbol.

The length of the CP should be greater than delay spread of a multipath channel. If the CP is less than delay spread of multipath channel then the head part of the next OFDM symbol will be altered by the tail part of previous OFDM symbol, leading to ISI. The cyclic prefix larger than the delay spread of the multipath channel maintains the orthogonality among the subcarriers.

2.1.1.1.2 Cyclic suffix

In cyclic suffix, small part or portion of transmitted symbols are taken and repeat that small portion as the suffix of transmitted symbol as shown in figure 2.3.

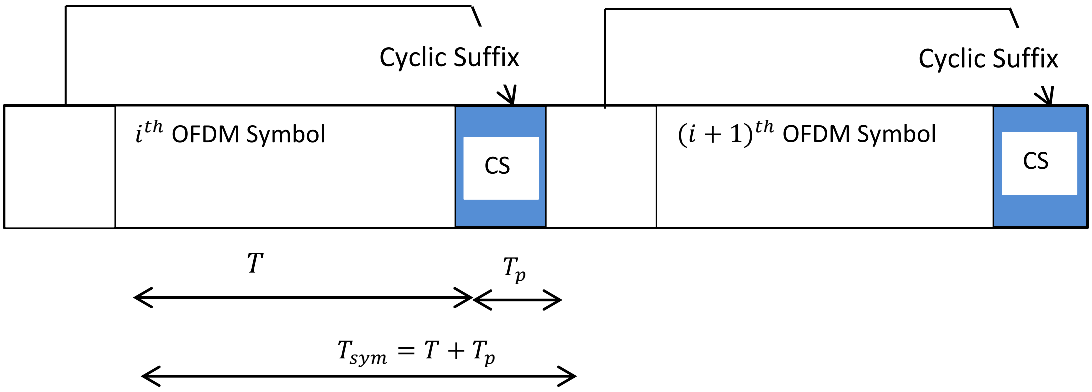


Figure 2.3 OFDM symbols with cyclic suffix

It copy upper portion of OFDM symbol to the bottom of the symbol to mitigate intersymbol interference (ISI). This method of insertion of guard interval is used for frequency hopping and radio frequency (RF) convergence.

2.1.1.1.3 Zero Padding

In zero padding (ZP) top and bottom portion of the transmitted symbols are filled with zeros as shown in figure 2.4.

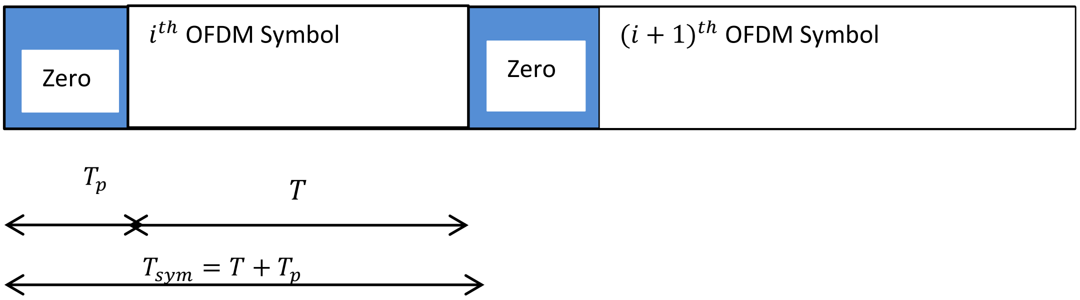


Figure 2.4 OFDM symbols with zero padding

2.1.2 Channel Model

The phenomenon of noise and multipath environment can be predicted by using channel model. Generation of noise can be done by adding few random data to the OFDM symbol and multipath environment can be generated by adding attenuated and delayed copies of the OFDM signal. The impulse response $h(\Gamma - \mathrm{t})$ for wireless channel is given by as [23].

$$h(\Gamma - t) = \sum_{l=0}^{L-1} h_l\,(t)\delta(t-\Gamma) \qquad (2.6)$$

where, $h_l(t)$ and Γ are the tap coefficient or complex amplitude and propagation delay.

The tap coefficients $h_l\,(t),\ l = 0,1,2,\ldots.,L-1$ are modelled as zero mean complex Gaussian random variables having variance 1. Rayleigh fading model provide a suitable environment on a wireless signal [23]. The amplitude of wireless signal follows the Rayleigh distribution because of multipath environment and its probability density function (pdf) is given as [24]-

$$f(r) = \frac{r}{\sigma^2}\exp\left\{-\frac{r^2}{2\sigma^2}\right\}, \qquad r \geq 0 \qquad (2.7)$$

where, r is envelope of received signal and σ^2 is a variance of envelope of received signal. In Rayleigh distribution, propagation of signal is along non line of sight (NLOS) between the transmitter and receiver.

After multipath fading channel $h(\Gamma, t)$, the received signal $y(t)$ is expressed as-

$$y(t) = \sum_{l=0}^{L-1} h_l\,(t) x_{ext}(t - \Gamma) + n(t) \tag{2.8}$$

where, $n(t)$ is the Additive White Gaussian Noise (AWGN).

2.1.3 Receiver

At the receiver, inverse of the transmitter is done. Here, first the guard interval of OFDM symbol is removed. Then, these unguarded OFDM symbol is converted from serial to parallel which are passed through FFT block. The FFT converts these parallel OFDM data streams into frequency domain. The output of FFT operation can be expressed as-

$$X(k) = F(k)x(k) + w(k), for\ 0 \le k \le N - 1 \tag{2.9}$$

where, $w(k)$ is the AWGN component in frequency domain and $F(k)$ denotes the FFT (frequency response of the multipath fading channel at the k sub channel) which is expressed as-

$$F(k) = \frac{1}{\sqrt{N}} \sum_{l=0}^{L-1} h_l\, e^{-\frac{j2\pi kn}{N}}, k = 0,1, \ldots\ldots, N - 1 \tag{2.10}$$

The complex data received symbol $x(k)$ can be recovered by single tap frequency domain equalizer and expressed as-

$$G(K) = \frac{1}{F(k)} \tag{2.11}$$

The tap coefficients of the filter are calculated based on channel information [25].

Finally, the recovered data symbol are converted back into serial stream and demodulated by using scheme like (M-PSK, M-QAM) to baseband.

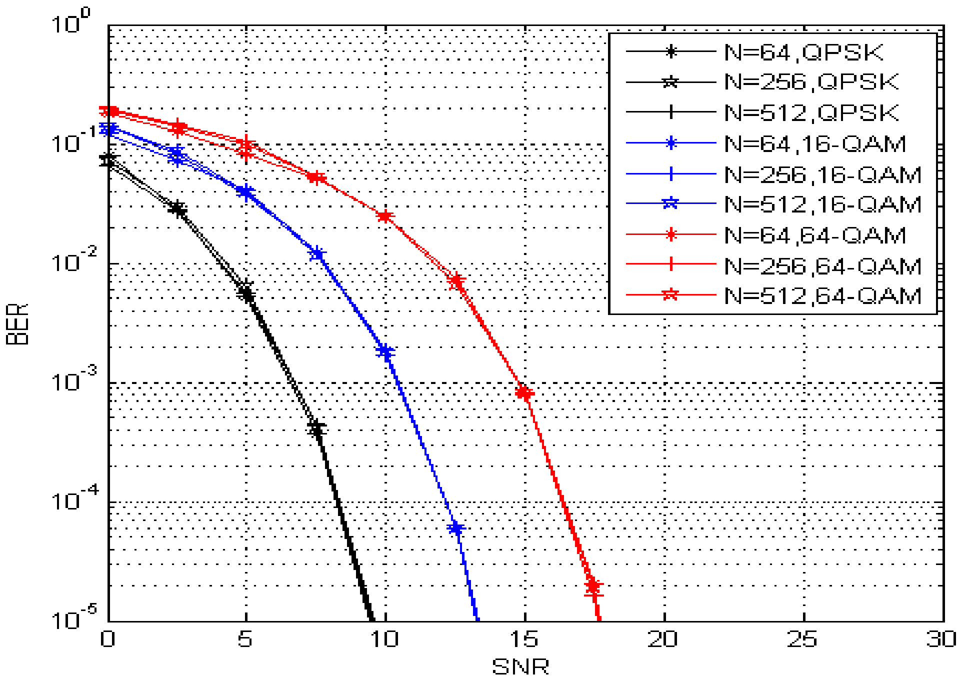
2.2 BER Performance of OFDM system

For evaluation of system performance over AWGN and Rayleigh fading channel, SNR v/s BER graph has been determined using MATLAB. Figure 2.5 shows the BER performance of OFDM system over AWGN and Rayleigh channel with adding and without adding cyclic prefix. SNR v/s BER plot for different sub-carriers (N=64, 256, 512) with QPSK, 16-QAM and 64-QAM modulation schemes over AWGN and Rayleigh channel have been performed. To obtain the result, 20000 random OFDM blocks are generated. In figure 2.5(a), SNR is compared over AWGN channel for different subcarriers and modulations with addition of cyclic prefix (CF)=$N/4$ between successive OFDM symbols. The most obvious trend in the graph is that to maintain a 10^{-5} BER, SNR increases as modulation schemes level goes on high as well as there is no effect of sub-carriers on the BER performance. For different subcarriers with QPSK, 16-QAM and 64-QAM modulations SNR of 9.4dB, 13.2dB and 17.6dB to maintain a BER of 10^{-5} are required respectively.

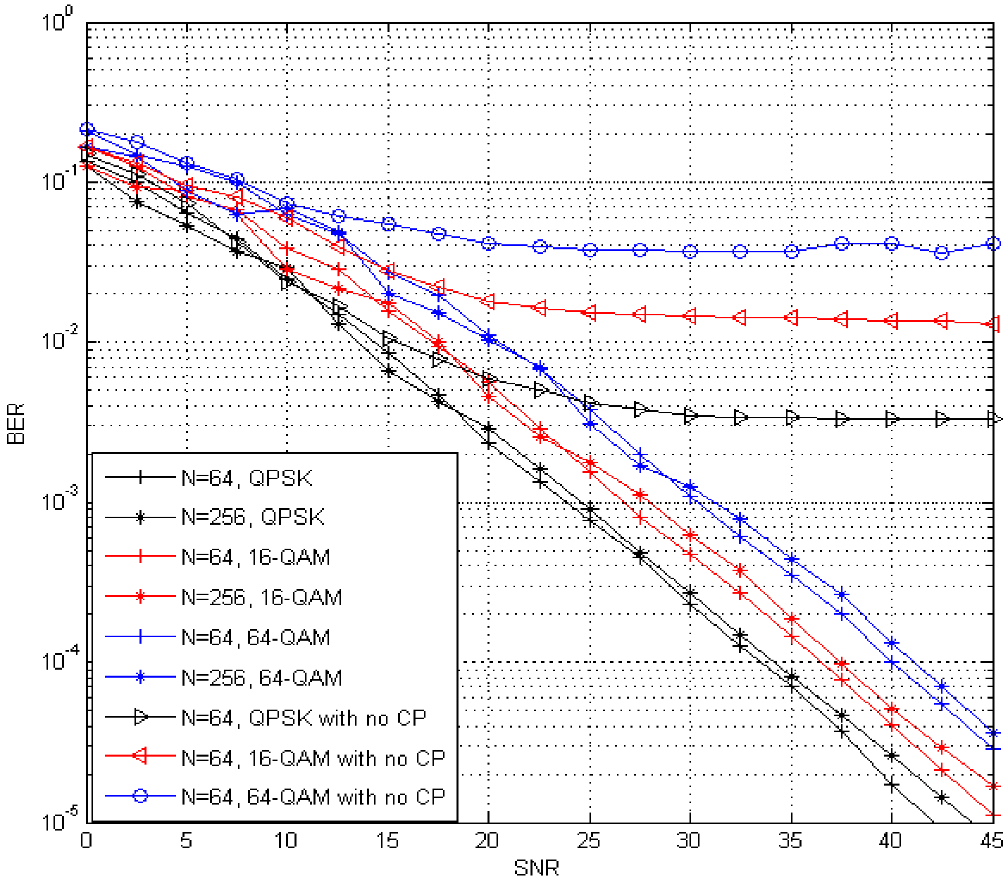
In figure 2.5(b), BER performance is compared over Rayleigh channel for different subcarriers and modulations with addition of cyclic prefix (CF)=$N/4$ between successive OFDM symbols. Here, same trend as in AWGN channel of increasing SNR to maintain the same error rate on higher modulation scheme with insignificant effect of subcarriers on BER performance have observed. For different subcarriers with QPSK, 16-QAM and 64-QAM modulation schemes SNR around 34dB, 36dB and 40dB are required to maintain a BER of 10^{-4} respectively. The worst BER performance is obtained without using cyclic prefix (CP=0). The simulated values of SNR for different subcarriers and modulation schemes over AWGN and Rayleigh channels are shown in table 2.1.

Table-2.1: BER Performance of OFDM system over AWGN and Rayleigh channel.

Number of sub-carriers	Modulation used	SNR (dB)	Channel
64, 256, 512	QPSK	9.4 dB at BER of 10^{-5}	AWGN
64, 256, 512	16-QAM	13.2 dB at BER of 10^{-5}	
64, 256, 512	64-QAM	17.6 dB at BER of 10^{-5}	
64 256	QPSK	33.56 dB at BER of 10^{-4} 34.15 dB at BER of 10^{-4}	Rayleigh
64 256	16-QAM	36.37 dB at BER of 10^{-4} 37.52 dB at BER of 10^{-4}	
64 256	64-QAM	39.99 dB at BER of 10^{-4} 41.19 dB at BER of 10^{-4}	
64	QPSK	44.81 dB at BER of 0.0033	Rayleigh with no CP
64	16-QAM	44.68 dB at BER of 0.013	
64	64-QAM	44.85 dB at BER of 0.041	



(a) AWGN Channel



(b) Rayleigh Channel

Figure-2.5: BER performance of OFDM system with different subcarriers (N) and modulation schemes over AWGN and Rayleigh channel.

2.3 Conclusion

This chapter elaborates the OFDM system model with its mathematics. It explains transmission module which include formation of OFDM symbols and importance of guard interval for removing ISI in the transmitter. Here, three methods of inserting guard interval: cyclic prefix (CP), cyclic suffix (CS) and zero padding (ZP) are analysed. Phenomenon of generating noise and multipath environment are discussed as well as they are mathematically analysed in channel model. It is found that Rayleigh fading model provide a suitable environment on a wireless signal. In the receiver, mathematics of FFT and equalizer are analysed for recovery of OFDM signal.

Simulation results of BER performance of OFDM system over AWGN and Rayleigh channel shows that when we move from lower modulation scheme i.e. M-PSK, to higher modulation scheme i.e. M-QAM, the BER performance decreases because the large number of bits is combined to form a symbol. Also, in the absence of cyclic prefix between successive OFDM symbols in multipath environment, BER performance become worst as modulation level increases because current OFDM symbol is interrupted by previous OFDM symbol leading to ISI.

CHAPTER 3

Literature Review

Literature review is the main channel for researchers to gain the knowledge in the particular research field. It provides thorough study of published document for lucid understanding of that particular field. Hence, this chapter provides a profound literature review on the PAPR of OFDM system. The main issue of the OFDM system is high PAPR of transmitted signal in transmitter side which degrades the performance of the system when a non-linear HPA is used. So, it is necessary to use an appropriate PAPR reduction technique at the transmitter side. In this chapter, the detailed analysis of PAPR, its impact and definition, parameter to analysis PAPR and different methods of PAPR reduction are included. Simulation results are discussed and analysed.

3.1 Introduction

PAPR occurs due to large dynamic range of OFDM symbol waveforms. High PAPR in OFDM essentially arises because of IFFT pre-processing (i.e. OFDM signal consists of a number of independently modulated sub-carriers which can give a large peak when added up with same phases). Here, data symbols across sub-carriers add up to produce high Peak value signals [26-28].

As long as signal swing is limited to dynamic or linear range, input and output is linearly related as shown in figure 3.1. (i.e. around this mean, if the deviation of the voltage is small, then signal will still confined to linear amplification range.) But in OFDM system, swing of instantaneous power is very high compare to mean. So, it will cross over into the non-linear range where amplification is non-linear. As amplification is non-linear all the property of OFDM is lost (i.e. orthogonality is lost), then there will be extreme intercarrier interference. So, high PAPR in OFDM results in amplifier saturation, thus leading to ISI.

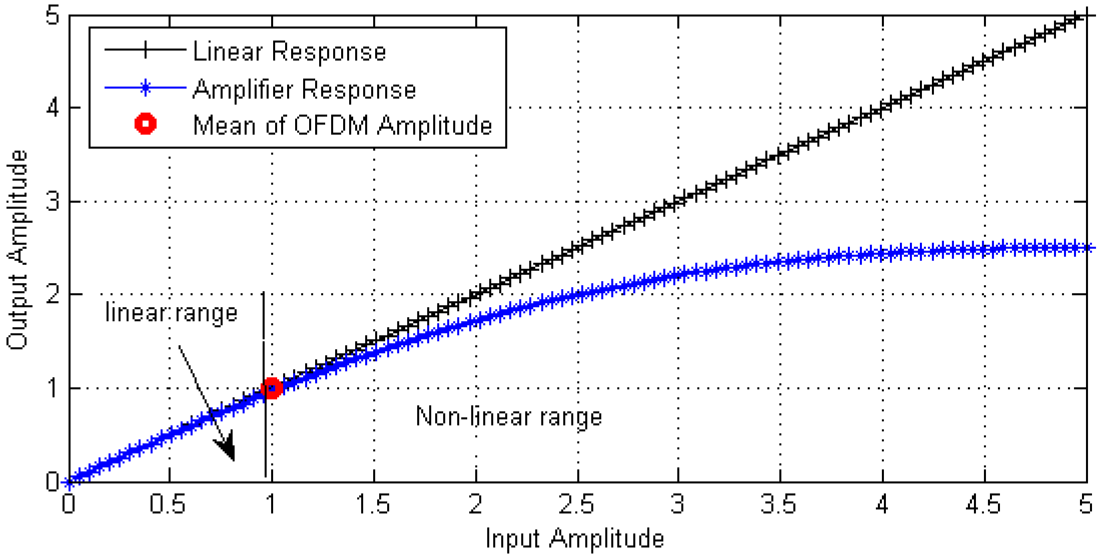


Figure-3.1: Amplifier Characteristics

3.2 Impact of PAPR on the system

Generally**,** the radio system uses HPA in the transmitter side to obtain maximum output power efficiency. The operating area of HPA is normally at or near the saturation region. Also the nonlinear characteristics of the HPA are very tender to the difference of the signal amplitudes. This difference in the OFDM amplitudes is very large with high PAPR. So, the high PAPR on the HPA will introduce intermodulation between different sub-carriers and interference into the systems. This interference decreases the BER performance. Also, this high PAPR forces the amplifier for having huge back off power for linear amplification of the signal. This type of linear working amplifier has poor power efficiency [26-29].

