STUDIES ON PAPR REDUCTION TECHNIQUES FOR OFDM AND MIMO-OFDM SYSTEMS

THESIS

Submitted by

P.MUKUNTHAN

in partial fulfilment for the award of the degree

of

DOCTOR OF PHILOSOPHY

in

ELECTRONICS AND COMMUNICATION ENGINEERING

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

PONDICHERRY ENGINEERING COLLEGE

PONDICHERRY UNIVERSITY

PUDUCHERRY - 605 014

INDIA

SEPTEMBER 2013

Dr. P. Dananjayan
Professor,
Department of Electronics and Communication Engineering,
Pondicherry Engineering College,
Puducherry - 605 014.

CERTIFICATE

Certified that this thesis entitled **“STUDIES ON PAPR REDUCTION TECHNIQUES FOR OFDM AND MIMO-OFDM SYSTEMS”** submitted for the award of the degree of **DOCTOR OF PHILOSOPHY** in ELECTRONICS AND COMMUNICATION ENGINEERING of the Pondicherry University, Puducherry is a record of original research work done by **Mr. P. MUKUNTHAN** during the period of study under my supervision and that the thesis has not previously formed the basis for the award to the candidate of any Degree, Diploma, Associateship, Fellowship or other similar titles. This thesis represents independent work on the part of the candidate.

Supervisor
(Dr. P. Dananjayan)

Date :
Place : Puducherry

ABSTRACT

The demand for high data rate wireless multi-media applications has increased significantly over the past few years in the market because of the tremendous growth in network mobility, scalability and connectivity to different networks. The wireless users have put pressure on designers where they need to fulfill their requirements without compromise. However, the designers are facing problem in limited availability of Radio Frequency (RF) spectrum and the time variation of the channel strengths due to the multipath fading. Hence, they have an uphill task to address these challenges. The present wireless systems aim for two conflicting goals, viz., providing quality of service such as delay, fairness to users, and maximizing the throughput of the system.

Several techniques have been developed for increasing bandwidth with high data rate. Among these techniques, Orthogonal Frequency Division Multiplexing (OFDM) is a special form of multicarrier technique where all the subcarriers are orthogonal to each other. OFDM offers higher data rate and high immunity to the multipath fading channel without degrading the Bit Error Rate (BER) performance. It has gained popularity for broadband communication system because of its high spectral efficiency and capacity to combat multipath fading. At the same time, it has some limitations such as Inter-Symbol Interference (ISI), Inter-Carrier Interference (ICI) and high Peak-to-Average Power Ratio (PAPR).

The limitations of ISI and ICI are avoided by guard band insertion. The major problem in OFDM system is large PAPR, which is the ratio of peak to average power. The operating point of the linear power amplifier reaches the saturation region due to the high PAPR which leads to in-band distortion and out-band noise. This can be avoided with increasing the dynamic range of power amplifier which leads to high cost and high power consumption at the base station. Practically, it is not possible to operate the power amplifier in linear region. To reduce the PAPR, several techniques such as clipping, interleaving, block coding, Selective Mapping (SLM) and Partial Transmit Sequences (PTS) are in practice. The

basic idea of these methods is to achieve better PAPR reduction at the cost of high transmit signal power, degradation of BER and large computational complexity.

Among the various PAPR reduction techniques, PTS technique is very flexible to work with arbitrary number of subcarriers and suitable to all types of modulation applied to them. In this approach, subband signals are partitioned into multiple disjoint subblocks and each subblock is multiplied by phase weighting factors to reduce the PAPR. However, it has large computational complexity. In order to make a trade-off between PAPR and computational complexity, the modified PTS (MPTS) technique has been proposed. To improve the power amplifier efficiency, the modified PTS has been combined with various PAPR reduction techniques such as interleaving, Forward Error Correction (FEC), superimposed training sequence and pulse shaping in OFDM and MIMO-OFDM systems. This cascading approach provides better PAPR reduction.

The interleaving technique is an efficient PAPR reduction technique which has burst error control, minimum computational complexity and protects the data sequence from fading channel. On the other hand, latency is a major drawback in interleaving technique because it takes long time and hides all kinds of error structures which affect the performance of the system. This can be overcome by modified PTS combined with interleaving technique because it has an optimum set of phase rotation factors which leads to achieve better PAPR reduction performance. However, modified PTS with interleaving technique has no inherent error control.

So, an alternative method based on FEC coding technique such as turbo codes and Golay codes and called as modified PTS with FEC has been proposed. It contains an efficient encoding, good error-correcting capability and tightly controlled PAPR. Coding technique seems to be attractive because it does not create any out-of-band noise. But, it fails to maintain a reasonable coding rate for large number of subcarriers. However, the high linear power amplifier is required with effective utilization of bandwidth for distortionless transmission and this is carried out by certain amount of back-off power.

The modified PTS with superimposed training sequence method requires the use of perfect training sequence. Certain power has to be allocated to the superimposed training sequence which could otherwise be allocated to the information signal. Therefore, the foremost requirement in this method of PAPR reduction is the judicial selection of the superimposed training sequence so that a little power is wasted in it. The average output power can be increased without increasing the DC or peak.

The modified PTS with interleaving and pulse shaping method is based on proper selection of the different subcarriers and subblocks. Each subcarrier has different pulse shapes which are derived from cyclic shift of the same pulse. This will reduce the PAPR of the transmitted signal because the peak amplitude of the different pulse shapes will never occur at the same time. Here, the use of extra IFFT stages has been avoided and the transmitter power is effectively used. This makes this approach to be suitable for the high data rate MIMO-OFDM system such as a digital multimedia wireless broadband mobile communication system.

In summary, an attempt has been made in this research work to enhance the power amplifier efficiency and reduce the high PAPR of the OFDM and MIMO-OFDM systems through modified PTS approach combined with some PAPR reduction techniques.

ACKNOWLEDGEMENT

I express my profound indebtness to my supervisor and mentor, **Dr.P.Dananjayan**, Professor, Department of Electronics and Communication Engineering, Pondicherry Engineering College, for his support, selfless motivation and continued enthusiasm from the inception of the research to the completion stage. It would have been insurmountable to present this thesis without his support. It has been a great previlage and honour to work under him. I also extend my gratefulness to **Mrs.Angayarkanni Dananjayan** and **Mr.D.Sathian** for their unwavering encouragement which has inspired me to work harder and attain the goal.

I express my sincere gratitude to the Doctoral Committee members **Dr.R.Nakkeeran,** Associate Professor and Head, Department of Electronics Engineering and **Dr.K.Porsezian**, Professor, Department of Physics, Pondicherry University for their unswerving motivation and lively contributions of their busy schedule. I express my deep gratitude and loyalty for their magnanimous benignity and compassion, which has enthused me to comprehend the work.

I express my gratitude to **Dr.G.B.Senthil Kumar**, Correspondent, **Dr.S.Jayashri,** Director, and **Dr.V.Ramasamy**, Principal, Adhiparasakthi Engineering College for their constant, inspiration and support to pursue this research work.

I am grateful to **Dr.D.Govindarajulu**, Principal, Pondicherry Engineering College, **Dr.V.Prithiviraj**, Formar Principal, Pondicherry Engineering College, **Dr.E.Srinivasan** and **Dr.G.Nagarajan**, Professor and Head, Department of Electronics and Communication Engineering for their whole hearted support and for permitting me to make use of the facilities in the college for the research work.

I profusely thank **Dr.S.Sivamurthy Reddy,** Professor, Department of Civil Engineering for the moral support and timely help rendered during the course of this research work. I am thankful to **Dr.L.Nithyanandan**, **Dr.G.Sivaradje,** and **Dr.K.Jayanthi,** Assistant Professors, Department of Electronics and

Communication Engineering for many valuable suggestions, comments and inputs in shaping the thesis.

I genuinely thank **Mr.M.Thanigasalam,** Head, Department of Electronics and Communication Engineering, Karaikal polytechnic and **Dr.R.Valli,** Professor and Head, Department of Information Technology, Adhiparasakthi Engineering College for the immeasurable and perpetual support received during the decisive periods of my research. I am greatly indebted to them for helping me get through those tough times.

I also wish to place on record my thanks to **Dr.K.Thirumalaivasan, Dr.S.Robinson,** and **Mr.P.Raja**, Associate Professor, Sri Manakula Vinayagar Engineering College, **Mr.K.Kannadasan**, **Mr.A.Sundhar**, **Mr.R.Sundaramurthy**, and **Mr.R.Shankar**, Assistant Professor, Sri Manakula Vinayagar Engineering College for their help extended during the period of my research work. I am thankful to M.Tech and B.Tech students **Mrs.R.Prema**, **Mr.K.Raaghesh, Mr.R.Vasanth, Mr.S.Vijai Kumar** and **Mr.B.Viknesh Kumar** for the innumerous help I have received from them at different times. I immensely thank the faculty members, non-teaching staff and students of the Department for the moral support rendered during the period of my research work.

With deep sense of gratitude, I wish to record my sincere thanks to my parents **Mr.V.Pandurangan** and **Mrs.P.Chellayee** for their incessant encouragement and sustained motivation provided throughout my career. My profound gratitude is to my wife, **Mrs.M.Priya,** my sons **M.Saravana Kumar** and **M.Yashwanth** for their patience, and affection offered during the crucial periods of my research.

I thank the Almighty for His blessings throughout the research period.

(P. MUKUNTHAN)

TABLE OF CONTENTS

CHAPTER No.	TITLE	PAGE No.

CHAPTER No.	TITLE	PAGE No.

CHAPTER No.	TITLE	PAGE No.

LIST OF FIGURES

FIGURE No.	TITLE	PAGE No.

FIGURE No.	TITLE	PAGE No.
5.8	PAPR reduction performance of MIMO-OFDM system for different subblocks with N=256	79
6.1	Block diagram of the modified PTS with interleaving and pulse shaping method for OFDM system	84
6.2	Block diagram of the modified PTS with interleaving and pulse shaping method for MIMO-OFDM system	84
6.3	CCDF comparison of an OFDM system using modified PTS, modified PTS with interleaving and modified PTS with interleaving and pulse shaping method	86
6.4	PAPR reduction performance of OFDM system for different subcarriers with V=4	87
6.5	PAPR reduction performance of OFDM system for different subblocks with N=256	88
6.6	CCDF comparison of modified PTS, modified PTS with interleaving and modified PTS with interleaving and pulse shaping method for MIMO-OFDM system	89
6.7	PAPR reduction performance of MIMO-OFDM system using modified PTS with interleaving and pulse shaping method for different subcarriers at V=4	90
6.8	PAPR reduction performance of MIMO-OFDM system for different subblocks with N=256	91

LIST OF TABLES

LIST OF ABBREVIATIONS

ACE	Active Constellation Extension
ACI	Adjacent Channel Interference
ADC	Analog to Digital Converter
AP-PTS	Adjacent Partitioning-Partial Transmit Sequences
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CCDF	Complementary Cumulative Distribution Function
CDS	Channel Dependent Scheduling
CFO	Carrier Frequency Offset
CSI	Channel State Information
DAB	Digital Audio Broadcasting
DAC	Digital to Analog Converter
dB	Decibel
DFT	Discrete Fourier Transform
DMT	Discrete MultiTone
D-PTS	Decomposition-Partial Transmit Sequences
DVB	Digital Video Broadcasting
EIP-PTS	Enhanced Interleaved Partitioning-Partial Transmit Sequences
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FSK	Frequency Shift Keying
GMC	Generalized MultiCarrier
GPRS	General Packet Radio Services
GSM	Global System for Mobile
HPA	High Power Amplifier
HSCSD	High-Speed Circuit Switched Data
ICI	Inter-Carrier Interference
IEEE	Institution of Electrical and Electronics Engineers
IFDMA	Interleaved Frequency Division Multiple Access

IFFT	Inverse Fast Fourier Transform
I-OFDMA	Interleaved-Orthogonal Frequency Division Multiple Access
IP	Internet Protocol
IP-PTS	Interleaved Partitioning-Partial Transmit Sequences
ISI	Inter-Symbol Interference
LSM	Least Square Method
LTE	Long Term Evolution
MC	MultiCarrier
MC-CDMA	MultiCarrier- Code Division Multiple Access
MCM	MultiCarrier Modulation
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MPTS	Modified Partial Transmit Sequence
MSR	Multiple Signal Representation
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSTBC	Orthogonal Space Time Block Coding
PAPR	Peak to Average Power Ratio
PEP	Pair-wise Error Probability
PN	Pseudo-random Noise
P/S	Parallel to Serial
PSK	Phase-Shift Keying
PSO	Particle Swarm Optimization
PTS	Partial Transmit Sequences
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RCF	Repeated Clipping and Filtering
RF	Radio Frequency
RM	Reed-Muller
RSC	Recursive Systematic Convolutional
SC	Single Carrier

SC-FDMA	Single Carrier-Frequency Division Multiple Access
SISO	Single Input Single Output
SLM	SeLective Mapping
SNR	Signal to Noise Ratio
S/P	Serial to Parallel
SPW	Subblock Phase Weighting
ST	Superimposed Training
STBC	Space Time Block Codes
STC	Space Time Coding
STTC	Space Time Trellis Codes
T-PTS	Transformation-Partial Transmit Sequences
TR	Tone Reservation
UWB	Ultra Wide Bandwidth
WBMCS	Wireless Broadband Multimedia Communication Systems
WCDMA	Wide band Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Networks
WMAN	Wireless Metropolitan Area Networks
4G	Fourth Generation

LIST OF SYMBOLS

ξ	The linear gain of the power amplifier
α	The roll-off factor which ranges between 0 and 1
$\Delta\phi$	The arbitrary phase offset
ϕ_i	The i^{th} phase sequence of $A_{n,k}$
σ_p^2	The average power of the information signal
$[.]^*$	Complex conjugate operation
$[.]^T$	Transpose operation
Δb	Phase vector
Δf	Frequency spacing
a	Constant
a_i	Integer
$A_{n,k}$	The codeword based on the complementary sequences of length N_l
$b_{n,k}$	Phase shift sequence of length N_l
b_v	Set of phase factors
$\tilde{b}_v$	Optimum set of phase factors
$b[n]$	Pilot sequence
$\|b(n)\|$	The magnitude of the superimposed pilot sequence
B	Bandwidth
C	An encoded set of codewords for any number of carriers
$E[.]$	Expectation of the average power value
Es	Time waveform with constant energy
f_n	Frequency of the n^{th} subcarrier
G	Cyclic prefix
$G_{n,k}$	Generator matrix
k	Length of the sequence
l	Interleaver

L	Oversampling factor
M	M-ary Phase Shift Keying
M_t	Transmitting antennas
$[n]_N$	The residue of n divided by N
N	Number of subcarriers
N_d	Number of subcarriers allotted to a user
N_l	Codeword sequence of length
P_{av}	The average power of the sampled OFDM signal
$P(t)$	The instantaneous power of $x(t)$
r_c	Coding rate
$r(t)$	The impulse response of a raised cosine filter
s_m	Set of subblocks
$s[n]$	Time domain of the superimposed training sequence
S	Spreading factor
S'	The superimposed training sequence for preamble symbol of OFDM
$S[k]$	Frequency domain of the superimposed training sequence
T	Symbol period
u	The integer sequences between [0, M-1] of length k
ν	Subset of block
V	Subblock
w	Phase weighting factor
w^{V-1}	Set of phase weighting factor
$x(t)$	Baseband OFDM signal
$x[n]$	The signal is independent and identically distributed complex Gaussian random variables with zero mean and unit variance
$\tilde{x}[n]$	The equivalent baseband transmitted signal
x_v	Partial transmit sequence from v^{th} subblock
$\tilde{x}$	Optimum time domain OFDM signal
$x_{mk}(n)$	Baseband OFDM signal of a block at the k^{th} subcarrier of the m^{th} transmitting antenna

x^*_k	Conjugate of k modulated signals
X	Input data vector
X_n	Data symbol transmitted in n^{th} subcarrier
X_v	The input data vector X is divided into V disjoint sets
X_{mk}	Data symbols at the k^{th} subcarrier of the m^{th} transmitting antenna
X_{1n}, X_{2n}	Space time encoder into two vectors
X^*_{11}, X^*_{20}	Reed-Muller codeword vectors
X'	Frequency domain OFDM signal
$X(f)$	Power spectrum of x
$Y(f)$	Power spectrum of y

CHAPTER 1

INTRODUCTION

1.1 GENERAL

In recent years wireless communication systems are facing several demands for high-speed wireless services such as switched traffic, Internet Protocol (IP) data packets and multimedia. This implies that a future generation system will be aiming at wideband, broadband and Ultra Wide Bandwidth (UWB), which are capable of achieving the high spectral efficiency by using the various wireless techniques. However, the system design should satisfy the customer's requirements without any compensation. A well-balanced complexity, flexibility, data rate, Quality-of-Service (QoS) and cost are the important considerations for commercial applications particularly. The great progress made in the fields of microelectronics, signal processing, mobile computing, etc., thrive in achieving spectral efficiency with high flexibility.

Recent developments in wireless communications have shown that by using multiple antenna elements at both transmitter and the receiver, it is possible to substantially increase the capacity in a wireless communication system without increasing the transmission power and bandwidth. This system with multiple antenna elements at both link-ends is termed the Multiple-Input Multiple-Output (MIMO) system.

There are two fundamental aspects of wireless system that make the problem challenging and interesting. First aspect is the time variation of the channel strengths due to the small-scale effect of multipath fading such as path loss via distance attenuation and shadowing by obstacles. The second aspect is, wireless users use free space as communication medium [1]; unlike to the wired world, where each transmitter–receiver pair are often an isolated point-to-point link. This makes the wireless users face a significant effect of noise interference between the transmitter–receiver pair. So, the designer should follow the designing principle of wireless systems which could focus on increasing the reliability of the system over fading channel and protection against interference. Wireless broadband communications systems are characterized by very dispersive channels. To face this phenomenon, two modulation techniques can be used: Single Carrier (SC) modulation and multicarrier modulation. The Single Carrier [2] system is a traditional digital transmission scheme in which data symbols are transported as a fixed-symbol-rate. SC mitigates Inter-Symbol Interference (ISI) but fails to protect the spectral utility due to non-overlapping of the symbols which is achieved by adding cyclic prefix between symbols.

The basic idea of MultiCarrier Modulation (MCM) is to divide the transmitted bit stream into many different substreams and send these over many different subchannels. Typically the subchannels are orthogonal under ideal propagation conditions. The data rate on each of the subchannels is much less than the total data rate, and the corresponding subchannel bandwidth is much less than the total system bandwidth. The number of sub streams is chosen to ensure that each subchannel has a bandwidth less than the coherence bandwidth of the channel. So the subchannels experience relatively flat fading. Thus, the inter-symbol interferenceon each subchannel is small. The subchannels in multicarrier modulation need not be contiguous, so a large continuous block of spectrum is not needed for high-rate multicarrier communications. Moreover, multicarrier modulation is efficiently implemented digitally. In this discrete implementation, called Orthogonal Frequency Division Multiplexing (OFDM), the ISI can be completely eliminated through the use of a cyclic prefixes. Multicarrier modulation out-performs single carrier modulation in case of flat fast fading since the fading signal is integrated over a longer symbol interval [3]. It is based upon the idea of Frequency Division Multiplexing (FDM). In normal FDM system, multiple signals are sent out at the same time, but on different frequency carriers which are spaced apart in such way that the signals can be received using conventional filters and demodulators. While in OFDM, a single transmitter transmits on many different orthogonal subcarriers, with baseband data on each subcarrier being independently modulated commonly using some type of Quadrature Amplitude Modulation (QAM) or Phase-Shift Keying (PSK).