Digital to Analog Converter (DAC) should have sufficient dynamic range to accommodate the large peaks of the OFDM signals because of the high PAPR. Even if, a high precision DAC supports high PAPR with low quantization noise but it is very expensive. On the other hand, low precision DAC is cheaper and its quantization noise is more [26-29].

For large number of OFDM sub-carriers, OFDM signals follow the Gaussian distribution. In such type of distribution average of the peak signal rarely occur and uniform quantization by the Analog to Digital Converter (ADC) is not desirable. If clipping of the signal is done, in-band distortion and out-of-band expansion (adjacent channel interference) will be occurred [26-29].

The major impact of a high PAPR are-

1. Increased complexity in the ADC and DAC.
2. Reduced in efficiency of radio frequency (RF) amplifiers.

3.3 Definition of PAPR

From equation (2.1), we know that OFDM signal is generated using input symbols X_k, as

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \, e^{j2\pi f_k t}, \qquad 0 \le t \le NT \tag{3.1}$$

where, N is the total number of sub-carriers and $X_k,\ k = (0,1, \dots, N-1)$ block of N input bits (symbols), f_k=*k*Δ*f*, where Δ*f=1/ (NT), T*=original symbol period.

Also, the discrete form of OFDM signal $x(n)$ is given by-

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \, e^{\frac{j2\pi kn}{N}}, \qquad for\ n = 0, 1, 2, 3 \dots N-1 \tag{3.2}$$

The PAPR of the continuous time baseband OFDM transmitted signal $x(t)$ is the ratio of the maximum instantaneous power and the average power.

By definition, $PAPR = \frac{max[x(t)]^2}{E\{|x(t)|^2\}}, for\ 0 \le t \le NT$ (3.3)

where, $E\,\{.\}$ denotes expectation operator and $E\{|x(t)|^2\}$ is average power of $x(t)$ as well as T is an original symbol period.

For a discrete OFDM signal $x(n)$, the PAPR is computed from L time oversampled OFDM signal, as-

$$\text{PAPR}=\frac{max[x(n)]^2}{E\{|x(n)|^2\}}, for\ 0 \le n \le NL-1 \tag{3.4}$$

where, N is the total number of sub-carriers and $E\{|x(n)|^2\}$ is average power of $x(n)$.

Practically, oversampling is needed in discrete OFDM signal. Oversampling is done by padding $(L-1)N$ zeros in frequency domain which corresponds to the oversampling in time domain where LN-points IFFT is computed. Oversampling is done to prevent aliasing.

3.4 Parameters influencing PAPR

The upper bound on PAPR is worst case of PAPR which is derived as below-
We know from equation (3.4),

$$PAPR = \frac{max[x(n)]^2}{E\{|x(n)|^2\}} = \frac{max\frac{1}{N}\left|\sum_{k=0}^{N-1} X_k\, e^{\frac{j2\pi kn}{N}}\right|^2}{E\{|X_k|^2\}}$$

$$\leq \frac{\max|\sum_{k=0}^{N-1} X_k\, e^{\frac{j2\pi kn}{N}}|^2}{E\{|X_k|^2\}} \qquad \because |\sum_{k=0}^{N-1} b_n|^2 \leq N\sum_{k=0}^{N-1}|b_n|^2$$

$$= \frac{\sum_{k=0}^{N-1}|X_k|^2}{E[|X_k|^2|]}$$

$$\leq \max_k \frac{N|X_k|^2}{E[|X_k|^2|]} \tag{3.5}$$

So, the upper bound on PAPR ($PAPR_{upper}$) is given by

$$PAPR_{upper} = \max_k \frac{N|X_k|^2}{E[|X_k|^2|]} \tag{3.6}$$

Let ξ be a PAPR of the input constellation and defined as

$$\xi = \max_k \frac{|X_k|^2}{E[|X_k|^2|]} \tag{3.7}$$

Hence, equation (3.6) can be written as-

$$PAPR_{upper} = N\xi \tag{3.8}$$

The parameters that influence the PAPR are-

1. **The number of subcarriers (N) in OFDM system**
   PAPR is directly proportional to the N as shown in equation (3.8). As N increases, PAPR of OFDM system also increases and decreasing on N decreases PAPR but code rate also decreases.

2. **Modulation schemes**

   Equation (3.8) shows that PAPR is linearly dependent on constellation of modulation schemes (ξ). It is known that ξ is more for M-QAM than M-PSK.

3.5 Distribution of PAPR

The Cumulative Distribution Function (CDF) is one of the most regularly used parameters to measure the efficiency of any PAPR technique. Normally, the Complementary Cumulative Distribution Function (CCDF) is used instead of CDF which helps us to measure the probability that the PAPR of a certain data block exceeds the given threshold.

By implementing the central limit theorem for a multi-carrier signal with a large number of sub-carriers (N), the real and imaginary part of the time domain signals have a mean of zero and a variance of 0.5 and also follow the Gaussian distribution. So, Rayleigh distribution is followed for the amplitude of the multi-carrier signal, where as a central chi-square distribution with two degrees of freedom is for the power distribution of the system. The CDF of the amplitude of a signal sample is given by

$$F(Z) = \left(1 - e^{-z^2}\right) \tag{3.9}$$

where, Z is a magnitude of complex samples.

The CCDF of the PAPR for non-oversampling data block is given as-

$$\begin{aligned} P(PAPR > z) &= 1 - F(Z)^N \\ &= 1 - \left(1 - e^{-z^2}\right)^N \qquad (3.10) \end{aligned}$$

where, N is assumed to be a large number of sub-carriers.

The CCDF of the PAPR for oversampling data block is obtained by multiplying equation (3.10) with N and some constant ($\propto$), which is expressed as-

$$CCDF = P(PAPR > z) \approx 1 - \left(1 - e^{-z^2}\right)^{\propto N} \tag{3.11}$$

The CCDF is generally used to estimate the bounds of the PAPR and as well as performance evaluation parameter for most of the PAPR reduction schemes.

Figure 3.2, shows the CCDF of the PAPR of QPSK OFDM symbols for 64, 128, 256, 512 and 1024 sub-carriers. The value ∝ is taken as 2.8. The most obvious trend in the graph is that PAPR goes on increasing as the number of sub-carriers increases. The theoretical value of CCDF is almost same as simulated value of CCDF. The deviation of simulated value is negligible to the calculated or theoretical value for small sub-carriers (i.e. N=64). As, N becomes large the simulated and theoretical values of the CCDF align in the same line. The highest PAPR of 11.5dB is obtained at CCDF=10^{-3} for N=1024. PAPR has probability that is greater than 10.4dB is 10^{-3}. For N=64, 128, 256 and 512 obtained PAPR are 10.9dB, 11.1dB, 11.5dB respectively at CCDF=10^{-3}.

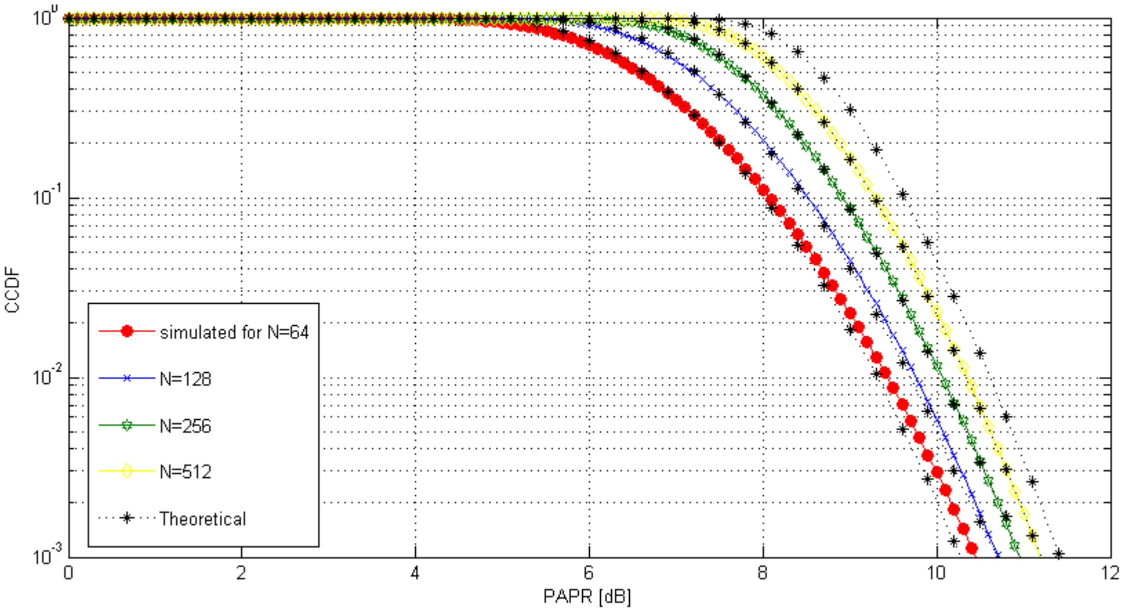


Figure-3.2: Simulated and Calculated CCDF of the PAPR for OFDM systems for different N.

Figure 3.3, reveals the CCDF of the PAPR of the OFDM signals for N = 64 sub-carriers which is oversampled by an oversampling factors (L) = 1, 2, 4, 8 and 16. The graph demonstrates that the increment of the PAPR is negligible after L = 4. So, the correct evaluation of PAPR for the discrete OFDM symbols can be achieved at oversampling factor L > 4.

Figure 3.4, shows the comparison of CCDF of the PAPR of the OFDM symbols for 64, 256, 512 and 1024 sub-carriers with QPSK, 16-QAM and 64-QAM modulation schemes respectively. Modulated data is oversampled by a factor of four. The most obvious trend in the graph is that PAPR goes on increasing as the number of sub-carriers increases.

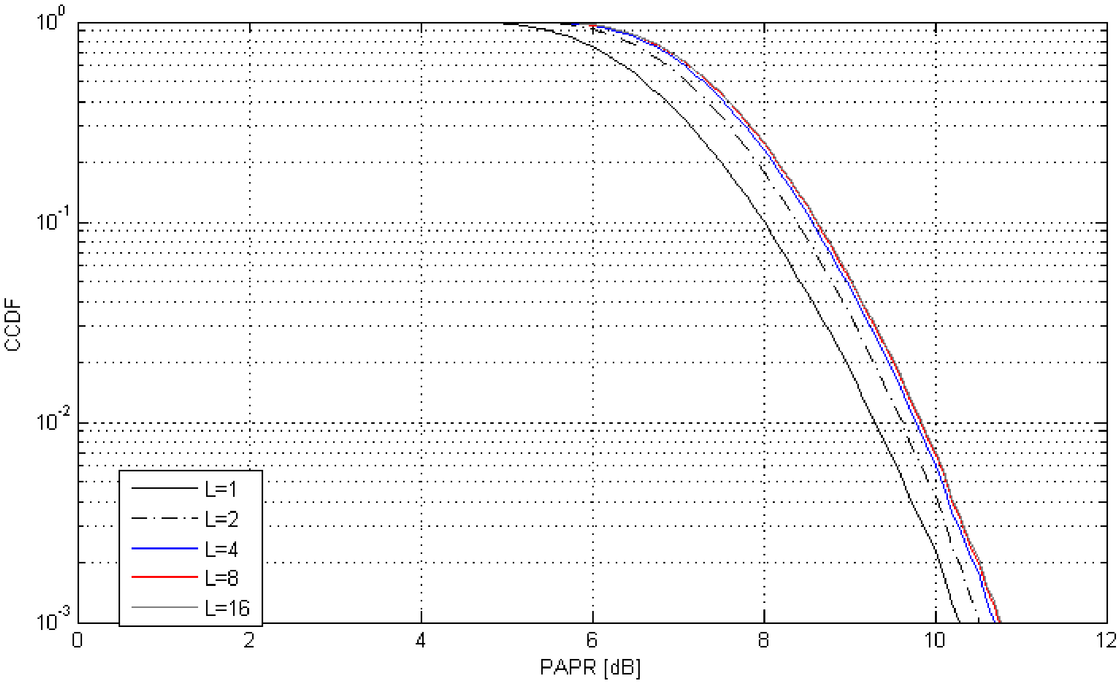


Figure-3.3: CCDF of the PAPR for OFDM systems for sub-carrier 64 oversampled by different oversampling factor (L).

Furthermore, the influences of modulation schemes are found to be negligible. The highest PAPR of 11.5dB is obtained at CCDF=10^{-3} for N=1024. PAPR has probability that is greater than 10.4dB is 10^{-3} for QPSK modulation scheme. About same PAPR of 10.3dB is obtained at CCDF=10^{-3} for same sub-carriers with using 16-QAM and 64-QAM. Similarly, for N=256, 512, 1024 using QPSK, 16-QAM and 64-QAM modulation schemes, PAPR has probability that exceeds 10.9dB, 11.1dB, 11.5dB respectively is 10^{-3}. Here, also the effect of high level modulation scheme is negligible.

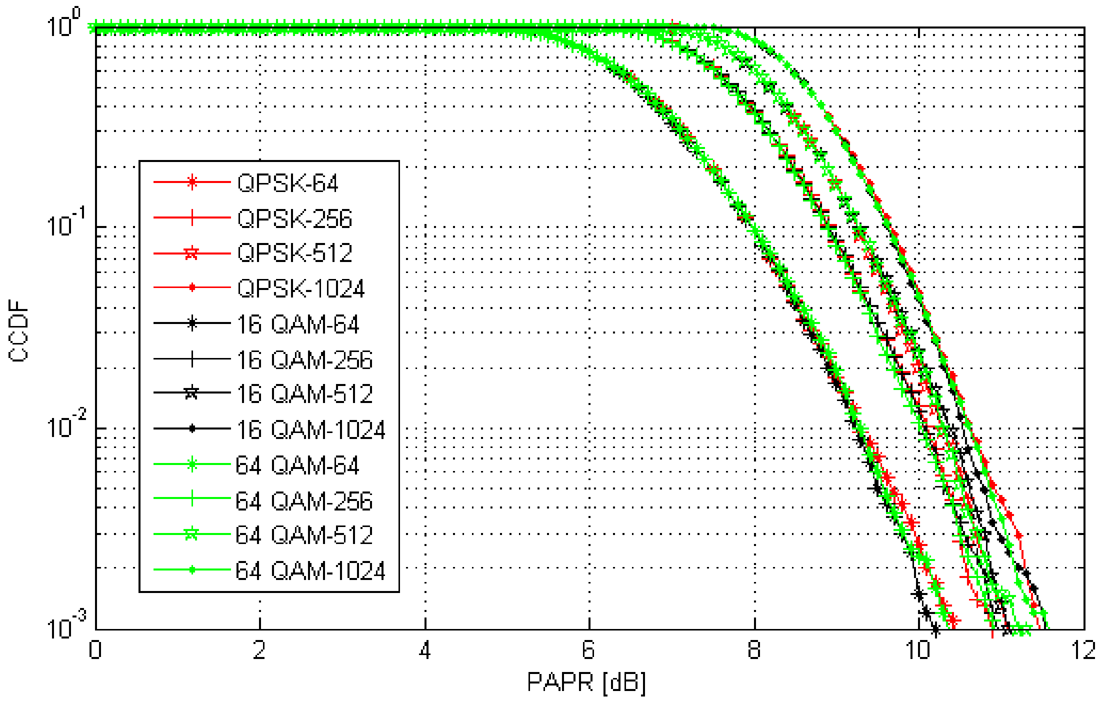


Figure 3.4 CCDF of the PAPR for OFDM systems for different *N* with different modulation schemes

3.6 PAPR reduction Methods

PAPR reduction methods can be mainly divided into two domain methods: frequency domain method and time domain method [30]. The basic notion of frequency domain method is to increase the cross correlation of the input signal before IDFT and decrease the output of the IDFT peak value or average value. Selective Mapping (SLM), Partial Transmit Sequence (PTS), Precoding etc. schemes are example of frequency domain method. However, in time domain method PAPR is reduced by distorting the signal before amplification and added of extra signals which increase the average power. Clipping and filtering, Peak widowing etc. are examples of time domain method. It is very simple method because it requires very less computational time but introduces the distortion, increases out of band radiation and also degrades BER performance. On comparing between these two domain methods, frequency domain PAPR reduction technique is the most efficient one because of its ability to compress the PAPR without distorting the transmitted signal, no production of in band distortion and out of band radiation in OFDM signals.

Broadly PAPR reduction techniques are classified into four sections [31].

1. Signal scrambling (Probabilistic) technique

Signal Scrambling technique scramble each OFDM symbol with different scrambling techniques and select the sequence that gives the smallest PAPR value. It includes methods like Selective Mapping (SLM) and Partial Transmit Sequence (PTS).

2. Signal distortion technique

This technique reduces the PAPR by distorting the OFDM signal non-linearly. The methods like clipping and filtering, peak windowing, and non-linear companding are the example of this technique. These methods are applied after the generation of OFDM signal (after the IFFT).

3. Coding technique

The coding technique employed some error correcting codes for the PAPR reduction. These methods are applied before the generation of OFDM signal (before IFFT). When N signals are added with the same phase, they produce a peak power, which is N times the average power. The basic idea of all coding schemes for the reduction of PAPR is to reduce the occurrence probability of the same phase of many signals. The coding methods select such code words that minimize or reduce the PAPR. It causes no distortion and creates no out of band radiation, but it suffers from bandwidth efficiency as the code rate is reduced. It also suffered from the complexity to find the best codes and to store large lookup tables for encoding and decoding, especially for a large number of subcarriers. The error correcting codes like block codes, cyclic codes, Golay complementary sequence, Reed-Solomon (RS) code, Reed-Muller (RM) code, Hadamard code and Low Density Parity Check (LDPC) code can be used.

4. Pre-distortion technique

The pre-distortion technique is based on the reorientation or spreading the energy of data symbol before taking IFFT. The pre-distortion scheme includes DFT spreading, pulse shaping or pre-coding and constellation shaping.