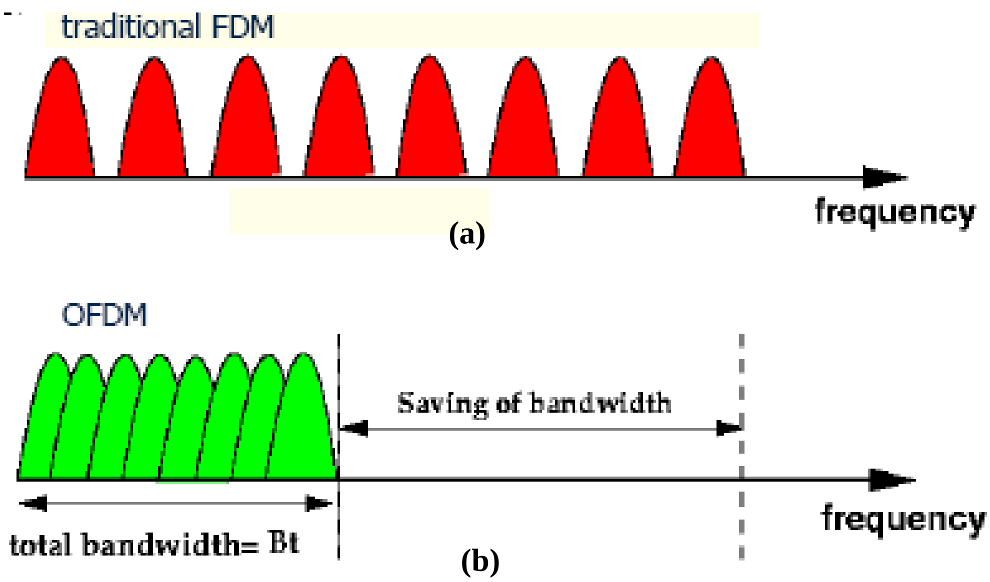

Figure 1.1 (a) Conventional multicarrier signal, (b) Orthogonal multicarrier modulation signal

Figure 1.1 illustrates the difference between the conventional nonoverlapping MultiCarrier (MC) signal and the overlapping multicarrier technique. By using the overlapping multicarrier modulation signal almost 50% of the bandwidth is saved when compared to traditional FDM. OFDM, a special case of multicarrier transmission technique offers considerable high spectral efficiency, multipath delay spread tolerance, immunity to the frequency selective fading channels and power efficiency.

1.2 OFDM SYSTEM

OFDM is a promising technique for achieving high data rate and combating multipath fading in wireless communications. It can be thought of as a hybrid of MCM and Frequency Shift Keying (FSK) modulation. MCM is the principle of transmitting data by dividing the stream into several parallel bit streams and modulating each of these data streams onto individual carriers or subcarriers [4]. FSK modulation is a technique whereby data is transmitted on one carrier from a set of orthogonal carriers in each symbol duration. Orthogonality amongst the carriers is achieved by separating the carriers by an integer multiple of the inverse of symbol duration of the parallel bit streams. With OFDM, all the orthogonal carriers are transmitted simultaneously.

In other words, the entire allocated channel is occupied through the aggregated sum of the narrow orthogonal subbands. By transmitting several symbols whose symbol duration is increased proportionately reduces the effects of ISI caused by the dispersive Rayleigh fading environment [5]. OFDM is a signaling technique that is widely adopted in many recently standardized broadband communication systems due to its ability to cope with frequency-selective fading. The robustness against frequency selective fading is very attractive, especially for high-speed data transmission.

Figure 1.2 (a) shows the spectrum of the individual data of the subchannel. The OFDM signal, multiplexed in the individual spectra with frequency spacing equal to the transmission speed of each subcarrier is shown in Figure 1.2 (b). Figure 1.2 shows the orthogonal carriers do not interfere with each other and there is no need of guard bands therefore make OFDM more spectrum efficient than FDM.

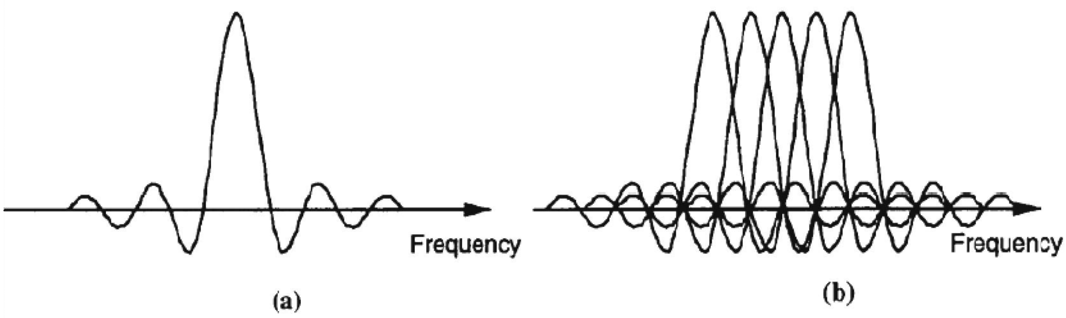

Figure 1.2 Frequency spectrum of (a) single carrier (b) multicarrier of OFDM signal

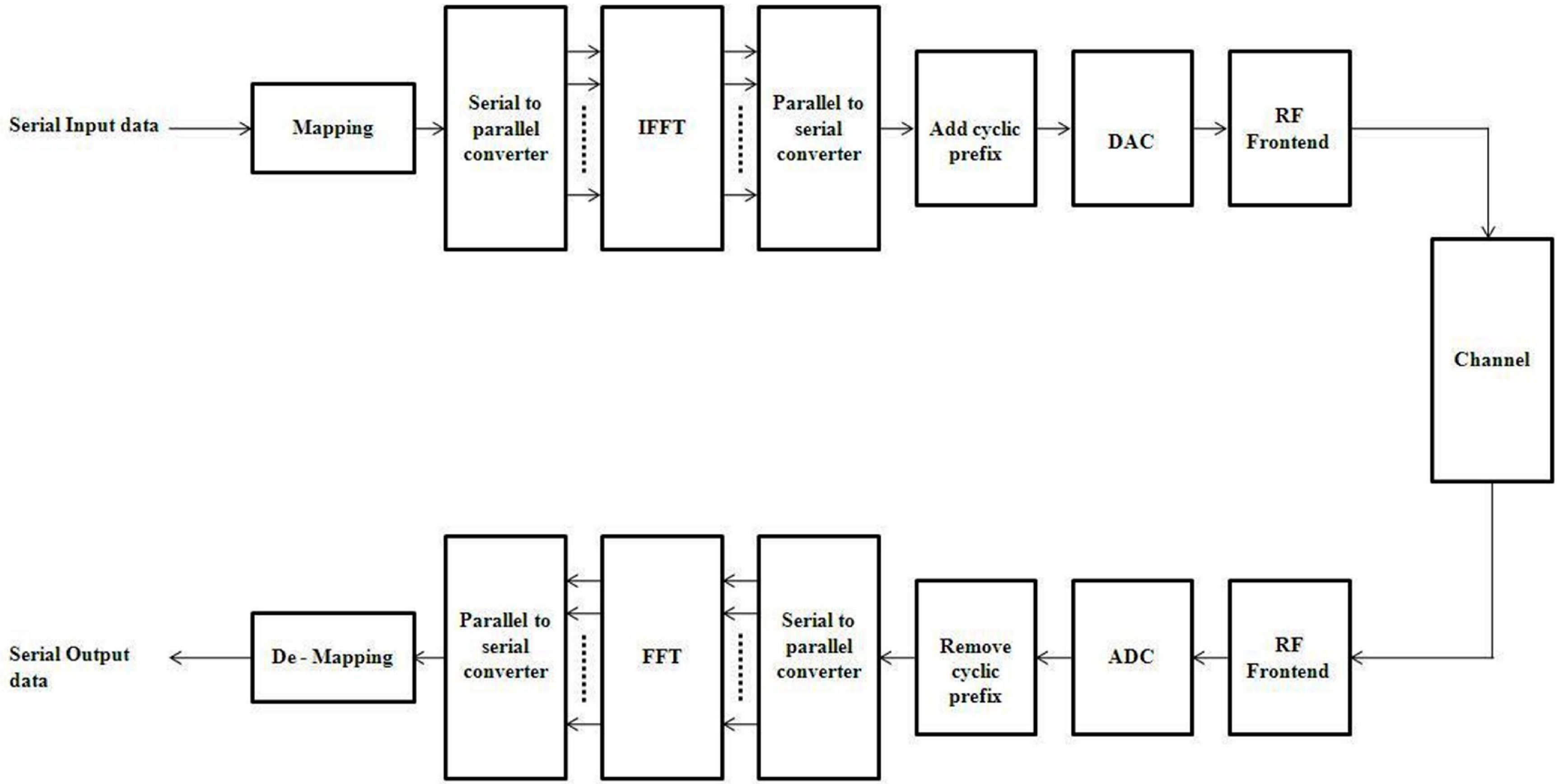

Figure 1.3. Block diagram of OFDM transceiver system

Figure 1.3 shows the block diagram of a typical OFDM system. The basic principle of OFDM is to divide a high-rate encoded data stream into lower rate parallel substreams that are transmitted simultaneously over a number of subcarriers. Each parallel bit stream is modulated on one of N subcarriers (i.e. data symbols with a symbol rate of $1/T_s$ employing a general phase and amplitude modulation scheme).

Then, it passes through Inverse Fast Fourier Transform (IFFT) where the real and imaginary parts correspond to the in-phase and quadrature parts of the OFDM signal. To achieve high bandwidth efficiency, the spectrum of the subcarriers is closely spaced, overlapped and orthogonality should be maintained between the number of subcarriers. Each subcarrier has exactly an integer number of cycle in the interval T, and the number of cycles between adjacent subcarriers differs by exactly one. These data symbols are transmitted serially along with addition of cyclic prefix to overcome the inter-symbol interference problem. Furthermore, in OFDM systems different modulation schemes can be employed for different subcarriers or even for different users.

Besides its implementation flexibility, the low complexity required in transmission and reception as well as the attainable high performance renders OFDM a highly attractive candidate for high-data-rate communications over time-varying frequency-selective radio channels. However, since the OFDM signal consists of a number of independently modulated subcarriers, it produces severe Peak-to-Average Power Ratio (PAPR) than single-carrier signals, requiring a large linear range for the OFDM transmitter’s output amplifier. In addition, OFDM is sensitive to Carrier Frequency Offset (CFO), resulting in Inter-Carrier Interference (ICI). A major drawback of multicarrier communication is the high PAPR, which can be evaluated by the Complementary Cumulative Distribution Function (CCDF). OFDM has become a potential candidate for the high performance 4G broadband wireless communication applications due to its greater immunity to multipath fading and impulse noise. It also eliminates the need for equalizer. Efficient hardware implementation is realized using the Fast Fourier Transform (FFT) techniques. As such, OFDM has been chosen for Digital Audio Broadcasting (DAB), Digital Video

Broadcasting (DVB), Wireless Local Area Networks (WLAN) standards (IEEE 802.11), Worldwide Interoperability for Microwave Access (WiMAX) (IEEE 802.16) and are being considered for Long Term Evolution (LTE).To ensure reliable communication over the radio channel, a system must overcome fading and interference and this can be achieved using MIMO technique.Subsequently, MIMO-OFDM has come into existence to improve reliability, capacity and throughput.

1.3 MIMO-OFDM SYSTEM

A system employing more than one transmitting and receiving antenna is called MIMO system. Figure 1.4 illustrates the block diagram of MIMO-OFDM system. Multiple antenna techniques can be used to increase diversity of wireless systems in order to increase the cell range, data rate through spatial multiplexing, and reduce interference from other users. Multiple-antenna techniques include MIMO diversity and MIMO spatial multiplexing. OFDM can transform such a frequency-selective MIMO channel into a set of parallel frequency-flat MIMO channels to decrease receiver complexity. MIMO diversity is a space-time modulation technique in which the core idea is to send dependent streams of data from each transmit antenna [6]. The combination of OFDM and MIMO systems [7] can achieve a lower error rate and enable high capacity of wireless communication system by flexibly exploiting diversity gain and the spatial multiplexing gain.

The space time coding method aims to improve the system's performance by exploiting the multiple antennas for diversity gain. It increases the network throughput by selecting quality signal paths such that high data rates can be achieved. This method is particularly attractive as it does not require channel knowledge in the transmitter. The resulting diversity gain improves the reliability of fading wireless links and hence improves the quality of the transmission. It is notable that the space time coding [8] method does not increase the capacity linearly with the number of transmit/receive elements used. However, it maximizes the wireless range and coverage by improving the quality of the transmission.

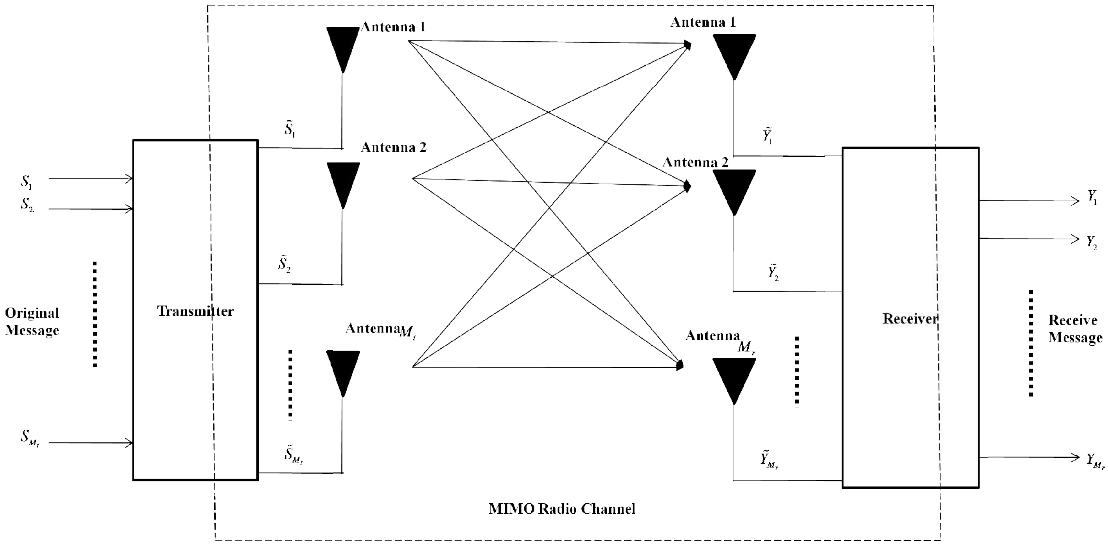

Figure 1.4 Block diagram of MIMO-OFDM system

A MIMO system takes advantage of the spatial diversity that is obtained by spatially separated antennas in a dense multipath scattering environment. MIMO system may be implemented in different ways to obtain either diversity gain to combat signal fading or to obtain capacity gain. MIMO can be easily realised through Space Time Coding (STC) such as Space Time Block Codes (STBC) and Space Time Trellis Codes (STTC) which transmits multiple copies of data stream across number of antennas.The space-time-frequency coded OFDM system is used to achieve maximum diversity. It provides increased spectral efficiency and is effective in handling the frequency selective fading nature of the wireless channel [9].

However, the above schemes require some side information to be transmitted to the receiver with high reliability. The transmission of side information reduces the spectral efficiency. The major confront for high-speed broadband mobile application is ISI. Further, the high PAPR in OFDM and MIMO-OFDM systems increase the complexity of Analog-to-Digital Converter (ADC) in the transmitter and also reduce the efficiency of the power amplifier. The ISI and high PAPR may outweigh all the potential benefits offered by MIMO-OFDM. Hence, it is essential to address PAPR and ISI to improve the power amplifier efficiency and to reduce the complexity of ADC.

1.4 PEAK-TO-AVERAGE POWER RATIO

The PAPR is the ratio of peak power to average power of time domain complex baseband signal or signal envelope variation. It is the most popular parameter used to evaluate the dynamic range of the time domain OFDM signal. The high PAPR increases the complexity of ADC in the transmitter and reduces the efficiency of the power amplifier. The phases of the different subcarriers are added constructively to form large peaks. When such peaks occur, they may be cut-off by amplifier non-linearities which lead to out-of-band radiations and ICI at the receiver. As a result, the BER performances may degrade considerably [10]. Hence, an expensive amplifier with a large linear range is required, which can increase the cost of the implementation of OFDM. The conventional solutions to reduce PAPR are to use a linear amplifier or to back-off the operating point of a non-linear amplifier. Both approaches result in a significant loss of power efficiency. To overcome these effects, many PAPR reduction techniques such as distortion and distortionless or coding technique have been proposed for OFDM signals.

1.4.1 Types of PAPR Reduction Techniques

There are two groups of techniques to reduce the PAPR of OFDM system. The techniques include distortion and distortionless method. The distortion method includes amplitude clipping and filtering, peak windowing, block coding, companding, active constellation extension and tone reservation method. The distortionless method includes SLM, PTS, interleaving and pulse shaping method. Clipping and filtering is the simplest method but it introduces both in-band distortion and out-of-band radiation into OFDM signals. Coding method provides better performance but the coding rate is lost. The interleaving technique is to randomize the data sequence to lower PAPR. This method is also called as phase rotation method, which must send the side information. If the side information about the selected interleaver is not transmitted to the receiver, it cannot entirely recover the data, resulting in poor BER performance. SLM method multiplies many phase sequence of the same information and selects a data sequence with lowest PAPR. In PTS, the OFDM signal is divided into several subblocks. The subblocks are multiplied by phase weighting factors and then added together to obtain the lower PAPR signal. SLM method and PTS method are similar in performance. The SLM requires high computational complexity due to the need of a block of IFFT. PTS generates more candidate signals for selection and achieves better performance than SLM. The computational complexity increases as the transmitted data is divided into more subblocks. The modified PTS approach with neighbourhood search algorithm is used to reduce the computational complexity and PAPR of OFDM signals. This algorithm finds the optimum set of phase factors. The phase factors are then multiplied with the corresponding subblocks to obtain an OFDM signal with low PAPR. The computational complexity in modified PTS is less than that of ordinary PTS. In order to improve the efficiency of power amplifier, it is essential to further reduce the PAPR.

Hence, an attempt has been made in the present work to further reduce the high PAPR of the OFDM and MIMO-OFDM systems through modified PTS approach combined with some other PAPR reduction techniques such as interleaving, forward error correction code, superimposed training sequences and pulse shaping method for future wireless broadband communications.

1.4.2 Significance of PAPR Reduction

In the OFDM system, the performance of the wireless networks fully depends upon the channel condition which influences network communication link between source and destination in the physical layer. The high PAPR makes the design and implementation of ADC, Digital-to-Analog Converter (DAC), High Power Amplifier (HPA) and RF amplifiers more complex. Hence, it is very much essential to reduce the PAPR for effective utilization. Unlike wired channels, which are static and predictable, wireless channels are subjected to time varying impairments such as noise, interference and fading. An OFDM signal has an approximately Gaussian amplitude distribution when the number of subcarriers is large. Therefore, very high peaks in the transmitted signal can occur [11]. Hence, the ADCs and DACs need to be designed with high demands on range and precision to transmit and receive these peaks without clipping the signal. If the dynamic ranges of the ADCs and DACs are increased, the resolution also needs to be enhanced to maintain the same quantization noise level. Therefore, a large PAPR of OFDM signal may increase complexity of the ADCs and DACs and reduces the efficiency of the RF power amplifier. Furthermore, suitable ADCs and DACs may not be available at all for some applications. A large power back-off of HPA is also necessary. Intentional or accidental clipping [12] of the OFDM signal often occurs in practice. The clipping of a received sample affects all subcarriers in the system. MIMO-OFDM is being actively considered in present and next generation wireless standards because of its enhanced spectral efficiency and efficient handling of the frequency selective fading nature of the channel. Despite its many advantages, MIMO-OFDM suffers with the problem of high PAPR and CFO sensitivity [13].