3.7 Factors for selecting the PAPR reduction technique

Several factors should be considered for selecting the technique that can reduce the PAPR effectively as well as can maintain high quality performance. These following factors are to be considered [26], [27] as :

- Without introducing in-band distortion and out-of-band radiation, PAPR reduction techniques should be enable to reduce the PAPR.
- Low average power: The raise in power requires a high linear operation region in HPA and hence degrades the BER performance.
- No BER performance degradation: The motive of PAPR reduction is to get better system performance as well as BER than that of the original OFDM system.
- Addition power: Power efficiency should be considered while reducing the PAPR. If the operation of the technique which reduces the PAPR needs more additional power, then it degrades the BER performance when the transmitted signals are normalized back to the original power signal.
- No spectral spillage: The PAPR reduction technique should not destroy the inherent feature (orthogonality) of OFDM signal.

The widely used technique of PAPR reduction is amplitude clipping. This technique can be implemented by clipping parts of the OFDM signals (after IFFT) that are greater than a threshold level. If OFDM signals are clipped, it will introduce in-band distortion and out-of-band radiation (adjacent channel interference) into the communication system as a result BER performance of the system degrades. Hence, the best solution is to reduce the PAPR before formation of OFDM symbols as well as prior transmitted OFDM symbols into nonlinear HPA and DAC [28].

Table-3.1: Comparison of PAPR reduction techniques [23], [32]

Methods	Average Power Increases	Computational Complexity	Bandwidth Expansion	BER Degradation	Side Information	Processing at transmitter and receiver sides
Clipping and filtering	No	Low	No	Yes	No	Tx: Amplitude clipping, filtering Rx: None
Coding	No	Low	Yes	No	No	Tx: Encoding or table search Rx: Decoding or table search
PTS	No	High	Yes	No	Yes	Tx: V IFFTs, W^{V-1} complex vector sums. Rx: Transmission of side information, Inverse PTS
SLM	No	High	Yes	No	Yes	Tx: need more IFFTs than PTS method. Rx: Transmission of side information, Inverse SLM
TR	Yes	High	Yes	No	No	Tx: need IFFTs, find value of peak reduction carriers (PRCs). Rx: Ignore non data bearing subcarriers.
TI	Yes	High	Yes	No	No	Tx: need IFFTs, search for maximum point in time, tones to be modified. Rx: Modulo-D operation.
Precoding	No	Low	Yes	No	No	Tx: increase in number of subcarriers Rx: Expansion of bandwidth

The most of the factors mentioned above for selecting the PAPR reduction technique are almost satisfied by frequency domain method (i.e. signal scrambling and pre-distortion methods) because they are distortionless.

The popular and frequently used frequency domain methods are discussed in detail-

3.8 Partial Transmit Sequence (PTS) method

In PTS method, the frequency domain symbol sequence (X) is partitioned into some disjoint subblocks (V) which are multiplied by set of phase sequence (w_v) correspondingly taking the IFFT of subblocks (transformed into the v time domain partial transmit sequence). The time domain partial sequence subblocks is optimally combine by independently multiplying with phase factors to obtain time domain OFDM symbols with lowest PAPR [33]. A block diagram of PTS technique is shown in figure 3.5. Here, input data block X of N symbols is separated into V disjoint subblocks which are represented by the vectors $\{X_v,\ v = 0,1,2,\ldots V-1\}$. The input data block X can be written in the form of X_v as follows-

$$X = \sum_{v=0}^{V-1} X_v \tag{3.12}$$

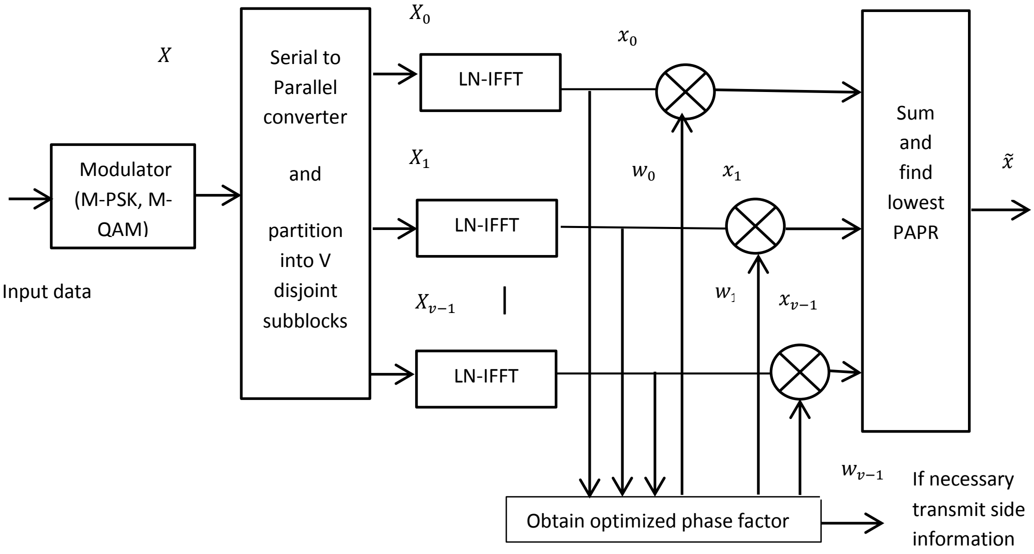
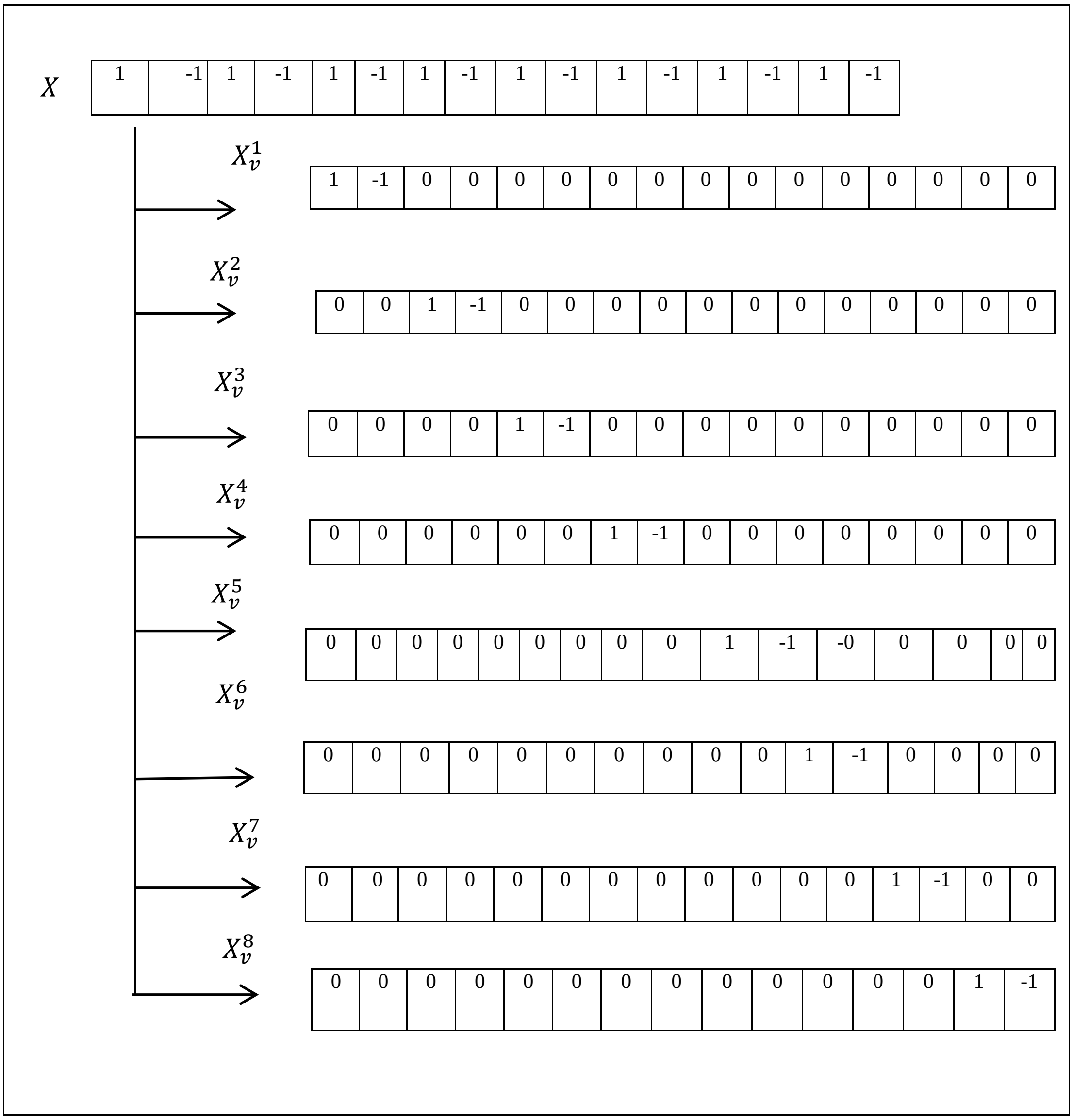


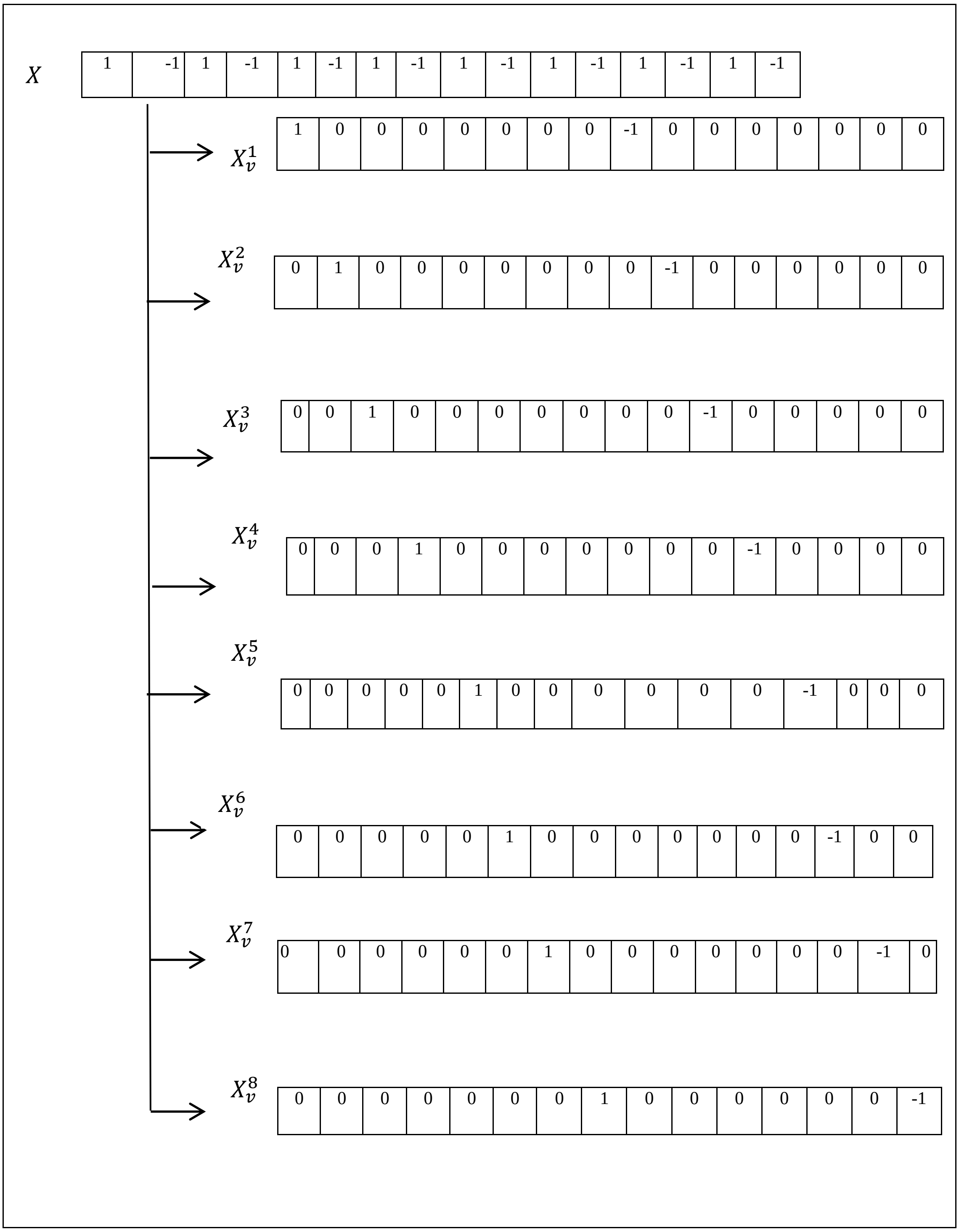
Figure 3.5: Block diagram of Partial Transmit Sequence (PTS)

where, $X_v = [X_v^0, X_v^1, X_v^2 \ldots\ldots X_v^{N-1}]^{\mathrm{T}}$ are the subblocks of same size. Partition of subblocks can be done by three methods: adjacent partition, pseudo-random partition and interleaved partition [33] and each subblock has equal size.

For instance- Partitioning of eight subblocks of OFDM PTS technique with sixteen sub-carriers is shown in figure 3.6. Binary phase factors of {+1,-1} has been taken. Figure 3.6 (a), (b), (c) depict the adjacent subblock partitioning, interleaved subblock partitioning and pseudo-random partitioning schemes for a data (X) of length 16. There are 32768 ($2^{(16-1)}$) ways to combine the subblocks.

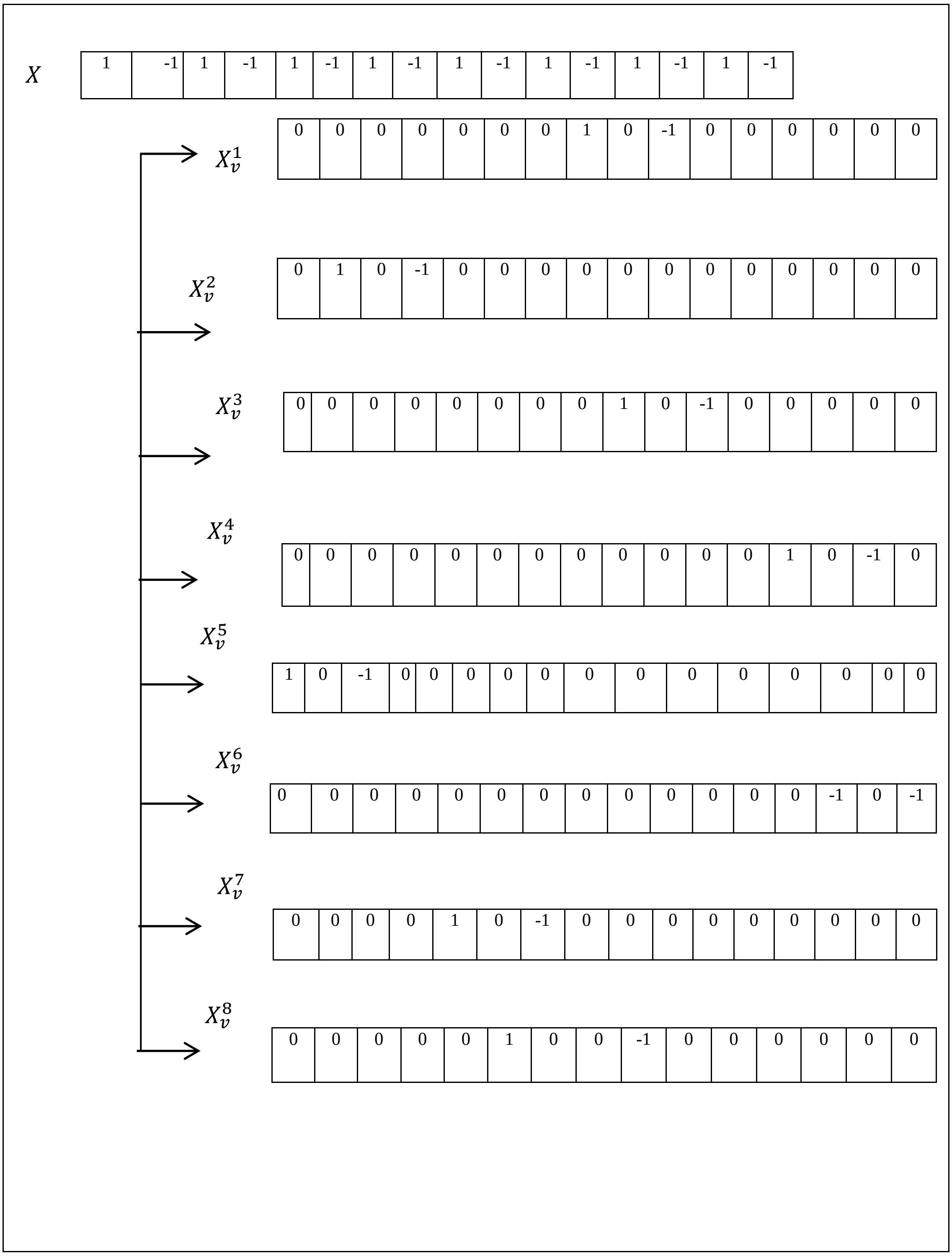


(a) Adjacent subblock partitioning technique.



X	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1
X_v^1	1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
X_v^2	0	1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
X_v^3	0	0	1	0	0	0	0	0	0	0	-1	0	0	0	0	0
X_v^4	0	0	0	1	0	0	0	0	0	0	0	-1	0	0	0	0
X_v^5	0	0	0	0	0	1	0	0	0	0	0	0	-1	0	0	0
X_v^6	0	0	0	0	0	1	0	0	0	0	0	0	0	-1	0	0
X_v^7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	-1	0
X_v^8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	-1	

(b) Interleaved subblock partitioning technique.



(c) Pseudo-random subblock partitioning scheme.