This major drawback of MIMO-OFDM significantly complicates implementation of the RF front end. To overcome these effects, many PAPR reduction techniques have been proposed for OFDM signals. These techniques achieve PAPR reduction at the expense of increased transmit signal power, BER, data rate loss, computational complexity etc. Therefore, an attempt has been made in the present work to reduce the high PAPR of the OFDM and MIMO-OFDM systems through modified PTS approach in combination with interleaving, forward error correction code, superimposed training sequences and interleaving with pulse shaping method.

1.5 SCOPE OF THE WORK

The PAPR reduction in OFDM and MIMO-OFDM systems is the most important area of research and development in wireless system. Such systems have their limitation on power dissipation and computational complexity due to interference and multipath fading. MIMO communication system has increased spectral efficiency in a wireless channel. It can provide both high-speed data transmission and spatial diversity between any transmit-receive pair. MIMO-OFDM suffers with the problem of high PAPR and carrier frequency offset sensitivity, regardless of its many recompenses.

The complex baseband OFDM signal is formed by the superimposition of all subcarriers in the MIMO-OFDM transmitter. The OFDM signal is almost Gaussian distributed and hence exhibits a very large PAPR. This major drawback of MIMO-OFDM significantly complicates implementation of the radio-frequency frontend. The search to accomplish this requirement is to consider PAPR reduction using interleaving, Forward Error Correction (FEC), superimposed training sequences and pulse shaping methods. PAPR reduction to reduce the dynamic range of the transmitted OFDM signal has to be done before it is applied to the HPAs used in radio transmitters. This HPA has nonlinear characteristics and cause significant distortion to OFDM signals. Even small amounts of intermodulation distortion can cause undesirable spectral regrowth. It increases the BER and causes spectral widening, resulting in Adjacent Channel Interference (ACI).

Further, modified PTS scheme has been proposed to further lower the computational complexity, while maintaining the similar PAPR reduction performance as that of ordinary PTS scheme. The interleaved partitioned ordinary PTS scheme has the lowest computational complexity but it has the worst PAPR performance as generated candidates are not fully independent. However, the interleaving method based on adaptive symbol selection yields better reduction in PAPR, but, it has high computational complexity due to increase in number of subcarriers.

Another approach to control the high PAPR is to use FEC coding across subcarriers and select such codewords which minimise the PAPR and also effectively improve the error rate performance. This will reduce the inherent redundancy; however, it should be exploited for error correcting. Moreover, the achievable code rate decreases with increasing code length. In order to maintain a reasonable rate, several shorter length codes can be used to encode a large number of OFDM sub channels.

Moreover, PAPR reduction requires the use of a perfect training sequence. Certain power has to be allocated to the superimposed training sequence which could otherwise be allocated to the information signal. Therefore, the foremost requirement in this method of PAPR reduction is the judicial selection of the superimposed training sequence so that a little power is wasted in it. Also, the enormous increase of the BER is prevented. Further, the pulse shaping method has been propounded to reduce the PAPR of the transmitted OFDM signals and improve its power spectrum simultaneously. However, different pulse shaping waveforms result in different error probabilities of the system. None of the aforementioned methods achieve simultaneously good PAPR reduction, high coding rate and low computation complexity.

Hence, in the present work an attempt have been made to further improve the PAPR reduction in OFDM and MIMO-OFDM systems to improve the efficiency of power amplifiers by adopting modified partial transmit sequence in combination with interleaving, FEC, superimposed training sequences and pulse shaping methods.

1.6 OBJECTIVE OF THE WORK

An attempt has been made in the present work to further reduce the PAPR of the OFDM and MIMO-OFDM systems through modified PTS approach combined with interleaving, forward error correction code, superimposed training sequences and interleaving with pulse shaping method. The set objectives of the present work are as follows:

- To reduce the PAPR using modified PTS with interleaving technique for OFDM and MIMO-OFDM systems
- To study the performance of modified PTS combined with forward error correction coding scheme in PAPR reduction in OFDM and MIMO-OFDM systems
- To analyse the performance of modified PTS with superimposed training sequence method on PAPR reduction in OFDM and MIMO-OFDM systems

- To evaluate the effect of modified PTS combined with interleaving and pulse shaping method on PAPR reduction in OFDM and MIMO-OFDM systems

1.7 ORGANIZATION OF THE THESIS

Chapter 1 provides an overview on wireless communication systems. The need, scope, the prime objectives pertaining to the present work and the organization of the thesis are presented in this chapter.

Extensive literature associated to the power distortion for efficient PAPR reduction, and MIMO schemes for Wireless Broadband Multimedia Communication Systems (WBMCS) have been critically reviewed and is presented in Chapter 2. Summary of the review of literature is also furnished at the end of the chapter.

Modified PTS with interleaving method for OFDM and MIMO-OFDM systems model for the PAPR reduction techniques using STBC is described in Chapter 3. The performance of PAPR reduction for OFDM and MIMO-OFDM systems are highlighted. Further, the simulation results in terms of CCDF of PAPR reduction ability are presented.

Chapter 4 deals with the threshold scheme for the FEC coding scheme such as Golay and turbo codes. A detailed discussion on the simulation results and the performance is succintly offered for the OFDM and MIMO-OFDM systems with and without PAPR reduction technique.

Chapter 5 examines superimposed training sequence based on PAPR reduction technique which also operates on the OFDM time domain symbols in either pairs or groups to create new symbols with low PAPR for OFDM and MIMO-OFDM systems. The PAPR reduction performance is analysed in detail.

Chapter 6 discusses the interleaving along with the pulse shaping method for OFDM and MIMO-OFDM system. The OFDM symbol added with pulse shapes indicates that each subcarrier pulse produces a new set of pulse shapes and its potential of reducing the PAPR of OFDM and MIMO-OFDM system are evaluated in detail.

Chapter 7 concludes the thesis by emphasizing the major implications of the study. A summary of research contribution and the scope for future studies are also furnished in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

An extensive literature associated with the PAPR reduction performance for OFDM and MIMO-OFDM system was collected, critically reviewed and presented in this chapter. A comprehensive review of literature on evolution of PAPR reduction techniques such as modified PTS, interleaving, Forward Error Correction (FEC) coding scheme, superimposed training sequences and pulse shaping method are also presented. Further, the summary of review of the literature is furnished at the end of the review to justify the scope of the present work.

2.2 REVIEW OF LITERATURE

In order to satisfy the demand of high data rate for wireless communication systems, many multicarrier systems have been proposed. Among them, OFDM has several properties which make it an attractive modulation scheme for high speed data transmission. The features of OFDM include low training overhead, low complexity compared to equalizers, easy scalability of bit rate and bandwidth. However, one of the serious drawbacks of the OFDM is high PAPR, which is due to the addition of different subcarriers in phase to form large peaks.

The occurrence of such peaks may cut-off subcarriers by amplifier non-linearities, leading to out of band radiations and ICI at the receiver. This will degrade the system performances [14]. The worst case of PAPR occurs, when equal amplitude cosine carriers happen to have zero phases at the same instant of the time. This increases the complexity of ADC in the transmitter and reduces the efficiency of the power amplifier. To prevent this unexpected effect, the peak of the signal has to be accommodated in the linear operating region of the power amplifier. This means the power amplifier has to operate with certain amount of back-off power. However, this is completely undesirable as increasing the back-off power decreases the coverage of the cell. Recently, there are two groups of methods, such as distortion and distortionless methods that have been used to reduce the PAPR values in the OFDM system. Distortion methods include amplitude clipping and filtering, peak windowing, and companding. Distortionless methods include Tone Reservation (TR), Active Constellation Extension (ACE), Selective Mapping (SLM), Partial Transmit Sequences (PTS), interleaving, block coding, superimposed training sequence and pulse shaping method.

L. J. Cimini and X. D. Li [15, 16] presented the simplest method, namely, amplitude clipping and filtering for reducing PAPR of multicarrier transmission system. Here the signals are clipped before amplification to effectively reduce PAPR. However, clipping is a nonlinear process and may cause significant in-band distortion. This degrades the BER performance as well as result in out-of-band noise, leading to reduction in spectral efficiency. Also, it suffers from additional clipping distortion, peak regrowth after DAC and out-of-band noise in the case of oversampled sequence clipping.

Further, H. Saeedi *et al.* [17] proposed a clipping method to OFDM signals to combat the effect of peak regrowth to mitigate the clipping distortion in the presence of channel noise at the expense of bandwidth expansion. The clipping distortion can be removed in oversampled signal by using the Least Square Method (LSM). Moreover, this method sets the trade-off between bandwidth expansion and clipping distortion. Subsequently, Shang-Kang Deng and Mao-Chao Lin [18] proposed the Repeated Clipping and Filtering (RCF) method to limit the distortion on each tone of the OFDM so as to achieve both low PAPR and low error. Sometimes, the approach does not guarantee the resulting distortion to be bounded.

The peak windowing method propounded by R. Van Nee and A. de. Wild [19] has minimised the PAPR value to around 4 dB for an arbitrary number of subcarriers, with a slight increase in BER and out-of-band noise. The loss in Signal-to-Noise Ratio (SNR) caused by the signal distraction is limited to about 0.3 dB. A back-off relative to the maximum output power of 5.5 dB is required in order to keep the undesired spectral distortion to be at least 30 dB below the in-band spectral density.

Subsequently, X. Huang *et al.* [20, 21] have put forward the companding technique to reduce PAPR. This technique compresses large signals while enhancing small signals. It has been proved that it can achieve significant reduction in PAPR with low implementation complexity. However, reduction in PAPR may be limited under certain performance constraints.

B. S. Krongold and D. L. Jones [22] designed a method to introduce new signal constellations to combat large signal peaks. This dynamically extends outer constellation points in active (data-carrying) channels, within margin-preserving constraints, in order to minimise the peak magnitude. Furthermore, there is no loss in data rate and no side information is required unlike other methods.

In contrast to previous method, the new active set approach has been proposed for PAPR reduction in OFDM via tone reservation [23]. It uses other unused or reserved tones to design a peak-cancelling signal that lowers the PAPR of a transmit OFDM block. It has been proved that the distortion techniques are the simplest approach for minimizing PAPR values in multicarrier modulation schemes. This does not create much computational complexity. However, it degrades the BER performance and also increases out-of-band noise leading to reduction in the spectral efficiency due to the low occurrence of PAPR. These statistical characteristics of PAPR reduction of the OFDM signal can be improved without signal distortion using distortionless techniques.

R. Baumal *et al*. [24] proposed SLM, a simple distortionless technique at the transmitter. One favourable signal with the lowest PAPR is selected for transmission from a set of different signals representing the same information. Thus, the probability of PAPR exceeding some threshold can be made as small as possible at the expense of added complexity. Subsequently, to recover the data, the receiver must know which “multiplying” sequence has been used. This can be transmitted as side information containing selected optimum phase patterns. In addition, it requires an additional bit that informs the receiver of the selected phase patterns.

Chin-Liang Wang *et al.* [25] proposed a low-complexity estimation method to estimate the PAPR for OFDM signal by using partial interpolated neighbourhood sampling. But, some criteria are used to determine the interpolation filter length and the threshold of sample power for the search process. This scheme achieves close performance with only about half of the computational complexity. The proposed approach can easily be combined with the selective mapping method for PAPR reduction, where the complexity is significantly reduced with slight degradation in the performance.

Subsequently, M. Breiling *et al.* [26] presented scrambling scheme that does not use explicit side information and demonstrated its operability for the special case of convolution coded OFDM transmission. Some additional complexity and nearly vanishing redundancy is introduced to achieve significantly improved transmit signal statistics. This scheme refrains from explicit transmission of side information by a label insertion and scrambling approach where only little redundancy needs to be introduced into the signal. On the other hand, the transmit signal statistics and the spectral properties in presence of transmitter nonlinearities are decisively improved such that a saving of 1 to 2 dB in back-off can easily be achieved.

In addition to this, Lei Wang *et al.* [27] analyzed a PAPR reduction system which combines SLM and a deliberate clipping technique. The system has effective PAPR reduction capability, moderate system complexity and reasonable BER performance. The effect of symbol selection scheme on the deliberate clipping was analyzed by deriving the probability density function of the samples amplitude of the adaptively-selected OFDM symbol. This method has the trade-off between the PAPR reduction ability and the BER performance.

S.H. Muller and L. B. Huber [28, 29] proposed and optimized a new approach for distortionless (PTS) peak power reduction in OFDM system. The approach is very flexible and works with arbitrary number of subcarriers, without restriction on the type of modulation applied to them. This is due to the coordination of appropriately phase rotated signal parts to minimise the peak power of the OFDM signal. This scheme simultaneously and slightly decreases the complexity while substantially reducing the redundancy.

Subsequently, S. G. Kang *et al.* [30] estimated the trade-off between performance of PAPR reduction and computational complexity. In this approach, the signals assigned randomly in partial subcarriers are duplicated and concatenated repetitively to generate subblock. Then, the phase of each subblock is modified by a set of phase rotation factors to achieve PAPR to be as low as possible.

Moreover, H. G. Ryu [31] dealt with the Subblock Phase Weighting (SPW) method which controls the phase of the subblocks in the input OFDM data block to reduce the PAPR of OFDM system. In this method, the input block of OFDM signal is divided into many subblocks and peak power is lowered by weighting the phase of each subblock properly. There are no signal distortions such as in-band distortion and spectral regrowth. Especially, it can be realized by one IFFT so that it is very efficient in the respect of system complexity and calculation burden, compared to conventional PTS and SLM methods requiring many IFFTs.

C. Tellambura [32, 33] suggested a new algorithm for computing a good set of phase factors for PTS. This method has improved the PAPR statistics of an OFDM signal. The PTS requires an exhaustive search of all combinations of allowed phase weighting factors, which in turn increase the computational complexity exponentially with the number of subblocks. Furthermore, P. Boonsrimuang *et al.* [34] proposed Decomposition PTS (D-PTS) with non-uniform phase weighting factors to achieve better PAPR performance with lower computational complexity without any increase in side information.

In addition, P. Liu *et al*. [35] presented a simple efficient phase search algorithm for phase adjustment of each subblock of data, which is to be rotated by an arbitrary phase angle. The number of allowed phase weighting factors should not be excessively high in order to keep the number of required side information bits and the search complexity to be within a reasonable limit. With a pre-specified number of iterations, it gives the best phase weighting factor for a combination of subblocks to achieve the smallest PAPR value.

S. K. Yusof *et al*. [36] propounded the partial transmit sequences approach to improve the PAPR statistics. This PTS technique manipulates the phase rotations of the partial transmit sequences and performs exhaustive search for optimised transmit signal to obtain an improved power distribution of the OFDM signal.

Subsequently, S. H. Han and J. H. Lee [37] proposed the PTS technique, where in, the data block to be transmitted is partitioned into disjoint subblocks and the subblocks are combined using phase weighting factors to minimise PAPR. The PAPR statistics of this technique is much better than that of the iterative flipping algorithm. Also, it is very close to that of the ordinary PTS technique with significant reduction in search complexity and little performance degradation.

However, the exhaustive search complexity of the PTS technique increases exponentially with the number of subblocks. Hence, it is practically not realizable for a large number of subblocks. Therefore, Y. Xin and I. J. Fair [38] suggested a new combining technique which is called sequence modification to reduce the complexity of conventional PTS for large number of subblocks. According to this approach, the number of IFFT operations and the complexity of the optimization process can be significantly reduced, so as to reject sequences with a high PAPR through a simple calculation. The advantage of this scheme is that the search precision can be easily controlled by a predetermined number of iterations and also the performance does not rely on the initial phase values.

L.J. Cimini and N. R. Sollenberger [39] studied the efficiency of the selective mapping and partial transmit sequence approach to improve the statistics of the PAPR of an OFDM signal at the expense of additional complexity (but with little loss in efficiency). At same time, the suboptimal strategies have been adopted for combining partial transmit sequences which are less complex, easier to implement with little performance degradation.

J.H. Wen *et al.* [40] carried out investigations on a sub-optimal PTS based on Particle Swarm Optimization (PSO) algorithm for low computational complexity and the reduction of the PAPR of an OFDM system. The PSO algorithm exploits heuristics to search the optimal combination of phase weighting factors with low computational complexity. This method provides a better trade-off between PAPR reduction and computational complexity.

Le Hu *et al.* [41] presented a modified sub-optimal algorithm for PAR reduction performance with low computational complexity than sub-optimal algorithm. Subsequently, the system complexity has been significantly reduced with only slight performance degradation [42]. Further, the phase angles of modulated symbols are changed such that the PAPR is reduced. However, the side information about these changes has to be sent to the receiver to reconstruct the original information without any loss of data rate. The PAPR statistics could be affected, if the side information is not considered at the optimization process [43]. Further, BER improvement is expected by using a simple forward error correction code to protect the side information.

Further, G. Lu *et al.* [44] studied on the PAPR reduction based on Transformation of PTS (T-PTS) in OFDM. In this method, certain transformations are applied on PTS to generate more candidates for increasing performance. In principle, the transformation can be made in many different ways to get different sets of transformed PTS from the original OFDM signal. The transformation includes conjugate operation, frequency reversal operation, circular shift operation and their combinations. Therefore, the T-PTS may have more candidates available than the conventional PTS to perform better. If the same number of candidates is used, then T-PTS has similar performance compared to conventional PTS, but has less computational complexity because of fewer IFFT operations.

Zi-Bin Zhao and Young-Hwan Kim [45] dealt with hybrid algorithm based on the PTS and guided scrambling techniques to significantly improve the statistics of the PAPR. Guided scrambling is a multimode coding technique, capable of guiding the scrambling process to produce a balanced encoded bit stream. Moreover, it does not need transmission of side information. The correlated pattern among subcarriers influences the PAPR, which is highly dependent on the pattern of the orthogonal subcarriers used. This hybrid algorithm provides much more PAPR reduction with a few error extensions during decoding and very small data loss. In order to enhance the quality of transmission, there are many combinations of methods for reducing the PAPR value of OFDM system.

Q. S. Wen *et al.* [46] investigated the computational complexity of two conventional PAPR reduction methods, namely clipping and PTS. Based on the complexity analysis, both clipping and PTS achieve good PAPR reduction performance at the cost of extra high computational complexity. This is due to the linear increase in the number of phase sequences and subblocks, which correspond to the number of IFFTs required to generate the alternative OFDM signals.

Hence, TianYa-fei *et al.* [47] investigated on possible means for reducing the complexity of the PTS technique. The modified version of PTS has been proposed to achieve higher reduction in complexity and is referred as “modified PTS technique”. It is one of the most efficient methods used to reduce the computational complexity and PAPR of OFDM signals based on neighbourhood search algorithm to find the optimum set of phase factors.