Figure-3.6 (a), (b), and (c): Different subblocks partitioning techniques

Then each partitioned subblock X_v is multiplied by a corresponding complex phase factor $w_v = e^{j\varphi v}$, $v = 1, 2, \ldots V,$ subsequently transforming into V time domain partial transmit sequence by taking the LN-point IFFT to yield

$$x = IFFT\left(\sum_{v=1}^{V} w_v\ X_v\right) = \sum_{v=1}^{V} w_v\,.\,IFFT(X_v) = \sum_{v=1}^{V} w_v\,X_v \qquad (3.13)$$

where, (X_v) is partial transmit sequence (PTS).The phase vector should be chosen in such a way that the PAPR can be minimized as given below [34]-

$$[\widetilde{w_0}..\widetilde{w_{v-1}}] = arg \min_{(w_0,\ldots w_{v-1})} \Big(\max_{n=0,1,\ldots LN-1} \big| \sum_{v=0}^{V-1} w_v x_v\,[n] \big| \Big) \;\; where\ n$$
$$= (0,1,.LN-1)\ and\ L\ is\ \text{oversampling factor} \qquad (3.14)$$

Then, the corresponding time-domain signal with the lowest PAPR vector can be expressed as-

$$\tilde{x} = \sum_{v=0}^{V-1} \widetilde{w_v}\,x_v \qquad (3.15)$$

The PTS technique requires V IFFT operations for each data block. The PAPR performance of the PTS technique is affected by not only the number of sunblocks (V), also the number of the allowed phase factors (w) as well as partition of the subblocks. The PTS technique suffers from the complexity of searching for the optimum set of phase vector when the number of subblocks increases.

3.9 Precoding Method

In precoding method, modulated data is multiplied with shaping matrix before the formation of OFDM symbol (before IFFT) as shown in figure (3.7). This type of technique utilizes the positive feature of the frequency selective multipath channel of OFDM system [35], [36]. In figure (3.7), first the input data is modulated in baseband using modulation scheme like M-PSK, M-QAM etc. The baseband-modulated data stream is transformed by precoding matrix. Different methods like pulse shaping function, discrete cosine transformation (DCT) matrix, Hadamard matrix, zadoff-chu sequence, generalized chrip-like (GCL) sequence etc. are used to generate precoding matrix. After that these precoded data are transmitted through IFFT and generate OFDM symbols. Each element of precoding matrix should be carefully designed, so that it can reduce the PAPR. Since, we are multiplying modulated data with predefined precoding matrix, there is no need of handshake between transmitter and receiver.

3.9.1 Generation of precoding matrix using pulse shaping function

For generating the precoding matrix, pulse shape function like raised cosine (RC), square root of raised cosine (SQRC) etc. are used. For this method, the predefined precoding matrix P of dimension $L \times N$ is defined as mention by Slimane Ben Slimane [64]-

$$P = \begin{bmatrix} p_{0,0} & p_{0,1} & \cdots & p_{0,N-1} \\ p_{1,0} & p_{1,1} & \cdots & p_{1,N-1} \\ \vdots & & \ddots & \vdots \\ p_{L-1,0} & p_{L-1,1} & \cdots & p_{L-1,N-1} \end{bmatrix} \tag{3.16}$$

where, pi,j are the element of precoding matrix (P) and $L = N + N_p$ is total subcarriers. N is user defined subcarriers and N_p is extra subcarriers. The element of precoding matrix can be determined as-

$$P(i,m) = (-1)e^{-\frac{j2\pi im}{N}} \frac{1}{N} P_{src}(f) \tag{3.17}$$

where, $P_{src}(f)$is pulse shaping function in frequency domain.

When precoding matrix (P) is omitted, the matrix P reduces to an $N \times N$ identity matrix.

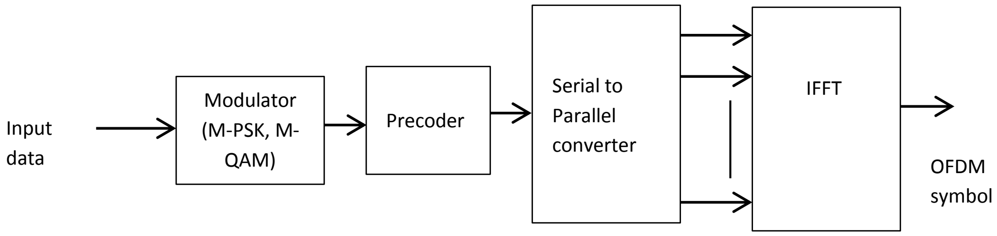


Figure 3.7 Transmitter block diagram of the precoded OFDM scheme.

The precoding matrix is selected using following condition -

$$P^{*}P = I \tag{3.18}$$

where, I is the $N \times N$ identity matrix and P^{*} represents the Hermitian transpose of the matrix P.

- **Pulse Shaping**

Pulse shaping changes the waveform of the transmitted signal. Mainly, pulse shaping makes the transmitted signal adapted to its purpose or the communication channel, especially by constraining the effective bandwidth of the transmission. By transforming the transmitted pulses using pulse shaping, the intersymbol interference due to channel can be control. The filter satisfying Nyquist criteria is used as pulse shaping filter because it does not produce intersymbol interference (ISI) [37], [38].

The Nyquist ISI standard is a generally used for evaluation because it relates the frequency spectrum of the transmitter signals to ISI. Nyquist ISI criteria states that at the cut off frequency, frequency characteristic has odd symmetry. Then, the impulse response will have zeros which are spaced in uniform intervals [37], [38], [39].

The commonly used pulse shaping filters in communication systems are: [37], [38], [39].

- Sinc shaped filter
- Raised-cosine filter

Sync filter

Theoretically, sinc filter is an ideal filter for pulse shaping but it is difficult to implement practically. It is a non-causal filter with slowly decaying tails. It creates problem in synchronisation because any phase error increases the ISI.

Raised-cosine filter

Raised-cosine filters are widely used in practice because of its sufficient bandwidth. The raised-cosine filter is commonly used in a digital modulation due to its ability to minimize the ISI. The non-zero part of the frequency spectrum i.e. when ($\beta = 1$), is a cosine function. The raised-cosine filter represents a low-pass Nyquist filter. The raised-cosine filter spectrum exhibits odd symmetry about $1/2\mathrm{T}$, where, T is the symbol-period.

The time domain function of RC is given as-

$$P_{RC}(t) = \begin{cases} \frac{1}{T}, & 0 \leq |t| \leq \frac{T(1-\beta)}{2} \\ \frac{1}{2T}\left\{1 + cos\frac{\pi}{\beta T}(|t| - \frac{T(1-\beta)}{2})\right\}, & \frac{T(1-\beta)}{2} < |t| \leq \frac{T(1+\beta)}{2} \\ 0, & otherwise \end{cases} \quad (3.19)$$

The frequency domain function of RC is given as-

$$P_{RC}(f) = \begin{cases} T, & 0 \leq |f| \leq \frac{(1-\beta)}{2T} \\ \frac{1}{2}\left\{1 + cos\frac{\pi T}{\beta}(|f| - \frac{(1-\beta)}{2T})\right\}, & \frac{(1-\beta)}{2T} < |f| \leq \frac{(1+\beta)}{2T} \\ 0, & otherwise \end{cases} \quad (3.20)$$

Simply by taking the square root of the raised cosine frequency response of equation (3.20), we can obtain the frequency response of root raised cosine.

The time domain function of BTRC is given as-

$$P_{BTRC}(t) = \begin{cases} \frac{1}{T}, & 0 \leq |t| \leq \frac{T(1-\beta)}{2} \\ \frac{1}{T}exp\left\{-\frac{2log2}{\beta T}(|t| - \frac{T(1-\beta)}{2})\right\}, & \frac{T(1-\beta)}{2} < |t| \leq \frac{T}{2} \\ \frac{1}{T}\left\{1 - exp\left\{-\frac{2log2}{\beta T}(\frac{T(1+\beta)}{2} - |t|)\right\}\right\}, & \frac{T}{2} \leq |t| \leq \frac{T(1+\beta)}{2} \\ 0\,, & otherwise \end{cases} \quad (3.21)$$

$0 \leq \beta \leq 1$ and characterised by two values: β, the roll-off factor and T, the reciprocal of the symbol-rate.

The impulse response of RC filter [37], [38], [39] is given by:

$$h_{RC}(t) = sinc\left(\frac{t}{T}\right)\frac{cos\left(\frac{\pi\beta t}{T}\right)}{1 - 4\beta^2 t^2} \quad (3.22)$$

in terms of the normalised sinc function.

As a roll off factor varies from 0-1, the amplitude response is affected as shown in figure (3.8). It is clearly visible from the graph (3.8) that the time domain ripple level increases as β decreases. From this, it can be concluded that at the expense of an elongated impulse response when roll off factor approaches to zero, the excess bandwidth of the filter can be reduced.

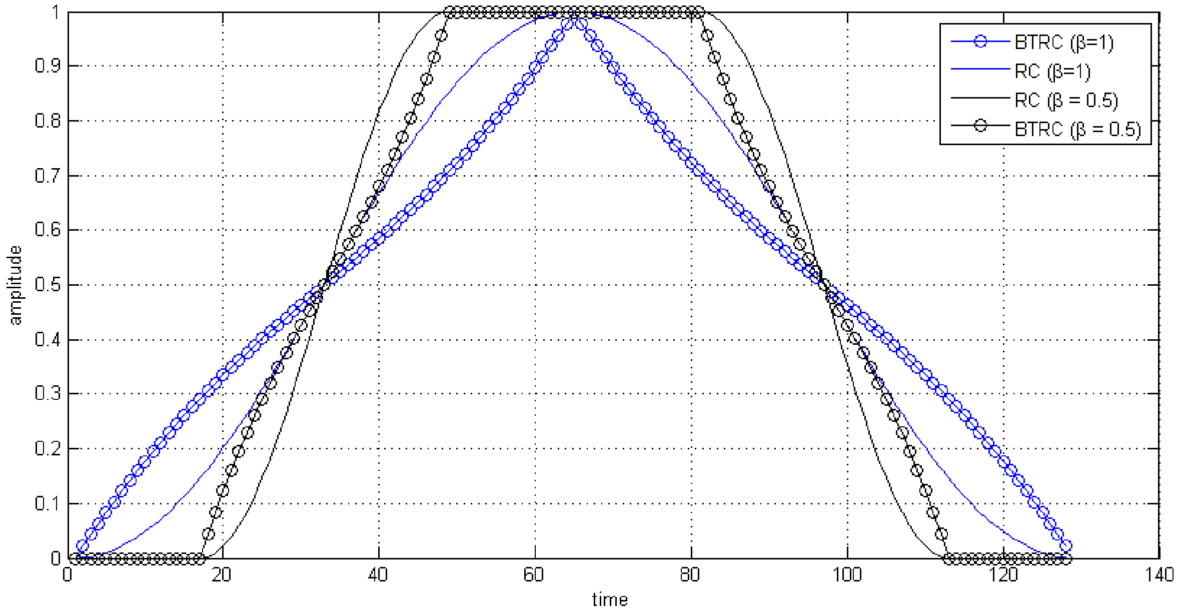


Figure-3.8: Time domain plot of BTRC and RC functions at $\beta = 1$ and $\beta = 0.5$.

3.9.2 Generation of precoding matrix using Discrete Fourier Transform (DFT) function

For generating the precoding matrix, DFT function is used. The size of DFT precoder is same as IFFT size. For this method, the predefined precoding matrix P of dimension $N \times N$ is defined as mention in [37]-

$$P = \begin{bmatrix} p_{0,0} & p_{0,1} & \cdots & p_{0,N-1} \\ p_{1,0} & p_{1,1} & \cdots & p_{1,N-1} \\ \vdots & & \ddots & \vdots \\ p_{N-1,0} & p_{N-1,1} & \cdots & p_{N-1,N-1} \end{bmatrix} \tag{3.23}$$

The element of the precoding matrix can be detemined as-

$$P(i,m) = e^{-i2\pi im/N} \tag{3.24}$$

where, i and $m = 0, 1, 2, 3, \ldots \ldots N - 1$.

Literature reviews of PTS and Precoding method have been mentioned.

3.10 PTS Technique

In 1997, S. H. Muller and J. B. Huber [40] proposed a new significant, useful and flexible PAPR reduction technique for OFDM system named as PTS. The performance of PTS is better than SLM. The main objective of this scheme is to scramble the partitioned sets by using rotation phase factors, $\{\pm 1, \pm j\}$, after that the IFFT within the transmitter is taken. Then, select the optimal sequences with the minimum PAPR as shown in Figure 3.5. The main two demerits of the PTS are as follows- First one is a high complexity. High complexity occurs when PTS search for optimal phase factor. This technique needs a complete search over all combinations of the allowed phase weighting factors. Furthermore, the searching process increases exponentially with the number of subblocks. Second one is to transmit the side information and to recover the side information at the receiver side safely.

3.10.1 Low complexity for searching phase factor

In 1999, Seog Geun Kang *et al.,* [41] proposed a novel subblock partition scheme (SPS) for the PTS technique. Partitioning of subblocks are done by three methods: interleaved, adjacent and pseudo-random partition. In the proposed technique, each subblock is formed by continuous copy and concatenating signals. The proposed method is a combination of pseudo-random and interleaved partition scheme. PAPR reduction performance of proposed method is almost same as the conventional pseudo-random PTS. Morely, computational complexity is reduced significantly. So, this scheme is suitable for modern wireless communication.

In 2000, L. J. Cimini and N. R. Sollenberger [42] proposed suboptimal scheme for combining the PTS with $\{\pm 1\}$ weighting factors only. The proposed suboptimal algorithm was based on iterative flipping. The main drawback of ordinary PTS technique is removed via this technique like optimization problem. In this technique, terminating threshold is set so that PAPR can be easily reduced. After fixing this threshold level the finding process is terminated as soon as PAPR drops below threshold rather than searching all the 2^{v-1} combination. Suboptimum combining or flipping algorithm for selecting optimized phase factor is given below [39] as-

- First of all oversampled precoded data block (X) is partition into V disjoint subblocks $X_v = [X_v^0, X_v^1, X_v^2 \ldots\ldots. X_v^{N-1}]^{\mathrm{T}}$ as shown in figure 3.6 (a) using adjacent subblock partitioning scheme.
- Fixed all phase factors $(w_v) = 1$ for all subblocks and calculate the PAPR of the combined signal using equation (3.13).
- Fixed all phase factors $(w_v) = -1$ for all subblocks and re-calculate the PAPR using same equation (3.13).
- If the new PAPR is lower than in the previous PAPR, regain w_v as part of the final phase sequence, if not reverse to its previous values.

The simulation result of this scheme is shown in figure 3.9 where comparison of iterative and optimum combining technique is performed with using QPSK modulation for 256 sub-carriers and 16 subblocks.

In 2005, Ali Alavi, Chintha Tellambura and Ivan Fair [43] proposed a novel algorithm for computing the optimal PTS phase factors. Only those phase vectors that guarantee that the PAPR is bounded are searched by this algorithm. This algorithm is based on Shortest Vector Problem (SVP) in a lattice which has to find the shortest non zero vector in the lattice. The premise of Fincke and Phost sphere decoder algorithm is used to solve SVP.

In 2007, Tao Jiang, Weidong Xiang, Paul C. Richardson, Jinhua Guo, and Guangxi Zhu [44] proposed a Simulated Annealing (SA) method to search the optimal combination of phase factors for PTS to obtain almost same PAPR as that of optimal PTS with low complexity. PTS scheme utilizes SA basic properties of global optimization technique for huge combination problems. Global optimization technique accepts increases trail to shun early convergence to local optimum solutions.

In 2009, Jung Chien Chen [45] proposed Cross Entropy (CE) algorithm for PTS method to reduce PAPR and computational complexity. The objective of CE algorithm is to find phase factor optimally. According to this method, first score function is defined as the amount of the PAPR, then after that this score function is overset into a stochastic approximation problem. Now, this problem can be solved effectively. The CE algorithm PTS method achieves almost same PAPR as to conventional PTS method with low complexity as shown by simulation results.

In 2010, Jung Chien Chen [46] proposed Electromagnetism-like (EM) algorithm for PTS method, a stochastic optimization approach, to achieve considerable PAPR reduction with low complexity. EM algorithm mainly works with four procedures: (1) initialization, which generate random samples within the boundary of number of subblocks and iteration, (2) local search procedure is used to search optimum phase factor, (3) calculation of total force procedure is used to calculate phase factor that combine with subblocks for low PAPR and rejects others, (4) movement of the particles procedure is used to update phase factor from number of subblocks.

In 2010, Sheng. Ju. Ku *et al.*, [47] proposed a new reduced complexity PTS scheme. In this scheme, a new cost function is created which can be defined as the sum of the power samples after taking IFFT in each subblock. The samples with cost function that are greater than or equal to a fixed threshold are selected. As a consequence, the signal with lowest PAPR for transmission is chosen from the selected candidates. The proposed scheme can achieve approximately the same PAPR as of the CPTS scheme with less computational complexity.

In 2010, Yajun Wang *et al.*, [48] proposed a Artificial Bee Colony (ABC) algorithm for reducing the phase complexity. For high number of subblocks ABC algorithm reduces computational complexity effectively. The searching capacity of combination of phase factor is high. As it has only three control parameters, it is easy to adjust.

In 2010, Jung Chien Chen [49] proposed Quantum-inspired Evolutionary Algorithm (QEA) which reduces the searching process for finding the optimal phase factors. Like in the evolutionary algorithms, the evolution function and the population dynamics parameters are used to characterize the QEA. Also, QEA follows the concept of generational population based search scheme same as genetic algorithm.

In 2011, Jun Hou *et al.*, 2011 [50] proposed a novel scheme for PTS method to reduce the computational complexity. This scheme utilizes the correlation among the weighting phase factors. In this scheme, instead of decreasing the number of candidate signals, it focused simplifying the computation for each candidate signal. Since the number of candidates is not decreased, the proposed scheme can achieve similar reduction in PAPR as compared to the PTS scheme with lower computational complexity**.**

In 2011, Lingyin Wang and Ju Liu [51] proposed a method which reduces the complexity by combining Grouping Phase Weighting (GPW) and Recursive Phase Weighting (RPW) methods. The combination of these two methods has low complexity for searching the phase factors than CPW and RPW individually. Also, it achieves same PAPR as conventional PTS.

In 2011, Pooria Varahram and Borhanuddin Mohd Ali [52] proposed an optimum PTS method which reduces the IFFT operations. In this technique random phase factors are multiplied with input signal. This technique reduces the complexity by decreasing the number of IFFT operation to about half.

In 2010, Toon Van Waterschoot, Vincent Le Nir *et al.*, [53] gives mathematics to calculate power spectral density (PSD) of OFDM system with addition of cyclic prefix and zero padding and also, it is verified by simulation results. The obtain results are compared with OFDM systems without guard interval.

In 2012, Seung Sik Eom, Haewoon Nam, and Young Chai Ko [54] proposed a scheme to reduce reduce the complexity by dealing with post IFFT. It works same as to single IFFT processor. On comparing, the proposed scheme with exiting scheme like circularly shifted phase sequences (CSPS), optimised circularly shifted phase sequences (OCSPS) schemes, the proposed method works with lower complexity because it only perform the phase rotating and cyclic shifting of OFDM symbols. Furthermore, due to employment of linear receiver like maximum likelihood (ML) detector, minimum mean square error (MMSE) estimator or zero forcing (ZF) estimators, no side information should be transmitted. Obtained simulation results of PAPR and BER over Rayleigh fading channel resembles with conventional PTS scheme.

3.10.2 Recovering information without transmitting side information (SI)

In 2000, L. J. Cimini and N. R. Sollenberger [55] gives a marking algorithm to reduce PAPR and detection of marking algorithm procedure to recover the data without transmission of side information at receiver side. The BER performance of this algorithm can be improved by increasing number of tones per subblock.

In 2003, A.D.S. Jayalath and C.Tellambura [56] proposed an algorithm to insert side information into PTS-OFDM system without affecting the reduced PAPR and improves BER performance. The proposed algorithm is modified of [55].

In 2007, Seon-Ae Kim and Heung-Gyoon Ryu [57] proposed a method that achieves the PAPR same to as conventional PTS scheme and recovered side information without transmitting phase factors. In this method, phase of reference symbols are used to give information of rotation factors at receiver side.

In 2011, L.Yang *et al.*,[58] proposed a PTS method that detect OFDM symbols without sending the side information. Main principle of this detection scheme is to generate the required signals through circularly shifting of each subblock sequence in time domain and combining them in a recursive manner. So, by utilizing the diversity of phase constellation for different required signals, the detector recovers the original signal. The BER performance of proposed scheme is similar to the conventional-PTS with perfect side information.

3.10.3 Combine method of PTS with others technique

In 2007, Houshou Chen and Hsinying Liang [59] proposed a combine method of PTS and binary Reed Muller (RM) codes for reducing PAPR and correcting errors. Reed Muller code is separated into two subcode. Scrambling subcode is used for reducing PAPR whereas correcting subcode is used for encoding information bits. OFDM sub-carriers are partitioned into different subblocks according to natural and cyclic ordering. Achieved numerical and simulation results shows that cyclic ordering has better PAPR performance than natural ordering.

In 2008, Josef Urban and Roman Marsalek [60] proposed a combine technique of PTS and clipping and filtering. PTS is applied before IFFT operation and Clipping and filtering is applied after IFFT operation. Clipping and filtering with bounded distortion reduces complexity. The obtained result of proposed method shows the better PAPR and BER than each individual scheme.

In 2010, Pooria Varahram, Wisam F. Al Azzo and Borhanuddin Mohd Ali [61] proposed a combine method which decreases the computational complexity of PTS. The proposed method is a combination of the Dummy Sequence Insertion (DSI) and

PTS. As comparison to the conventional PTS, the proposed method has 0.5 dB less PAPR for same CCDF and also reduces the requirement several IFFT operation.

In 2010, Abolfazl Ghassemi and T. Aaron Gulliver [62] proposed a technique that employ error correcting codes (ECCs) to the partitioned subblocks of PTS. The application of ECCs reduces the subcarriers that repeat within the suublocks. This technique utilizes periodic autocorrelation function of the vectors in the partitioned subblocks. This achieves the PAPR as to the conventional PTS as well as significantly reduces the computational complexity.

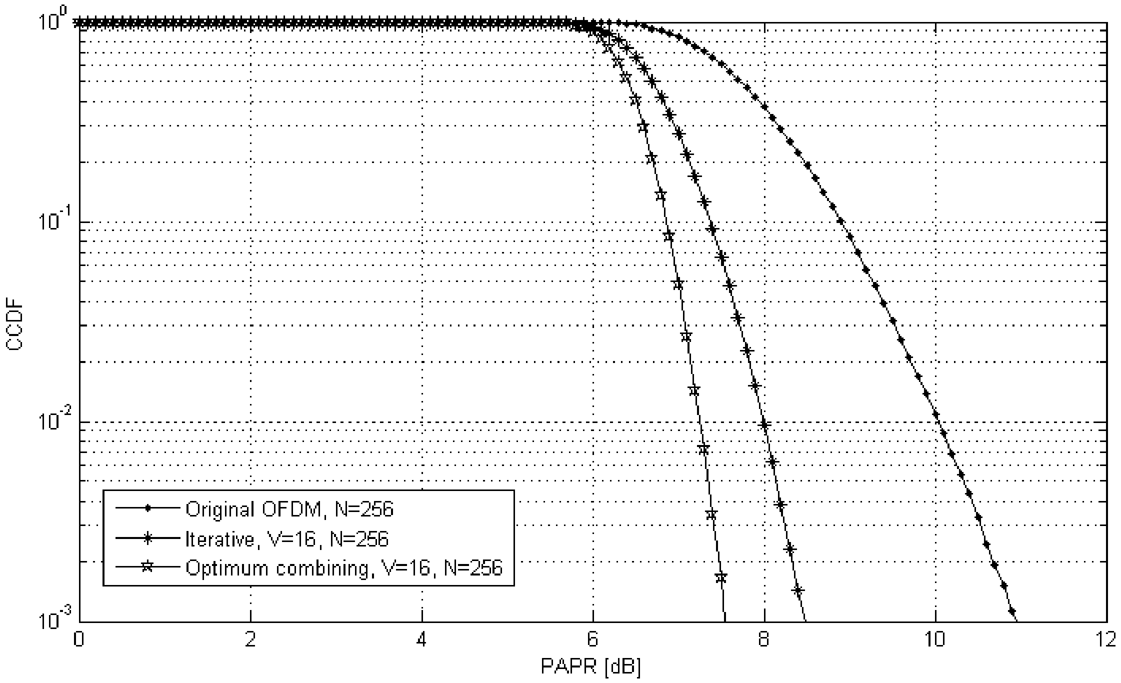


Figure-3.9: Comparison of CCDF of the PAPR of the iterative and optimum combining algorithm.

Table-3.2: Comparison of Complexity among different methods of PTS for phase factors.

PTS Schemes	Complexity
Conventional PTS [40]	➢ Search complexity is proportional to W^{V-1} . ➢ Complex multiplication: $LNVC + LNC$ ➢ Real additions : $2LNC(V-1) + (LNC-1)$
SPS PTS [41]	➢ Complex multiplication: $\frac{N}{2L} log_2 \frac{N}{L} + N$ ➢ Real additions $\frac{N}{L} log_2 \frac{N}{L}$
SOC PTS [42]	➢ Search complexity is proportional to $(V-1)W$
SD PTS [43]	➢ Complexity is proportional to generation of $V \times V$ matrices, factorization of matrices using Cholesky decomposition and to find the phase factor for calculating lowest PAPR signal by using sphere decoding. ➢ Complex multiplication: LNV^2 ➢ Real additions : LNV
SA PTS [44]	➢ Search complexity is proportional to $\frac{(V-1)W}{5}$
CE PTS [45]	➢ Score function is used to reduce the search complexity.
EM PTS [46]	➢ Computational complexity is proportional to the (number of particles + maximum number of local search iterations) × K
CF PTS [47]	➢ Complex multiplication: LNV ➢ Real additions : $LN(V-1)$
ABC PTS[48]	➢ Search complexity is proportional to SK ➢ Complex multiplication involves $L_p log L_p$ for each sample
QEA PTS [49]	➢ Search complexity is proportional to PK
DSI PTS [63]	➢ Requirement of half IFFT operation due to addition of dummy sequence as compare to convention PTS.
CACS PTS [50]	➢ Complex multiplication: $N\left[\left(\frac{W}{2}\right)^{V-1} - 1\right]$ ➢ Complex additions: One $(V-1)th$ of Conventional PTS.

<table>
<tr><td>GARPW PTS [51]</td><td>
<table>
<tr><th></th><th>Complex multiplication</th><th>Complex additions</th></tr>
<tr><td>GPW PTS</td><td>$LN\sum_{t=0}^{R-1}(r_{t+1}-r_t)W^{r_{t+1}-r_t}$</td><td>$LN[(r_1-r_0)W^{r_1-r_0}+\sum_{t=1}^{R-1}(r_{t+1}-r_t-1)W^{r_{t+1}-r_t}+\sum_{t=1}^{R-1}\prod_{h=0}^{t}W^{r_{h+1}-r_h}]$</td></tr>
<tr><td>RPW PTS</td><td>$\frac{1}{4}LN(V-1)W^{V-1}$
$(V>2)$
$\frac{1}{2}LNW\ (V=2)$</td><td>$LN\left(\frac{V}{4}+1\right)W^{V-1}(V>2)$
$LNW\ (V=2)$</td></tr>
</table>

GPW PTS – Grouping Phase Weighting PTS
RPW PTS- Recursive Phase Weighting PTS</td></tr>
<tr><td>NPS PTS [52]</td><td>➢ Search complexity is proportional to ${}^{3}/_{4VNlogN}+KVN$</td></tr>
<tr><td>SIFFT PTS [54]</td><td>➢ Scaling operation is performed for transmitting the signal.
➢ Complex multiplication: $\frac{N}{4}$</td></tr>
</table>

V= number of subblocks, W= allowed phase factor, S=random phase factor population size, K=maximum iteration number, L= Oversampling factor, N= number of subcarriers, C=number of candidate signals, P= population size, L_p= L-point IFFT

SPS PTS [41] - Subblock Partition Scheme Partial Transmit Sequence

SOC PTS [42] - Sub-Optimum Combining Partial Transmit Sequence

SD PTS [43] - Sphere Decoding Partial Transmit Sequence

SA PTS [44] - Simulated Annealing Partial Transmit sequence

CE PTS [45] - Cross Entropy Partial Transmit Sequence

EM PTS [46] – Electromagnetism-like Partial Transmit Sequence

CF PTS [47] - Cost function Partial Transmit Sequence

ABC PTS [48] - Artificial Bee Colony Partial Transmit Sequence

QEA PTS [60] – Quantum-inspired Evolutionary Algorithm Partial Transmit Sequence

DSI PTS [61] – Dummy Sequence Insertion Partial Transmit Sequence

CACS PTS [50] - Correlation Among Candidate Signals Partial Transmit Sequence

GARPW PTS [51] - Grouping and Recursive Phase Weighting Partial Transmit Sequence

NPS PTS [52] –New Phase Sequence Partial Transmit Sequence

SIFFT PTS [54] – Single Inverse Fast Fourier Transform Partial Transmit Sequence

3.11 Precoding Method

In 2002, Slimane Ben [63] proposed method reduces the PAPR of OFDM system by using pulse shaping. The PAPR of OFDM signal can be made very close to that of single carrier signal with the use of pulse shaping. Pulse shaping is used to shape the spectrum of the transmitted signal as well as to reduce PAPR. This technique is flexible and it can control the correlation between the OFDM block samples without destroying the orthogonality property between the subcarriers of the modulated signal. This technique can be used for OFDM and Discrete Multi-Tone (DMT) transmission.

In 2007, Slimane Ben Slimane [64] proposed a method that decreases the PAPR of OFDM signal through Precoding. This method is data independent and less complex. The reduction in PAPR is obtained through a proper selection of precoding scheme that distributes the power of each modulated symbol over the OFDM block. Also, this scheme takes the advantage of the frequency variations of the communication channel and can provide considerable performance gain in fading- multipath channels. The pre-defined precoding matrix is generated by RC and SQRC functions.

In 2010, Miin-Jong Hao and Chiu Hsiung Lai [30] give a theoretical condition and also, provide a systematic procedure for calculating an optimal precoding matrix. It achieves low error probability in AWGN and multipath path fading channels as well as low PAPR. Here, also RC and SQRC functions are used to generate precoding matrix.

In 2011, H.D. Joshi and Rajiv Saxena [65] proposed a combine method of clipping and precoding to reduce the PAPR. This combine method provides better PAPR than each individual method and also gives same BER as of precoding method. Here, SQRC and better than raised cosine (BTRC) pulse shapes are used to generate the precoding matrix.

In 2013, Mohamed A. Aboul-Dahab, Esam A.A.A. Hagras and Ahmad A. Elhaseeb [66] proposed precoding method with clipping. A precoded OFDM symbols are clipped and achieves low PAPR with improvement in BER performance than original OFDM. Here, Discrete Fourier Transform (DFT) is used for generating precoding matrix.

The simulation result of this scheme is shown in figure 3.10 where PAPR of precoding method is compared with DFT method and original OFDM. In this scheme, 64 sub-carriers and QPSK modulation is used. DFT matrix is used to generate precoding matrix with spreading factor of 4 and SQRC function is used for generating predefined precoding matrix with roll of factor 10 % and 20% as mention by Slimane Ben Slimane [654].

In figure 3.11, a comparison of precoding method for different sub-carriers (N= 64, 256, 512) at roll off factor (β)=10% and 20% as given by Slimane Ben Slimane [36] is performed.

In figure 3.12, the BER performance of precoding technique is compare over AWGN channel as given by Slimane Ben Slimane [55]. It used QPSK modulation for N= 64 at roll off factor (β)=10%. Here, RC and SQRC functions are used to generate precoding matrix. As shown in figure 3.12, SQRC precoding OFDM has less SNR to maintain a 10^{-4} than RC precoding OFDM.

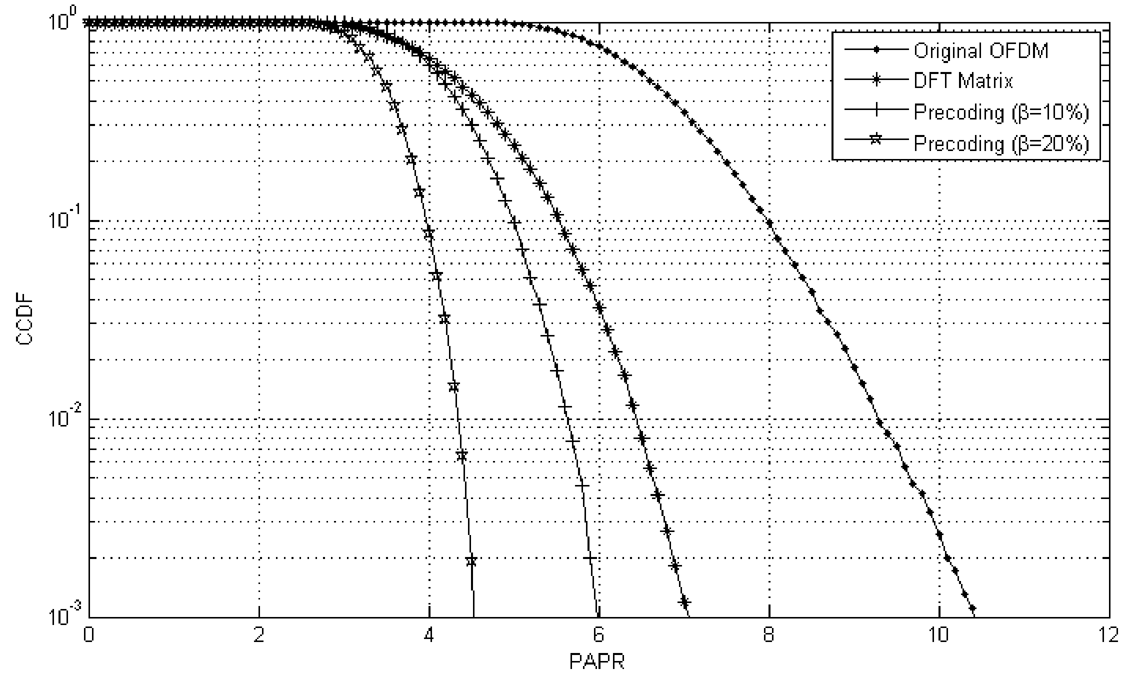


Figure-3.10: Comparison of CCDF of the PAPR of the precoding methods for N=64.

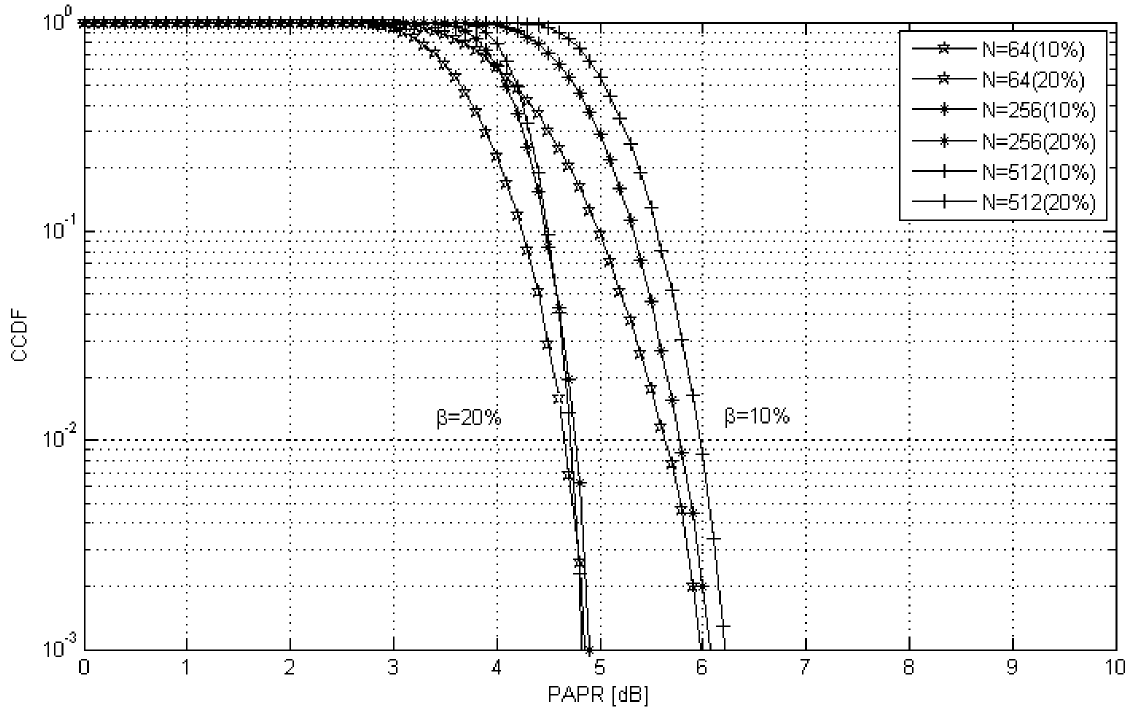


Figure-3.11: Comparison of CCDF of the PAPR of the precoding methods for different number of sub-carriers.