Subsequently, M. Sharif *et al.* [48] introduced a new bound for the peak of the continuous envelope of the OFDM signal, based on the maximum of its corresponding oversampled sequence. This new bound for the peak value of the OFDM signal was used to derive a closed-form probability upper bound for CCDF of PAPR of uncoded OFDM signal with large number of subcarriers. Thus, it is tightly evaluated for sufficiently large numbers of subcarriers using oversampling rate.

Further, A. D. S. Jayalath and C. Tellambura [49, 50] presented a technique for the reduction of the PAPR of the OFDM signal. The main problem for PTS is how to minimize the number of iterations necessary for locating the optimal phase weighting factors. For that it requires l-1 random interleavers to produce l-1 permuted sequences for the same information sequence. The PAPR of the permuted sequences and the original information sequence are then computed using l oversampled FFTs. Interleavers can combat the effect of noise bursts and fading.

Subsequently, Roman Marsalex [51] proposed Multiple Signal Representation (MSR) technique using different interleavers to improve PAPR reduction based on adaptive symbol selection principle. According to this, several replicas of signal are created by using a set of interleavers incorporated inside the IFFT block at OFDM transmitter. It is an element-by-element multiplication operation with unique interleaving pattern in each branch. The side information about selected branch can be implemented in pilot subcarriers. The main advantage of this approach is less complexity with no performance degradation.

Further, Heung-Gyoon Ryu *et al.* [52] explored the interleaving method which has the advantage of reduced PAPR without spectrum distortion. This new interleaving method is very flexible and does not require any side information to recover the information signal in the receiver. The pilot symbols are necessarily used for channel information and also it adopts for interleaver identification. That is, pilot symbols of different forms decide which interleaver is used to randomize. This method has almost same PAPR reduction and BER performances, compared with the common SLM method that needs additional side information.

Jin Chuan-xue and Li Shao-qian [53] attempted an iterative random interleaver design scheme for reducing the high PAPR of OFDM systems. The main idea is based on iterative interleaving with only one fixed pattern for saving the memory size of conventional transmitter and receiver. If the different interleaving patterns are introduced, then restoring capacity of transmitter and receiver will increase, which in turn increases the price for hardware implementation.

H. Sakran *et al.* [54] proposed a combined interleaving and companding technique to reduce the PAPR. This scheme has been compared with the system that uses clipping technique for the PAPR reduction. It has been demonstrated that the PAPR of OFDM signal is reduced by 6.8 dB over the original system. Also, SNR is decreased by more than 5 dB for BER of 10^{-3} over the original system. Moreover, the proposed scheme gives improvement of more than 4.5 dB for BER of 10^{-3} over the system with clipping technique. All these systems are evaluated in the presence of nonlinear power amplifier.

Subsequently, G. Jing *et al.* [55, 56] proposed a low complexity concurrent selective mapping algorithm to achieve much better PAPR reduction performance in the MIMO-OFDM system. It is proved that the conjugate symbols on two transmit antennas have the same PAPR property with orthogonal STBC. By using this characteristic, the computational complexity cost and the side information is significantly reduced than that of conventional concurrent SLM algorithm.

Harish Reddy and Tolga M. Duman [57] presented a general framework for the PAPR reduction for space-time coded OFDM systems and viterbi algorithms that can be used in space-time codes. The input sequence to the space-time encoder is modified such that the maximum PAPR among the signals of different transmit antennas is reduced. Although, modification of the input sequences will reduce the overall spectral efficiency, they do not result in performance degradation of the system in terms of frame error rate. Due to these, the PAPR significantly reduces at the cost of a slight decrease in the spectral efficiency.

Z. Xiuyan *et al.* [58] presented the optimum combination method for PAPR reduction based on PTS in MIMO-OFDM system. The PAPR performance has improved up to 2.5 dB by using iteration algorithm. The MIMO-OFDM system by using optimum combination of PTS can be used for ultra-wideband communications.

Subsequently, Ben Lu and Xiaodong Wang [59] analysed Pair-wise Error Probability (PEP) based on a Space-Time Coding (STC) over Rayleigh flat fading channel in OFDM system. The PEP indicated that STC-OFDM systems can potentially provide a diversity order as the product of the number of transmitter antennas, the number of receiver antennas and the frequency selectivity order. The STC's significantly improve the performance than STTC by efficiently exploiting both the spatial diversity and the frequency-selective-fading diversity.

Rick S. Blum *et al.* [60] attempted to develop an improved space time coding for MIMO-OFDM using QPSK modulation for multiple transmitting and receiving antennas. In this approach, the input data is divided into two streams and sent to a pair of space time encoders, one for each encoder. Before transmission, the system employed two 16 state, 2-antennas space-time codes with successive interference cancellation and channel estimation. After this cancellation, the MIMO-OFDM system attains minimum equalization complexity for multiple signal rates. It is most interesting to note that both transmission rate and diversity gain can be achieved, contrary to the STBC where full transmission rate cannot be achieved for more than two transmit antennas. The increase in number of antennas might cause a prohibitively large PAPR and high computational complexity.

T. Mata *et al*. [61] developed the concurrent PAPR reduction algorithm based on the property of Orthogonal STBC (OSTBC) in MIMO-OFDM system. A new determination method for the weighting factor of PTS in conjunction with the concurrent algorithm for the STBC MIMO-OFDM systems, which can improve both the PAPR reduction performance and computational complexity without any increase in side information.

Dong Guo-fang *et al.* [62] proposed the dynamic PTS algorithm with a simplified minimum maximum criterion to optimise the phase factor in MIMO-OFDM system. By adjusting the neighbourhood the complexity for deciding the optimal phase factor can be reduced on demand. Additionally, with the aid of guided scrambling, the phase factor can be obtained directly by descrambling with better PAPR reduction performance. Since, the side information is not required at the receiver, the overhead associated with the data transmission is reduced. However, it introduces a disturbance into the correlation among the subcarriers.

Subsequently D. Phetsomphou *et al*. [63] presented a new PTS technique which is used to effectively reduce the PAPR in MIMO-OFDM systems. This approach achieved the better PAPR reduction performance using phase rotation factors, but it demands a quite large calculation cost and performance is not maintained for large number of subblocks.

Xu Yan *et al*. [64] suggested an algorithm of PTS with multi-antenna cooperative working by proving the strict conjugated relationship between phase weighting factors on the double antennas. This will reduce the amount of side information by half and increase the effective data transmitting rate. In addition to this, spectral growth of the OFDM signal is prevented due to removal of Adjacent Channel Interference (ACI) among subcarriers to enhance the system capacity.

One of the attractive ways of dealing with the high PAPR problem is to use FEC coding and to select codewords which minimise the PAPR and also effectively improve the error rate performance. In addition to these, H. Ochiai and H. Imai [65] proposed the algorithm based on forward error correction coding scheme which significantly reduce the PAPR of multicarrier signals. To avoid the high PAPR, only a small part of possible codewords can be allowed for transmission [66]. This will reduce the inherent redundancy. However, the achievable code rate decreases with increasing code length. In order to maintain a reasonable rate, several shorter length codes can be used to encode a large number of OFDM sub channels. Interleaving of the short codes in the frequency domain additionally makes the system resistant to burst errors.

Kenneth G. Paterson and V. Tarokh [67, 68] attempted to combine coding techniques such as Golay complementary and Reed Muller codes to obtain a tightly controlled PAPR for OFDM systems. This approach works very well for length of 64 codewords but becomes computationally infeasible beyond that point. It is due to the need to evaluate the PAPR of large numbers of codewords numerically.

The use of Golay complementary sequences as codewords to control the modulation of carrier signals results in OFDM with PAPR of at most 2. These codes enjoy efficient encoding, good error correcting capability and tightly controlled PAPR. But this approach makes no predictions about the number of cosets satisfying a given PAPR. It needs a large amount of computation for large values of subcarriers to complete cosets into groups by the maximum tolerable PAPR.

S. Uppal [69] demonstrated the possibility of using complementary codes having good properties to serve as both PAPR codes and FEC codes in OFDM system. It is stated that reasonable coding rates can be achieved up to a length of 16. Further, the specific subsets of complementary codes exist which have a minimum distance equal to half the code length, while their PAPR is only 3 dB. Unfortunately, the achievable code rate decreases for increasing code length. By interleaving the short codes in the frequency domain has maximum benefit from the diversity of the frequency selective channels.

A. Ghassemi and T. Aaron Gulliver [70] developed a new PTS subblocking technique using error correcting codes in OFDM system. This technique minimizes the number of repeated subcarriers within a subblock and provided better PAPR reduction. In general, new PTS subblocking significantly decreases the computational complexity than conventional PTS. However, it provides comparable PAPR reduction even with a small number of IFFT stages after PTS partitioning.

Subsequently, Mao-Chao Lin *et al*. [71] have proposed turbo coded OFDM system to mitigate the PAPR problem. It has been proved that all the three turbo coded systems using maximum-length sequences, distinct interleavers and both can achieve significant PAPR reduction and satisfactory error performance over Additive White Gaussian Noise (AWGN) channels.

Yung-Chih Tsai *et al*. [72] proposed a selective mapping scheme which does not require the transmission of side information to reduce the PAPR in turbo coded OFDM systems. The reason that side information can be waived is due to the powerful discriminating capability of turbo decoding against the incorrect interleaver. The waiver of side information can avoid the degradation of error rate performance which results from the incorrect recovery of side information at receiver in the conventional SLM OFDM system.

Furthermore, the turbo decoding principle has been successfully applied in some other applications such as joint decoding and detection of users in the OFDM system. Pawan Sharma and Seema Verma [73] proposed the PAPR reduction of OFDM signal using selective mapping with turbo codes. The turbo encoder is used for both error correction and PAPR reduction. However, turbo coding and SLM can be combined to reduce the PAPR of OFDM signal with quite moderate additional complexity. But, PAPR reduction performance improves by reducing the number of subcarriers and minimizing hardware complexity.