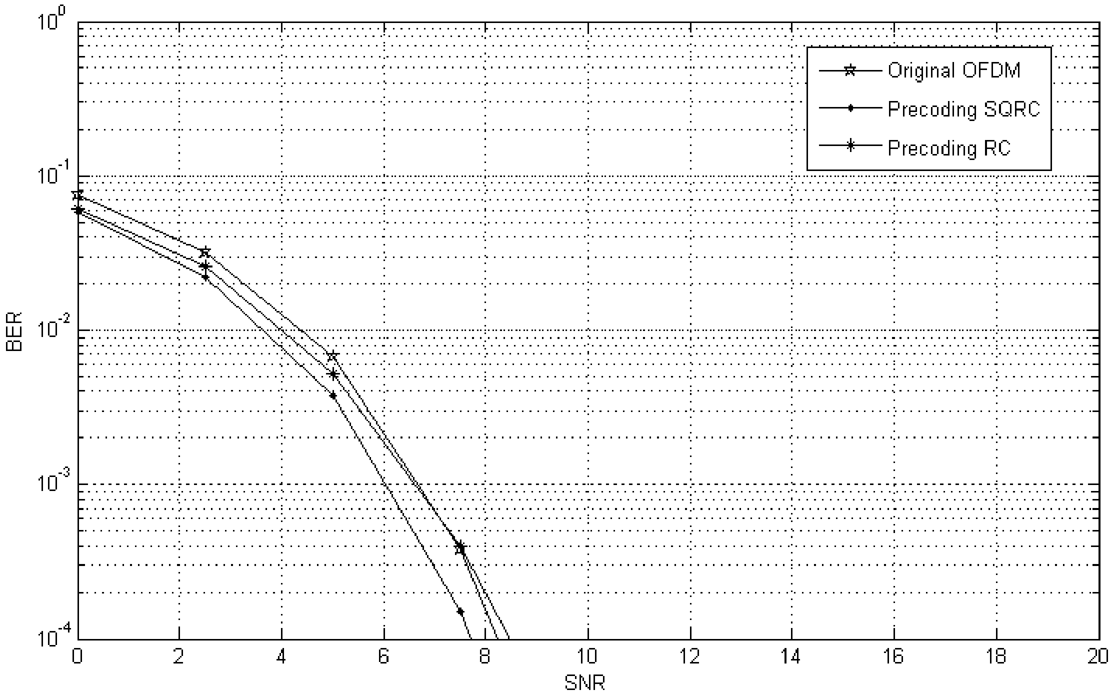


Figure-3.12: Comparison of BER performance of precoded QPSK OFDM over AWGN channel.

3.12 Conclusion

This chapter performs literature review on high PAPR problem in OFDM system. It explains the occurrence of high PAPR in this system including its definition and its measurement parameters as well as the consequences of high PAPR in amplifier, converters (ADC and DAC) and on BER performance. It also gives an overview on different PAPR reduction techniques. PTS and precoding are efficient techniques because it utilizes frequency domain and they are distortionless techniques. In spite of good performance than other techniques, complexity is challenging issue of these techniques. From the literature survey of PTS, it can be concluded that complexity arises mainly due to selection of the weighting phase factors, V IFFT operations and transmission of $log_2 W^V$bits of side information. The literature surveys of current research scenario on the PTS method for reducing PAPR with less complexity regarding the selection of phase factors, recovering the information without transmitting side information and hybrid combine method of PTS with others scheme have been presented. Similarly, literature surveys on precoding method for reducing PAPR have been presented. The precoding matrices are generated by pulse shaping and

DFT sequence. The simulation results of PTS and precoding techniques are also performed. The complexity due to V IFFT operations for each data block is also a crucial issue. So, we are mainly concern to develop a scheme that reduces the PAPR considerably with using few numbers of subblocks. As a result, IFFT operations for each OFDM block also decreases.

CHAPTER 4

Proposed Technique for PAPR Reduction

In this chapter, a new hybrid technique is proposed to reduce the PAPR. This proposed technique is a combination of precoding and PTS methods and it is less complex than PTS method. Furthermore, it reduces the PAPR considerably with only few numbers of subblocks as compare to PTS technique. This chapter described in detail the system model and PAPR as well as power spectral density (PSD) for this model. Simulation results are done to evaluate the PAPR and PSD performance. At last, simulation results as well as conclusion is discussed.

4.1. Introduction

From the literature survey, it has been found that the frequency domain PAPR reduction technique is better than time domain because of its ability to reduce the PAPR without distorting the transmitted signals and thus not producing any in band distortion and out of band radiation. Among many available techniques of frequency domain, PTS and precoding are the best frequency domain methods to reduce PAPR as compare to others. PTS method is distortionless method because it divides frequency vector into some sub-blocks before applying the phase transformation. The main issue of this scheme is increment in complexity due to increased number of subblocks, number of selection of phase factors and amount of side information to be sent for recovery of original signal. Precoding technique reduces the PAPR with less complexity but the number of subcarriers increases with increase in roll off factor. Here, we proposed the combine technique of precoding and PTS to reduce the PAPR of OFDM system. This method is mainly focused to reduce PAPR and to minimize the complexity which arises due to number of subblocks. The complexity associated with PTS regarding the increased number of subblocks is the requirement of more IFFT operation to be performed for subblocks. So, this proposed method obtain the considerable reduction in PAPR using few number of subblocks as comparison to the PAPR obtained by using large number of subblocks in PTS scheme.

4.2. System Model

A proposed system based on precoding of encoded data applying to PTS OFDM with N sub-carriers is shown in figure 4.1. In this system, M-ary data encoder converts the input data bits into complex data symbols at the beginning of the system model. Different type of modulation techniques (e.g. BPSK, QPSK, QAM etc.) can be used for data encoder. After that, encoded data (X) with data rate $1/T_s$, is arranged into blocks of length of N symbols each. These N symbols are converted from serial to parallel. Each N symbols block is precoded by precoding matrix of size LXN**.**

$$X(k) = \sum_{n=0}^{N-1} p_{k,n} \times X, \;\; k = 0,1,2, \ldots\ldots L-1 \tag{4.1}$$

where, $\mathrm{p}_{k,n}$ is the element of precoder matrix P which is defined as-

$$\mathrm{P} = \begin{bmatrix} p_{0,0} & p_{0,1} & \cdots & p_{0,N-1} \\ p_{1,0} & p_{1,1} & \cdots & p_{1,N-1} \\ \vdots & & \ddots & \vdots \\ p_{L-1,0} & p_{L-1,1} & \ldots & p_{L-1,N-1} \end{bmatrix} \tag{4.2}$$

These precoded symbols $\left[X_p(0), X_p(1), X_p(2)..X_p(L-1)\right]^T$ are oversampled by a sampling factor L_s to provide better estimation of PAPR [38], by inserting $(L_s-1)N$ zeros in the precoded symbol. These oversampled precoded symbols are partition into V disjoint subblocks.

$$X_v = \sum_{\mathrm{m}=1}^{\mathrm{V}} X_p \tag{4.3}$$

Here, adjacent partition scheme is used to separate subblocks. Then the V subblocks are multiplied by complex phase factor w_v=exp$(j\emptyset m)$, where $m = 1, 2, 3 \ldots V$ and taking IFFT of each subblock at the same time.

$$x = \sum_{m=1}^{V} w_v \times IFFT\{X_v\} = \sum_{m=1}^{V} w_v \times x_v \tag{4.4}$$

x_v is called partial transmit sequence (PTS). After selecting appropriate phase factor the lowest PAPR vector in time domain is given as-

$$\breve{x} = \sum_{m=1}^{V} \widetilde{w_v} \times x_v \qquad (4.5)$$

At the receiver, the received signal $Y = [Y(0), Y(1), \dots Y(LN-1)]^T$ is partitioned again into V disjoint subblocks using the same partition scheme of transmitter side. Each partition subblocks are multiplied by their optimized phase factors $w^* = [w_1^*, w_2^*, \dots. w_v^*]$ which are calculated in the transmitter side, where w^* is a transpose of w. Each time domain subblock is converted to frequency domain by using LN- point FFT. Frequency domain subblock is multiplied with matrix P^*, where P^* is the hermitan transpose of P. After multiplication we get a vector of length N.

$$\tilde{X} = P^* \times Y, \qquad for\, n = 0,1,2, \dots .. N-1. \qquad (4.6)$$

Then obtain result of vector $\tilde{X}$ is decoded by using different decoded scheme (e.g., MPSK, MQAM) to recover transmitted symbol.

4.3. PAPR in OFDM System

In the transmitter side, the PAPR of transmitted signal is defined by-

$$PAPR = \frac{P_{peak}}{p_{avg}} = \max_{0 \le t \le T} |x(t)|^2 / E\{|x(t)|^2\} \qquad (4.7)$$

where, $|x(t)|^2$ is the instantaneous power and $E\{|x(t)|^2\}$ is average power of the precoded-PTS OFDM signal $x(t)$.The transmitted OFDM signal x can be defined as-

$$x(t) = \sum_{n=0}^{N-1} X_p \times X_v \qquad (4.8)$$

where,

$$X_p(t) = \sum_{n=0}^{N-1} X \times P(t), 0 \le t \le T$$

Also, P(t) is a set of time limited function used to generate precoding matrix and it is defined by-

$$P(t) = \sum_{k=0}^{L-1} P_{k,n} e^{\frac{j2\pi k}{T}}, 0 \le t \le T \qquad (4.9)$$

for $n = 0,1, \dots N-1$.

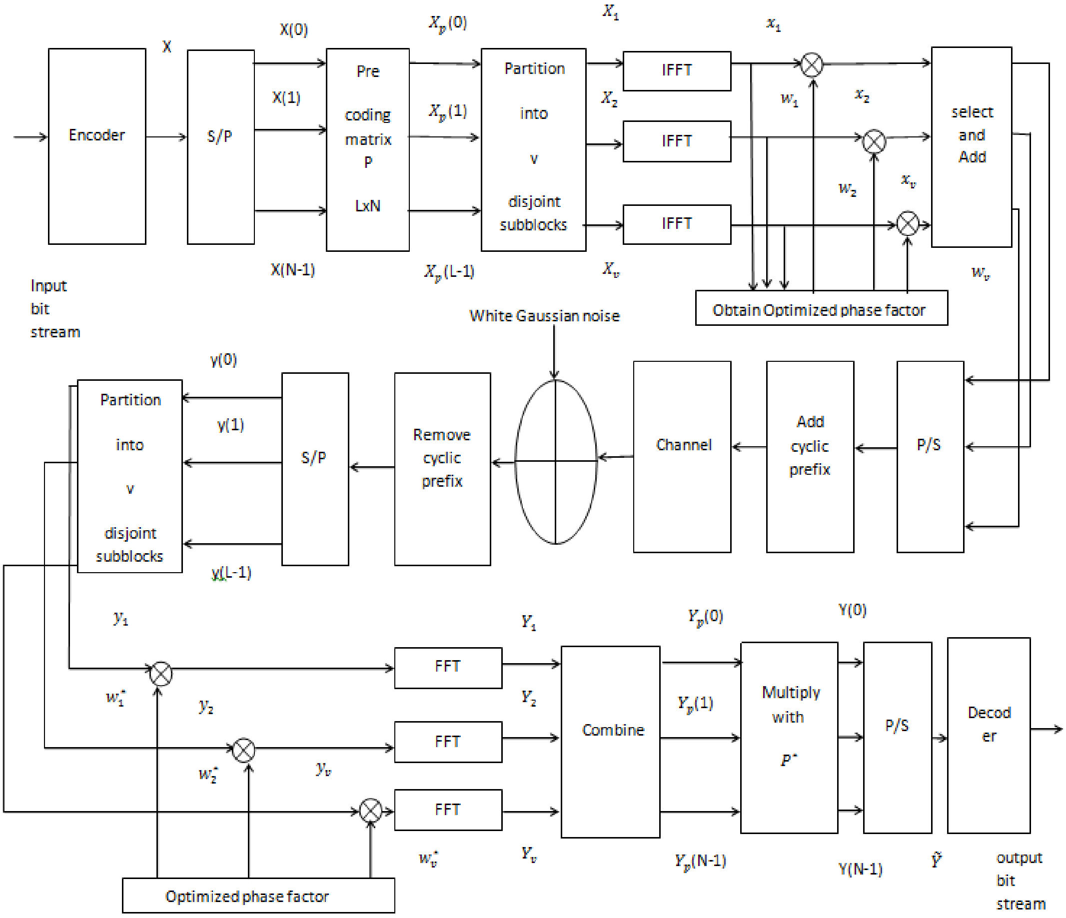


Figure-4.1: Block diagram of Precoding PTS OFDM system with N subcarriers.

Also, X is as defined in equation (4.1). Here, selection of phase factor should be done in an optimized way to reduce the PAPR as given below [34]-

$$[\widetilde{w_1} \dots \widetilde{w_v}] = \frac{\arg\min}{[w_1 \dots . w_v]} \left(\max_{n=0,1,\dots L-1} \sum_{m=1}^{V} |w_v * x_v\,[n]| \right) \tag{4.10}$$

The OFDM signal $x(t)$ at first depends on the elements of precoding matrix P and also $x(t)$ depends on the phase factor. So, the PAPR of $x(t)$ can be controlled by proper selection of precoding matrix $P(t)$ as well as proper selection of phase factor w_v.

The element of precoding matrix can be determined from the fundamental properties of $P(t)$ as mentioned below-

$$P_{k,n} = e^{\frac{-j2\Pi kn}{N}} \frac{1}{T} \int_0^T p(t) e^{\frac{-j2\Pi k}{N}} dt \tag{4.11}$$

After taking Fourier transform and simplifying equation (4.11),

$$P(k,n) = (-1)^k e^{-\frac{j2\pi kn}{N}} \frac{1}{T} P\left(\frac{k}{NT_s}\right) \tag{4.12}$$

where, $P(\frac{k}{NT_s})$ is the fourier transform of $P(t)$.

Pulse shapes like SQRC, RC, and BTRC functions are used to generate precoding matrix in this thesis. The RC, SQRC and BTRC functions in frequency domain are defined as respectively [65] -

$$P_{RC}(f) = \begin{cases} T_s \sin^2\left(\frac{\pi f Ts}{\beta}\right), & 0 < f \le \frac{\beta}{T_s} \\ T_{s,} & \frac{\beta}{T_s} < f \le \frac{1}{T_s} \\ T_s \sin^2\left(\frac{\pi(fTs-1)}{2\beta} + \frac{\pi}{2}\right), & \frac{1}{T_s} < f \le \frac{1+\beta}{T_s} \end{cases} \tag{4.13}$$

$$P_{SQRC}(f) = \begin{cases} T_s \sin\left(\frac{\pi f Ts}{2\beta}\right), & 0 < f \le \frac{\beta}{T_s} \\ T_{s,} & \frac{\beta}{T_s} < f \le \frac{1}{T_s} \\ T_s \sin\left(\frac{\pi(fTs-1)}{2\beta} + \frac{\pi}{2}\right), & \frac{1}{T_s} < f \le \frac{1+\beta}{T_s} \end{cases} \tag{4.14}$$

$$P_{BTRC}(f) = \begin{cases} T_s\left(1 - e^{-\frac{2ln2}{\beta} fT_s}\right), & 0 < f \le \frac{\beta}{2T_s} \\ T_s(-\frac{2ln2}{\beta}(\beta - fT_s), & \frac{\beta}{2T_s} < f \le \frac{\beta}{T_s} \\ T_{s,} & \frac{\beta}{T_s} < f \le \frac{1}{T_s} \\ T_s(e^{-\frac{2ln2}{\beta}(-1+fT_s)}, & \frac{1}{T_s} < f \le \frac{(1+0.5\beta)}{T_s} \\ T_s\left(1 - e^{-\frac{2ln2}{\beta}(1+\beta-fT_s)}\right), & \frac{(1+0.5\beta)}{T_s} \end{cases} \tag{4.15}$$

where, β is a roll-off factor ranging from 0 to 1.

From (4.10), $\mathrm{w_i}$=$\{\mathrm{e}^{\mathrm{j}2\pi\mathrm{i}/\mathrm{q}}, \mathrm{i} = 0, \ldots.., \mathrm{q}-1\}$ is a set of allowed phase factor. Here, $\mathrm{q}^{\mathrm{v}-1}$ sets of phase factor have to be verified for solving equation (4.10). So, as the number of subblocks increases, the process of verifying equation (10) also increases. Normally, choosing the phase factors $\{\mathrm{w_v}\}_{\mathrm{m=1}}^{\mathrm{V}}$ is restricted to number of subblocks to reduce the search complexity [42].

4.3.1 Complexity in PTS

In PTS method, IFFT of each subblock (i.e, V IFFT operation) as well as log_2q^V bits of side information is required. The calculation of minimum PAPR by PTS method depends on the selection of number of subblocks and the number of phase factors. For reducing the search of phase factor process different algorithm has been proposed [42], [43], [44], [47]. In this paper, phase optimization is done by using suboptimum combining algorithm which uses binary phase factors of {+1,-1} as explained in [42].

Another, issue of complexity for PTS method is the number of subblocks which is addressed in this thesis. As the partition of subblocks increase, the number of IFFTs to be performed also increase. So, this proposed method obtains the better result at minimum number of subblocks. Using only few subblocks better reduction in PAPR is obtained as compare to PTS method with more subblocks. As a better PAPR is obtained at minimum subblocks, not only the requirement of more IFFT operation is reduced but also the number of side information to be transmitted for recovering the original data block is also minimized. The number of required side information bits in PTS is log_2q^V where q is number of allowed phase factor.

4.4 Power spectral density (PSD)

Power spectral density (PSD) evaluates the change in power or energy as a function of frequency. It gives the characteristics of power at different frequency whether it is strong or weak. One of the main reasons for calculating the PSD is the need for predicting in-band distortion and out-of-band radiation produced by OFDM transmitters. The unit of PSD is energy per frequency and energy is defined by integrating PSD within a certain frequency range. Mathematically, the PSD of analog baseband transmitted OFDM signal $x(t)$ is defined as [53]-

$$PSD(f) = \lim_{t\to\infty}\left(\frac{1}{T}E\{|F\{x(t)\}|^2\}\right) \tag{4.16}$$

where, $E\{.\}$ and $F\{.\}$ denotes the expectation operator and Fourier transform operator respectively.

To obtain the result of CCDF, 20000 random OFDM blocks are generated with number of sub-carriers (N)= 64. Encoded signal is oversampled by a factor of four. The results are performed by using QPSK modulation scheme. We use binary phase factors of $\{1, -1\}$.

Figure 4.2 shows CCDF of the proposed technique at roll-off factor (β) =12% for different number of subblocks (V). SQRC pulse shape is used to generate predefined precoding matrix. The most obvious trend in the graph is that PAPR goes on decreasing as the number of subblocks increases at the same roll of factor. The least PAPR of 4.7dB is obtained at CCDF=10^{-3} for proposed method with V=32 at β=12%. The increment of PAPR on decreasing subblocks is observed. The proposed method with subblocks 24, 16, 4 has peak value of approximately 4.9dB, 5.1dB and 5.5dB respectively. The PAPR for proposed method decreases drastically in comparison to the PTS method for subbblocks 16 and 4. The proposed method at 12% roll off factor has about 2.5dB less PAPR than PTS method for subblocks 4. Similarly, for subblocks 16 there is about 1.3dB difference in PAPR between these two methods.

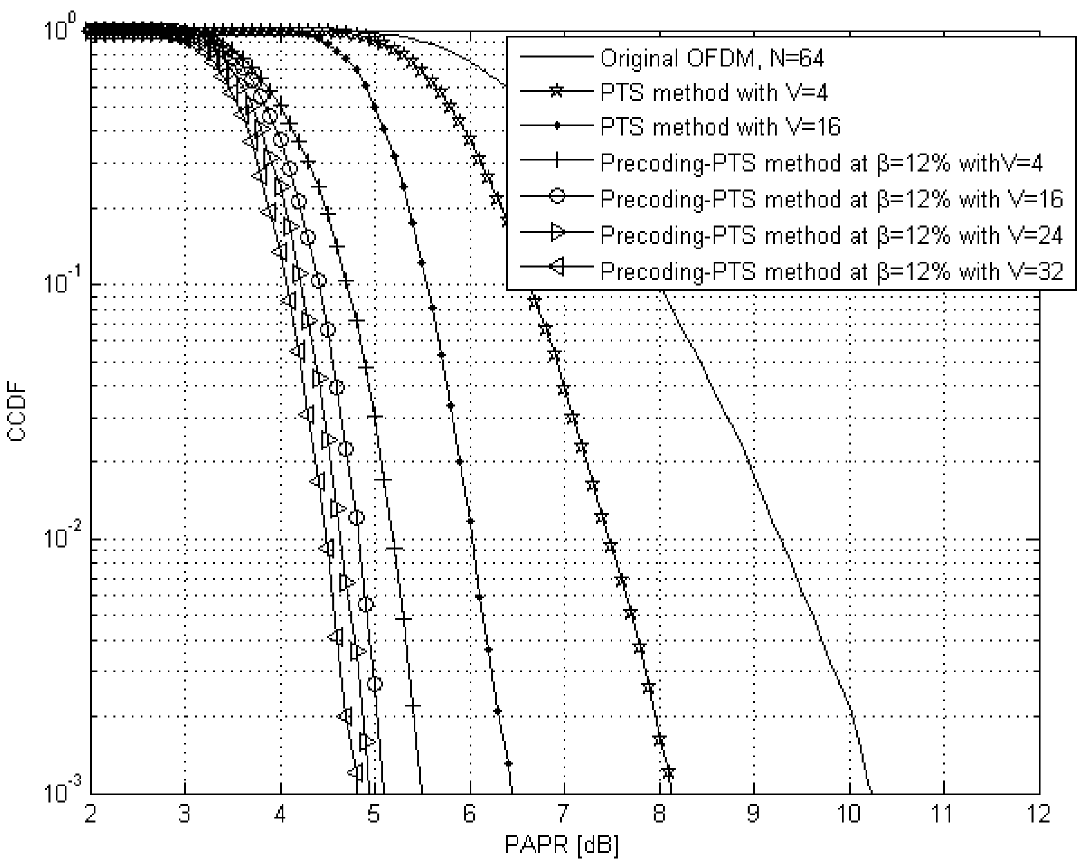


Figure-4.2: Complementary cumulative distribution function performance of the proposed method with N=64 sub-carriers for roll off factor β=12% for different subblocks.

Figure 4.3 shows the CCDF for the proposed technique at β=12% and V=4, precoding technique with same roll-off factor and PTS technique with subblocks 16 and 4. Peak power for proposed method with V=4 decreases 2.6 dB from PTS method for same subblocks at CCDF=10^{-3}. This graph illustrates that at lower number of subblocks least PAPR is achieved. So, the complexity issue on PTS due to number of subblocks is addressed by achieving minimum PAPR at minimum subblocks with low roll-off factor. Not only that, proposed method have PAPR of 5.5dB which is minimum in comparison to precoding technique at same roll-off factor with 5.8dB peak value as well as PTS technique with subblocks 16 and 4 have 6.4dB and 8.1dB respectively at CCDF=10^{-3}.

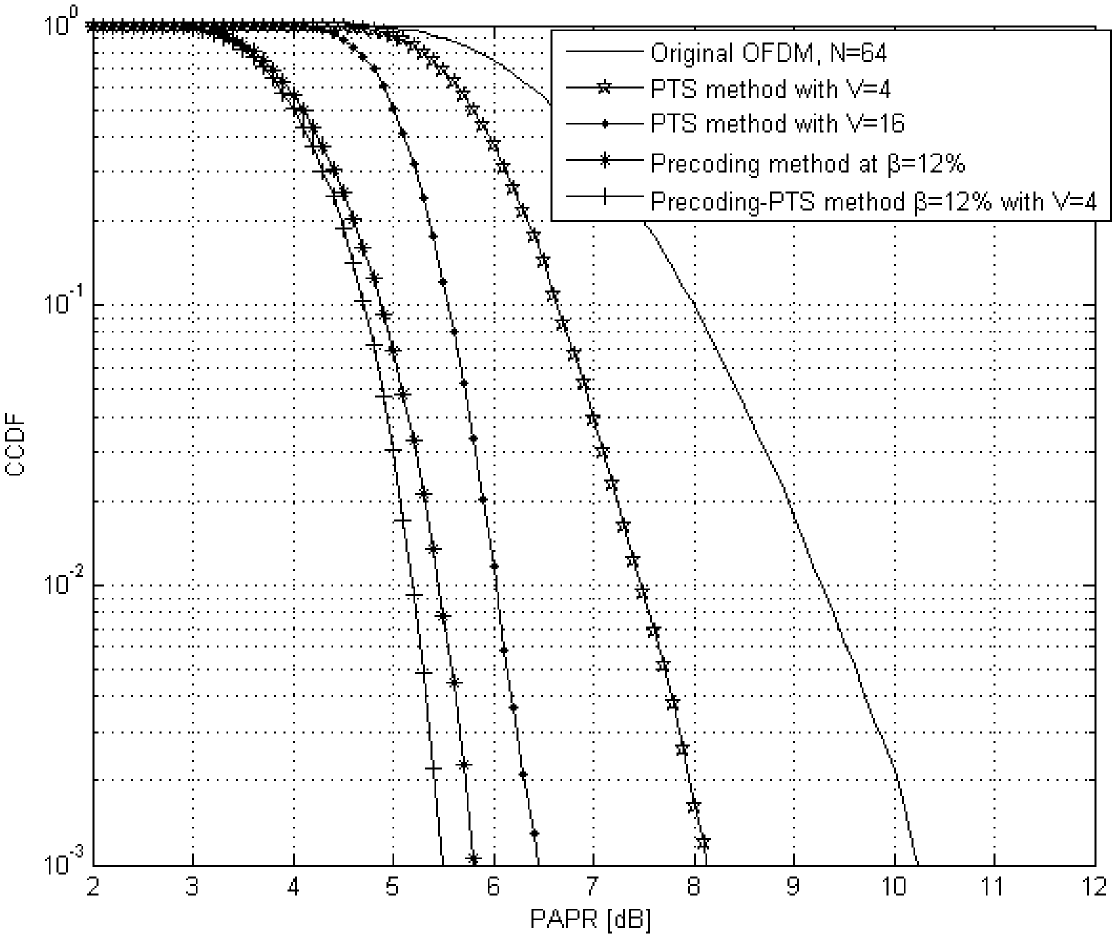


Figure-4.3: Comparison of CCDF performance for PTS, precoding and proposed technique.

In figure.4.4 three different pulse shapes as RC, BTRC, and SQRC are used to generate precoding matrix (P) for proposed method at β=12% with V=4 and precoding method with same roll-off factor. The performance of SQRC is best among BTRC and RC as well as RC has worst performance in both methods. Proposed method has less PAPR then precoding method for three different pulse shapes. For the proposed method, SQRC and BTRC have almost same PAPR approximately 5.5dB and RC has 5.7dB. Similarly, for precoding method SQRC, BTRC and RC have PAPR of about 5.7dB, 5.9dB and 6.1dB. It is clear from given data that performance of BTRC is almost same as SQRC for proposed method. So, in proposed method we can use BTRC for generating precoding.

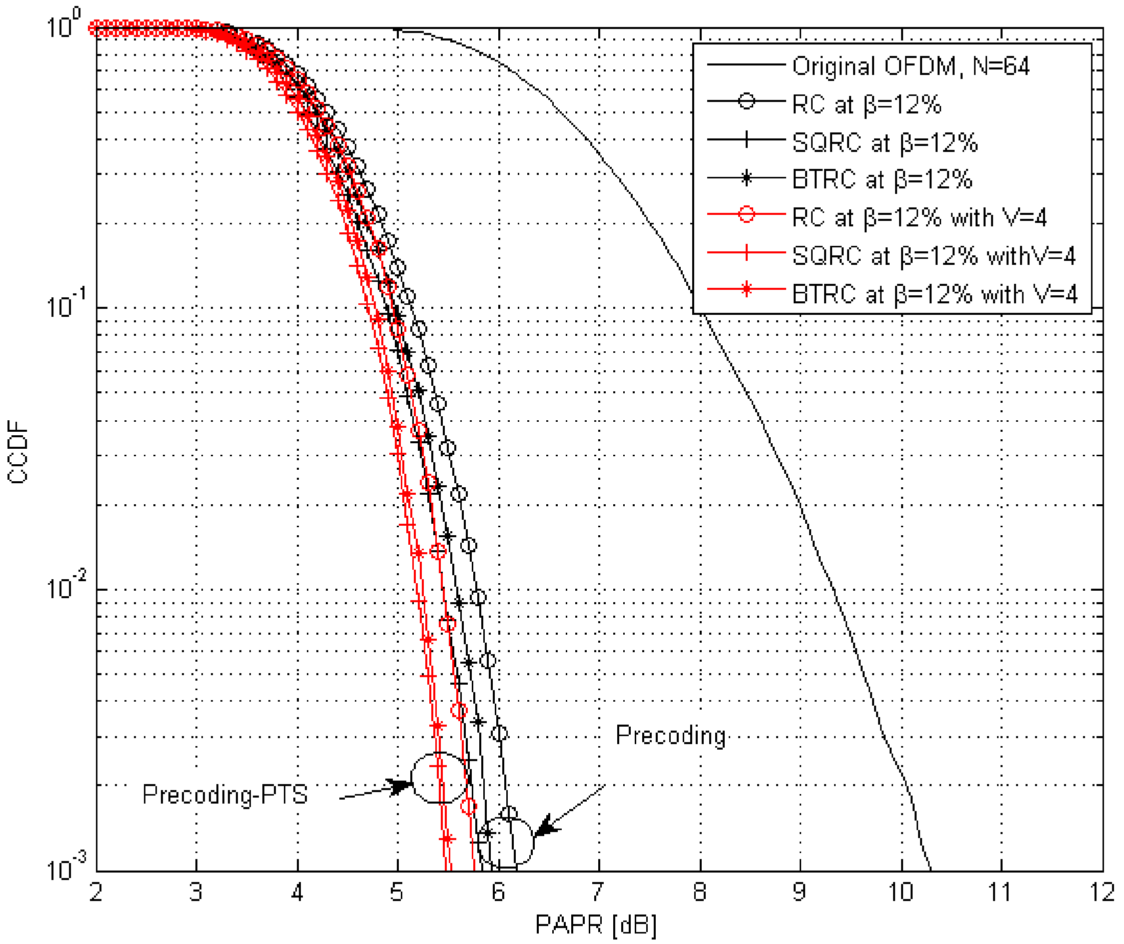


Figure-4.4: Comparison of CCDF of the PAPR for generating of precoding matrix by different pulse shapes for proposed technique.

Figure 4.5 show that the proposed method has low PSD as compared to the original OFDM. 12% roll of factor, four subblocks as well as oversampling factor four is used for this method. Power spectral density for proposed method is approximately -50dB/MHz and about -40dB/MHz for original OFDM. PSD has constant transmit spectrum within the range of -0.5 to 0.5MHz. From -2MHz to 0MHZ and 0MHz to 2MHz show side lobes of transmit spectrum. The PSD strength within the range of -0.5 to 0.5MHz.

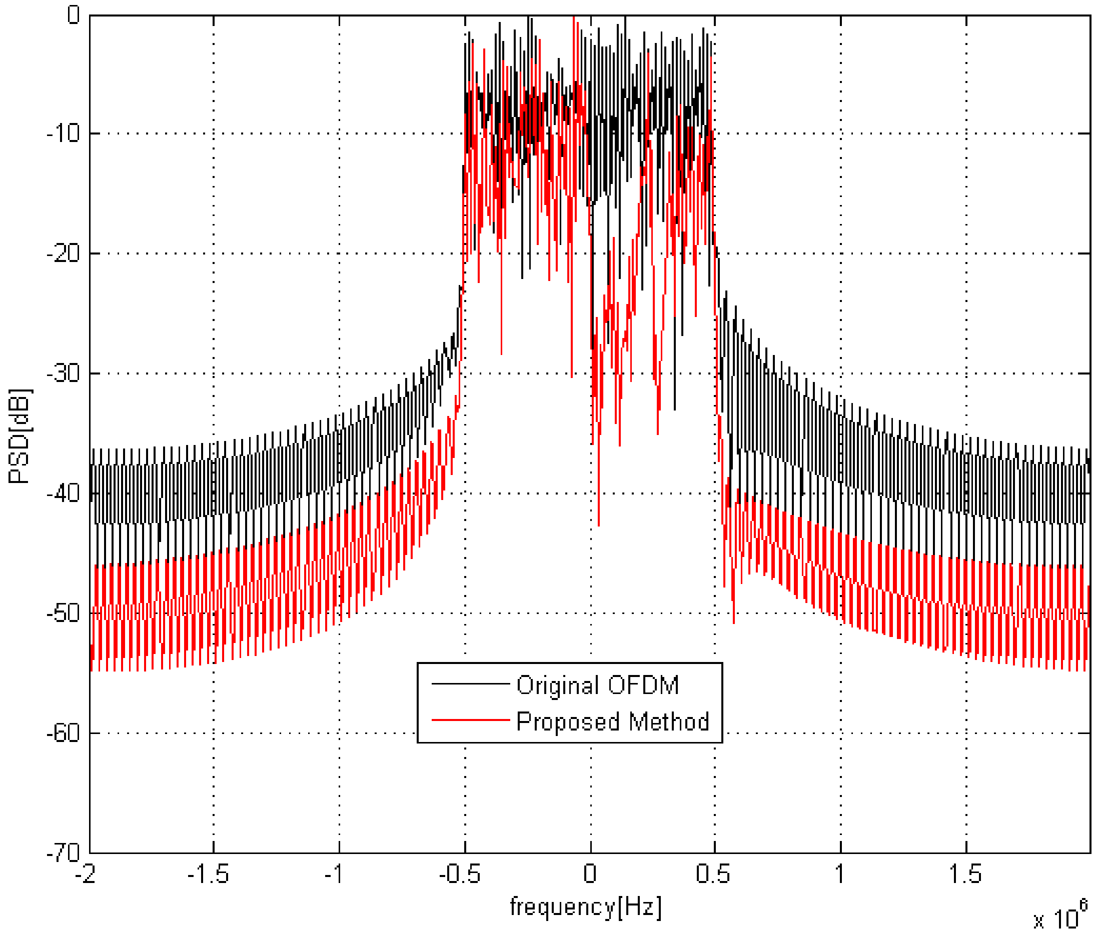


Figure-4.5: Power spectral density (PSD) of proposed method.

Table-4.1: Comparison of PAPR with different subblocks.

Parameter (CCDF)	Different Techniques	Number of subblocks (V)	Number of IFFT requirement	PAPR (dB)
10^{-3}	OFDM	-	-	10.4dB
10^{-3}	PTS	4 16	4 16	8dB 6.4dB
10^{-3}	Proposed	4 16 24 32	4 16 24 32	5.5dB 5.1dB 4.9dB 4.7dB

4.5 Conclusion

The proposed technique performance is analyzed using matlab simulation. The main concept of the proposed method is to multiply encoded data with predefined precoding matrix and applying these precoded data to PTS method where precoded data are partitioned into subblocks and choosing the optimized phase factor, the lowest PAPR is obtained. From the result of the simulations, the proposed technique has low PAPR as compare to PTS and Precoding method. Using a few number of subblocks, a remarkable reduction in PAPR is achieved that can’t be achieved in PTS by large number of subblocks. Therefore, complexity of more IFFT operations for PTS method has been omitted because the proposed scheme achieves low PAPR by using few numbers of subblocks.

CHAPTER 5

Conclusion and Future work

In this chapter the conclusion of the thesis is given from analytical and simulation studies as well as possible extension of the thesis is also presented.

5.1 Conclusion

One of the promising multicarrier communication systems, OFDM, has been adopted by many wireless communication standards due to its several advantageous features in multipath environments. The evolutionary history of OFDM, its advantages and disadvantages including its implementation in different wired and wireless standards are presented in first chapter. The rapid development of OFDM system begins after the implementation of DFT instead of bank of modulators as given by Weinstein and Ebert in 1971. Recently, it is widely exploited by wireless communication standards like IEEE 802.11 a/g/n standards, DAB, DVB, MC-CDMA and WiMAX.

Chapter 2 illuminates the theory and mathematics behind OFDM. The role of IFFT and cyclic prefix in OFDM system is mathematically analysed. Furthermore, the simulation results of BER performance over multipath environment including and excluding cyclic prefix using different mapping schemes for different number of subcarriers revealed the inflation of BER at absent of cyclic prefix and at high modulation level as well as insignificant effect of large number sub-carriers on BER performance.

Despite of numerous beneficiary features of OFDM system, synchronization and high PAPR are major issues of this system. So, for the complete exploitation these tremendous features of OFDM system these two major problems should be resolved. This thesis is concern to reduce the inherent problem of high PAPR in OFDM system. Chapter 3 presents the literature review on PAPR, impact of PAPR on the performance and different established methods to reduce the PAPR. Main reason of occurrence of high PAPR in OFDM is due to addition of data symbols across a number of independent modulated sub-carriers with same phase. The main impact of large peaks is -

- Saturation of the HPA as a result reduced in efficiency of amplifier.

- Complexity in ADC and DAC rise up.

The evaluation of PAPR performance is done by CCDF parameters. PAPR increases due to number of sub-carriers as shown in the simulation result. For accurate performance of PAPR oversampling is done by padding zeros in frequency domain.

Literature survey shows frequency domain method like PTS and Precoding schemes obtain less PAPR than time method like clipping, peak windowing, companding etc. The ability to reduce the PAPR without distorting transmitted signals and without producing any in band distortion and out of band radiation as well as no degradation on BER performance makes frequency domain method the promising one then time domain method. PTS method is distortionless method because it divides frequency vector into some subblocks before applying the phase transformation. But in this scheme complexity increases due to increment of subblocks, number of selection of phase factors, and amount of side information to be sent for recovery of original signal. From literature survey, it has been found that since from 1999 to recent year, many algorithms for reducing the searching phase factors and eliminated side information methods have been proposed. Precoding technique reduces the PAPR with less complexity but the number of sub-carriers increases with increase in roll off factor. From literature survey, it has been found that functions like RC, SQRC and DFT etc. can be used for generating the precoding matrix.

Chapter 4 describes the proposed technique to reduce the PAPR as well as PSD. The proposed technique is a hybrid combination of precoding and PTS method. In this method the precoded data is generated by multiplying predefined precoding matrix with encoded data. RC, SQRC and BTRC functions in frequency domain are used to generate predefined precoding matrix. Then these precoded data is applied to PTS method where precoded data are partitioned into subblocks. In this proposed technique, adjacent partitioning scheme is used to partition subblocks and optimization of phase factor is done by optimum algorithm. From the simulation result, the proposed method obtain low PAPR of 8dB at CCDF 10^{-3} at subblocks 4 with roll off factor 12% which is about 2.5 dB less than PTS method with same subblocks and 0.5dB less than precoding method with same roll off factor for N=64. The proposed method has low PSD of -50dB/MHz using subblocks 4 and 12% roll off factor for N=64 as compare to the original OFDM which has PSD of -40dB/MHz. As low PAPR is obtained for proposed method using few number of subblocks then PTS method, the requirement of more IFFT operation is reduced. Hence, the complexity due to number of subblocks has been reduced. Furthermore, expansion of bandwidth in proposed method is less as compare to precoding method because PAPR of proposed method can be decreased by increasing number of subblocks at constant roll off factor.

5.2 Future Work

In the present scenario, the PAPR problem is still challenging issue mostly for the devices where the minimization of linear range of power amplifier is importance. In this thesis, a new concept to combine precoding and PTS technique to reduce the PAPR of OFDM system is presented. This proposed system can be made more reliable by implementing a technique to recover the original signal in multipath environment without transmitting side information. Further enhancement on improving the complexity of the searching phase factors can be done. Different optimized phase factors searching algorithm as presented in the literature survey chapter can be applied. Furthermore, window functions like Discrete Fourier Transform (DCT), Modified Bartlett-Hanning (MBH), Discrete Hartley Transform (DHT), Zadoff- Chu Transform (ZCT) etc can be applied to generate the precoding matrix.

The proposed PAPR reduction technique can be applied with multiple input multiple output (MIMO) OFDM system.

REFERENCES

1. A. R. S. Bahai and B. R. Saltzberg, “Multi-Carrier Digital Communications: Theory and Applications of OFDM,” Kluwer Academic Publishers, New York, 2000.

2. R. Van. Nee and R. Prasad, “OFDM for Wireless Multimedia Communication,” Artech house Publisher, London, 2000.

3. P. A. Bello, “Selective fading limitations of the KATHRYN*,” IEEE Transactions on Communication Technology*, vol. 13, pp. 320-333 September 1965.

4. M. S. Zimmerman and A. L. Kirsch, “The AN/GSC-10 (KATHRYN) variable rate data modem for HF radio,” *IEEE Transactions on Communication Technolgy*, vol. 15, pp. 197-205 April 1967.

5. E. N. Powers and M. S. Zimmermann, “A digital implementation of a multichannel data modem,” *in Proc. IEEE Int. Conf. Commun*. Philadelphia, PA, 1968.

6. B. R. Saltzberg, “Performance of an efficient parallel data transmission system,” *IEEE Transactions on Communication*. Technology, vol. 15, pp.805-813 Dec. 1967.

7. H. F. Marmuth, “On the transmission of Information by Orthogonal Time Functions,” *AIEE Transactions on (Communication and Electronics).* Tech., vol. 79, pp. 248-255 July 1960.

8. “Orthogonal Frequency Division Multiplexing,” *U.S. Patent No*. 3,488,455, Filed Nov.14, 1996, Issued Jan.6, 1970.

9. S.B. Weinstein and P.M. Ebert, “Data Transmission by Frequency-Division Multiplexing Using the Discrete Fourier Transform,” *IEEE Transactions on Communication. Tech.,* vol. 19, pp. 628-634 October 1971.

10. L. j. Cimini (jr) “Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing,” *IEEE Transactions communication*, vol. 33, pp. 665-675, July 1985.

11. Osamu Mino, Takanori Fujiwara and Hideshi Nishizawa “Development of North America Terrestrial Digital Audio Broadcasting Receiver (HD Radio),” *FUJITSU TEN TECH*, no. 25, pp. 42-53, 2005.

12. P. S. Chow, J. C. Tu and J. M. Cioffi, “Performance evaluation of a multichannel System for ADSL and VHDSL services,” *IEEE Selected Area*, vol., SAC-9, no. 6, pp.909-91, August 1991.

13. Anton Monk, Ronald Lee and Yoav Hebron, “The multimedia over Coax Alliance,” *Proceeding of the IEEE,* pp. 1-17, 2013.

14. IEEE Standard 802.11a, “Wireless LAN medium access control (MAC) and physical layer (PHY) specifications,” 1999.

15. IEEE Standard 802.11g, “Further Higher-Speed Physical Layer Extension in the 2.4 GHz Band,” 2003.

16. IEEE Standard 802.11n, “TM/D2.00. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications,” 2007.

17. http://en.wikipedia.org/wiki/IEEE_802.15.

18. T. Jiang, W. Xiang, H. H. Chen and Q. Ni, “Multicast broadcasting services support in OFDMA-based WiMAX systems,” *IEEE Communications Magazine*, vol. 45, no. 8, pp. 78–86, Aug. 2007.

19. Draft Supplement to Standard for Telecommunications and Information Exchange Between Systems-LAN/MAN Specific Requirements–Part 11: Wireless MAC and PHY Specification: High Speed Physical layer in the 5 GHz Band, IEEE802.11, May 1999. P802.11a/D6.0.

20. H. Sari, G. Karma and I. Jeanclaude, “Transmission techniques for digital terrestrial TV broadcasting,” *IEEE Communication Magazine*, vol. 33, pp. 100-109, February 1995.

21. H. Schulze and C. Luders, “Theory and Applications of OFDM and CDMA,” 1st Edition, John Wiley & Sons, England, 2005.

22. Slimane Ben Slimane, “Peak to Average Power ratio reduction of OFDM signals using Pulse Shaping,” *IEEE,* pp. 1412-1416, 2000.

23. H.D. Joshi and R. Saxena, "OFDM and its Major Concerns: A Study with Way Out," *IETE Journal of Education*, vol. 54, Issued. 1, pp. 1-49, Jan-Jun. 2013.

24. T. S. Rappaport, Wireless Communications, Principles and Practice. Prentice Hall, New Jersey, 1996.

25. Zou, W.Y. and Wu, Y., "COFDM: An Overview," *IEEE transactions on broadcasting*, vol. 41, no. 1, pp. 1-8, March 1995.

26. S. H. Han and J. H. Lee, "An overview of peak to average power ratio reductions techniques multicarrier transmission," *IEEE Wireless communication*, vol. 12, no.2, pp.56-65, July 2005.

27. T. Jiang and Y. Wu, "An overview: Peak to Average power ratio reductions techniques for OFDM Signals," *IEEE Trans on Broadcasting*, Vol. 54, no. 2, pp. 257-268, July 2008.

28. P.K. Sharma and A. Basu, "Performance analysis of Peak to Average Power Ratio reduction for wireless communication use OFDM," *International conference on advances in recent technologies for wireless communication using OFDM signals*, pp. 89-95, 2010.

29. V. Vijayarangan and DR. (MRS) R. Sukanesh, "An overview of techniques for reducing peak to average power ratio and its selection criteria for orthogonal Frequency Division Multiplexing radio systems," *Journal of Theoretical and Information Technology*, pp.25-36, 2009.

30. Miin-Jong Hao and Chiu Hsiung Lai., "Precoding for PAPR Reduction of OFDM Signals With Minimum Error Probability," *IEEE Transactions on Broadcasting*, vol. 56, no. 1, pp. 120-128, November 2010.

31. H.D. Joshi and R. Saxena, "OFDM and its Major Concerns: A Study with Way Out," *IETE Journal of Education*, vol. 54, Issued. 1, pp. 1-49, Jan-Jun. 2013.

32. Seung Hee Han and Jae Hong Lee, "An Overview of Peak to Average Power ratio reduction techniques for Multicarrier transmission," *IEEE Wireless Communication*, vol. 12, no. 2, pp. 56–65, April 2005.

33. Seog Geun Kang, Jeong Goo Kim and Eon Kyeong, "A novel subblock scheme for Partial Transmit Sequence OFDM ,"*IEEE Transactions on Broadcasting*, vol.45, no. 3, pp. 313-338, March 1999.

34. S.H. Muller and J.B. Huber, "OFDM with reduced peak-to-average power ratio by optimum combination of partial transmit sequences," *Electronic. Letters*, vol. 33, no. 5 pp. 368–369, Feb. 1997.

35. Z. Liu, Y. Xin and G. B. Giannakis, "Linear constellation precoding for OFDM with maximum multipath diversity and coding gains," *IEEE Trans. Commun.*, vol. 51, no. 3, pp. 416–427, Mar. 2003.

36. Z. Wang and G. B. Giannakis, "Wireless multicarrier communications: where Fourier meets Shannon," *IEEE Signal Process. Mag.*, vol. 17, no. 3, pp. 29–48, May 2000.

37. John. G. Proakis, Digital Communications. New York: McGraw-Hill: 4th edition, 2001

38. Bernard Sklar, Digital Communications. Los Angeles: Prentice-Hall: 2nd edition, 2001.

39. T. S. Rappaport, Wireless Communications, Principles and Practice. Prentice Hall, New Jersey, 1996.

40. S. Muller, and J. Hubber "OFDM with reduced peak to average power ratio by optimum combination of Partial transmit sequences," *Elect. Lett., Communication Letters*, vol.33, no. 5, pp. 368-369, Feb. 1997.

41. Seog Geun Kang, Jeong Goo Kim and Eon Kyeong, "A novel subblock scheme for Partial Transmit Sequence OFDM ,"*IEEE Transactions on Broadcasting*, vol.45, no. 3, pp. 313-338, March 1999.

42. Leonard J. Cimini, Jr and Nelson R. Sollenberger, "Peak to Average Power Reduction of an OFDM signal Using Partial Transmit Sequences," *IEEE Communications Letters*, vol. 4, no. 3, pp. 1089-10811, 2000.

43. Ali Alavia, Chintha Tellambura and Ivan Fair, “PAPR reduction of OFDM signals using Partial Transmit Sequence : An Optimal Approach Using Sphere Decoding,” *IEEE Communication letters*, vol.9, no.11, pp.982-984, November 2005.

44. Tao Jiang and Yiyan Wu, “PAPR reduction of OFDM signals using Partial Transmit Sequence with Low Computational Complexity,” *IEEE Transactions on Broadcasting*, vol. 53, no. 3, pp. 719-724, September 2007.

45. Jung Chien Chen, “Partial Transmit Sequences for Peak to Average Power Ratio Reduction of OFDM Signals with the Cross Entropy Method,” *IEEE signal processing Letters*, vol. 16, no.6, pp.545-548, June 2009.

46. Jung Chien Chen, “Partial Transmit Sequences for Peak to Average Power Ratio Reduction of OFDM Signals with Stochastic Optimization Techniques,” *IEEE Transactions on Consumer Electronics*, vol. 56, no.3, pp.545-548, August 2010.

47. Sheng. Ju. Ku, Chin. Liang. Wang and Chiuan. Hsu. Chen, “A reduced-complexity PTS-based PAPR reduction scheme for OFDM systems,” *IEEE Trans. Wireless Communication*, vol. 9, no. 8, pp. 2455–2460, Aug. 2010.

48. Yajun Wang, Wen Chen, and Chintha Tellambura “A PAPR Reduction Method Based on Artificial Bee Colony Algorithm for OFDM Signals”, *IEEE Transactions on Wireless Communications*, vol. 9, no. 10, pp. 2994-2999, October 2010.

49. Jung Chien Chen, “Application of Quantum Inspired Evolutionary Algorithm to Reduce PAPR of an OFDM Signal Using Partial Transmit Sequence Technique,” *IEEE Transactions on Broadcasting*, vol. 56, no. 1, pp. 110-113, March 2010.

50. J. Hou, J. Ge and J. Li, “Peak-to-average power ratio reduction of OFDM signals using PTS scheme with low computational complexity,” *IEEE Trans. Broadcast.*, vol. 57, no. 1, pp. 143–148, Mar. 2011.

51. Lingyin Wang and Ju Liu, “PAPR Reduction of OFDM Signals by PTS With Grouping and Recursive Phase Weighting Methods,” *IEEE Transactions on Broadcasting*, vol.57, no.2, pp.299-306, June 2011.

52. Pooria Varahram and Borhanuddin Mohd Ali, "Partial Transmit Sequence Scheme with New Phase Sequence for PAPR Reduction in OFDM Systems," *IEEE Transactions on Consumer Electronics*, vol.57, no.2, pp.366-371, May 2011.

53. Toon Van Waterschoot, Vincent Le Nir, Jonathan Duplicy and Marc Moonen, "Analytical Expressions for the Power Spectral Density of CP-OFDM and ZP-OFDM signals," *IEEE signal processing letters*, vol.17, no.4, pp.371-374, April 2010.

54. Seung Sik Eom, Haewoon Nam and Young Chai Ko, "Low Complexity PAPR Reduction Scheme Without Side Information for OFDM Systems," *IEEE transactions on signal processing*, vol. 60, no.7, pp.3657-3669, July 2012.

55. Leonard J. Cimini, Jr and Nelson R. Sollenberger, "Peak to Average Power Reduction of an OFDM signal Using Partial Transmit Sequences with Embedded Side Information," *IEEE*, pp. 746-750, 2000.

56. A.D.S. Jayalath and C.Tellambura, "Side Information in PAR Reduced PTS-OFDM Signals," *IEEE International Symposium on Personal, Indoor and Mobile Radio Communication*, pp. 226-230, 2003.

57. Seon-Ae Kim and Heung-Gyoon Ryu, "Design and Analysis of Side Information Embeded PTS Scheme in the OFDM Communication System," *IEEE Pacific Rim*, pp.300-303, Aug 2007.

58. L.Yang, K. K. Soo, S. Q. Li and Y. M. Siu, "PAPR Reduction Using Low Computational Complexity PTS to Construct of OFDM Signals Without Side Information," *IEEE Transactions on Broadcasting*, vol.57, no.2, pp.284-290, June 2011.

59. Houshou Chen and Hsinying Liang, "PAPR Reduction of OFDM Signals Using Partial Transmit Sequence and Reed Muller Codes," *IEEE Communications letters*, vol. 11, no.6, pp.528-530, June 2007.

60. Josef Urban and Roman Marsalek, "OFDM PAPR Reduction by Partial Transmit Sequences and Simplified Clipping with Bounded Distortion," *18th IEEE International Conference*, pp. 1-4, April 2008.

61. Pooria Varahram, Wisam F. Al Azoo and Borhanuddin Mohd Ali, “A low Complexity Partial Transmit Sequence Scheme by Use of Dummy Signals for PAPR Reduction in OFDM Systems,” *IEEE Transactions on Consumer Electronics,* vol.56, no.4, pp.2416-2420, November 2010.

62. Abolfazl Ghassemi and T. Aaron Gulliver, “PAPR Reduction of OFDM Using PTS and Error Correcting Code Subblocking,” *IEEE Transactions on wireless communications,* vol. 9, no. 3, pp. 980-989, March 2010.

63. Slimane Ben Slimane, “Peak to Average Power ratio reduction of OFDM signals using Broadband Pulse Shaping,” *IEEE,* pp. 889-893, 2002.

64. Slimane Ben Slimane, “Reducing the Peak to Average Power Ratio of OFDM Signals Through Precoding*,” IEEE Transactions on Vehicular Technology*, vol. 56, no. 2, pp. 686-695, 2007.

65. H.D. Joshi and Rajiv. Saxena, “PAPR reduction in OFDM Systems Using Precoding with Clipping*,” IEEE International Conference on communications, Computing and Control Applications*, pp. 1-5, March 2011.

66. Mohamed A. Aboul-Dahab, Esam A.A.A. Hagras and Ahmad A. Elhaseeb “PAPR reduction based on DFT Precoding for OFDM Signals,” *International Journal of Future Computer and Communication*, vol. 2, no.4 , pp. 325–328, April 2013.