Houshou Che and Hsinying Liang [74] proposed a modified selective mapping algorithm to use a correction subcode for error control and a scrambling subcode for PAPR control. The transmitted OFDM sequence is selected with minimum PAPR from a number of candidates which form a coset of scrambling subcode for each codeword of correction subcode. The received signal of the modified SLM can be decoded without the need of explicit side information and achieves good PAPR reduction performance.

The block coding seems to be an attractive technique because it does not create any out-of-band noise [75]. The development of the technique in terms of the selection of suitable sets of codewords with the potential for error detection/correction capability based on Golay complementary sequences has been investigated. However, all sets of codewords are non-ideal which affect the potential benefits of error detection and correction. The non-linear block codes have improved PAPR reduction and avoided excessive peak envelope powers. Later, Tao Jiang and Guangxi Zhu [76] proposed modified complementary block coding method to reduce the PAPR of the OFDM signal and detect the transmission errors. This method is more suitable for OFDM systems with large frame sizes and high coding rate.

J.A. Davis and J. Jedwab [77] proposed a coding scheme for OFDM transmission by exploiting a connection between pairs of Golay complementary sequences and Reed-Muller codes. This scheme solves the problem of power control in OFDM systems by maintaining a PAPR of at most 3 dB, while allowing encoding and decoding at high code rates. It has tightly bounded PAPR and simultaneously has good error correction capability. It is due to partitioning the second-order Reed-Muller code into cosets such that codewords with large values of PAPR are isolated.

Fangling PU *et al.* [78] proposed a method to reduce PAPR in OFDM with combination of the PTS with Golay complementary sequences and Reed-Muller codes by dividing the subcarriers of OFDM into several disjoint subblocks. One subblock for pilots and the other subblocks of Golay complementary sequences are generated from particular cosets of the Reed-Muller code for information and phase rotation factors of PTS. The optimal combination of phase rotation factors is obtained to minimise the PAPR of an OFDM symbol. However, certain subcarriers are occupied by the encoded side information. Although, the data rate is reducing a little, the side information is transmitted reliably.

Further, H. Bakhshi and M. Shirvani [79] explored possibility of reducing PAPR in OFDM systems by combining selective mapping and Golay complementary sequences. This scheme can be used for arbitrary numbers of carriers. The PAPR has been restricted by isolating codewords with large values of PAPR with the help of Golay complementary sequence. The reduction of PAPR, increase the error correction capability and code rate in OFDM system, making this scheme as highly suitable for certain practical application. Moreover, the FEC offers a powerful low rate error correction capability with reduced transmitter and receiver complexity. It has been shown that the lower coding rate can be translated to a higher achievable frequency diversity gain over frequency selective channels at the cost of bandwidth efficiency.

In order to improve the bandwidth efficiency, Ning Chen and G. Tong Zhou [80] proposed the superimposed training sequences. These sequences sacrifice a little power dedicated to the information signal but gain a lot from the power devoted to channel sounding for the same amount of average power consumed by a class A or class AB power amplifier. The goal of PAPR reduction is to increase power efficiency while keeping the probability of clipping at an acceptably low level. For better power efficiency, the conventional SLM combined with superimposed training sequence method is used to reduce the PAPR as well as to improve the power efficiency. In the superimposed training, the training pilots are “added onto” the information data instead of being “inserted into” the data stream as in conventional dedicated training. The average power of the transmitted superimposed OFDM signal can be increased without increasing the peak power rendering the power amplifier more efficient.

Subsequently, Luoren-ze*et al.* [81] presented an effective approach for PAPR reduction using improved PTS combined with superimposed training sequence method. The proposed scheme has good compromise between the PAPR reduction and computational complexity of the system. At the same time, there is no significant effect on system performance. It can be considered as an improved scheme for PAPR reduction as it has little effect on BER of the system in the Rayleigh fading channel.

Youngseok Oh *et al.*[82] proposed the new PTS technique for OFDM signal which does not require side information about the PTS phase factors to the receiver. The receiver jointly estimates the channel and phase factors from the pilot subcarriers based on the OFDM symbol structure. The performance of this technique is effective under perfect Channel State Information (CSI) at the receiver. However, it is observed that this method is sensitive to the channel estimation errors and also complex to implement. The amount of PAPR reduction is limited as this method exploits only pilot subcarriers to reduce the PAPR with negligible BER loss.

G. Tong Zhou *et al.* [83] implemented a superimposed periodic pilot scheme and employed the simple first statistical method for channel estimation. It provides high bandwidth efficiency, low computational complexity and improved power amplifier efficiency. This scheme neither lose throughput due to side information nor degrade BER due to errors in the side information. However, a reduction in throughput occurs due to the pilot tones used for channel estimation.

Subsequently, T. Y. Han *et al.* [84] proposed a technique to estimate the side information superimposed over the pilot and data symbols in an OFDM system to reduce the PAPR using PTS scheme. The phases of the rotation vectors are added to those pilots and data symbols by interlaying them between any two pilot symbols. It is stated that bandwidth efficiency is improved by not using the subcarriers that are assigned for the reduction of the PAPR. Also, the enormous increase of the BER is prevented. The receiver restores the data symbols by using the channel estimation of pilot symbols. Hence, the bandwidth efficiency and BER has been improved substantially.

S. Ben Slimane [85] proposed the efficient pulse shaping technique for reducing the PAPR of OFDM signals. This method is based on a proper selection of the time-limited waveforms of the different subcarriers. Its implementation complexity is also much less than interleaving method. The significant improvement in PAPR permits the reduction of the complexity and cost of the transmitter significantly. This will also reduce the PAPR of the OFDM transmitter signal as the peak amplitude of the different pulse shapes will never occur at the same time, unless rectangular pulse is used.

Single Carrier Frequency Division Multiple Access (SC-FDMA) utilises single carrier modulation and frequency domain equalization and exhibits similar performance with the same overall complexity as that of OFDM, in which high PAPR is a major drawback. The lower PAPR is the significant advantage of SC-FDMA due its single carrier structure. Hyung G Myung *et al.* [86] has analysed the PAPR of SC-FDMA signals with pulse shaping. The SC-FDMA signals have lower PAPR than that of Orthogonal Frequency Division Multiple Access (OFDMA). It is also stated that localized FDMA has higher PAPR than interleaved FDMA. However, these two forms of SC-FDMA show lower PAPR than OFDMA.

S. Zid and R. Bouallegue [87] proposed a novel low complexity PAPR reduction scheme using SLM and PTS approach for Interleaved Orthogonal Frequency Division Multiple Access (I-OFDMA) systems. The basic idea is to explore the special structure of interleaved OFDMA, so as to reduce the complexity of PAPR reduction. The scalable frequency resource is effectively granulated into many small units by orthogonal subcarriers for flexible and optimum resource allocation among multiple users. In the interleaved subcarrier assignment, subcarriers assigned to different users are interleaved over the whole bandwidth and also the subcarriers belong to the same user are of equal size. Therefore, it has the potential to reap more diversity gains with subcarriers for one or several sub-bands. Hence, to monitor the radio activities of all sub-channels in interleaved OFDMA, it is required to focus on a small continuous portion of the bandwidth with each sub-channel having one or two sub-carriers within the range.

Lei Xia *et al.* [88] presented a novel method to design phase factor for PTS with pseudo-random subblock partitioning to achieve better PAPR performance. This approach highlights the importance of designing the phase factors to ensure the independency of candidate signals to reduce PAPR. Pseudo-random subblock partitioning method was adopted to design quasi-orthogonal phase factors to achieve lower correlation among all candidate signals. Also, it is evident that increasing the number of subblocks is more efficient than increasing the number of candidate signals to reduce the PAPR

Subsequently, Jae-Kwon Lee *et al.* [89] proposed a new systematic subblock partition method for PAPR reduction. The performance of the Adjacent Partitioning PTS (AP-PTS) has lower computational complexity than ordinary PTS. Also, new subblock partition is much easier to design than random subblock partitioning scheme. Therefore, the new PTS method is more feasible for high-speed mobile communication system.

G. Lu *et al.* [90] presented the Interleaved Partitioning PTS (IP-PTS) for PAPR reduction based on adaptive symbol selective principle. The candidates generated in the existing IP-PTS are not fully independent. This results in less number of effective candidates leading to inferior performance than that of AP-PTS. Subsequently, a new type of phase sequences has been proposed to create fully independent candidate to enhance the performance of existing IP-PTS. Further, the Enhanced IP-PTS (EIP-PTS) using these new phase sequences has improved the performance similar to that of AP-PTS, while keeping low complexity. Subsequently, J. Sarawong *et al*. [91] proposed a new phase factors for PTS method with interleaved partitioning scheme to improve the PAPR performance without increasing side information and the computational complexity.

Moreover, Shukla *et al.*[92] presented the PAPR reduction techniques for OFDM system such as interleaving and different phase rotation schemes for helical interleaver in OFDM system. Here, SLM and PTS are applied with distinct conditions for the reduction of system complexity and memory requirement as well.

2.3 SUMMARY

It is evidently known from the critical review of literature that exhaustive research work has been done by several researchers in the area of the PAPR reduction in the multicarrier modulation schemes. A variety of PAPR reduction techniques such as clipping, interleaving method, SLM, PTS, coding techniques, superimposed training sequence, pulse shaping and various combinations of the above were proposed by researchers to reduce the PAPR of the transmitted signals in OFDM systems. None of the aforementioned methods achieves simultaneously good PAPR reduction, high coding rate and low computation complexity. Hence, in the present work an attempt has been made to further improve the PAPR reduction in the OFDM and MIMO-OFDM systems by adopting modified partial transmit sequence in combination with interleaving, FEC, superimposed training sequences and pulse shaping methods.

CHAPTER 3

MODIFIED PTS WITH INTERLEAVING TECHNIQUE FOR OFDM AND MIMO-OFDM SYSTEMS

3.1 INTRODUCTION

OFDM signals have high PAPR and are thus not power efficient [12]. High PAPR values lead to severe power penalty problem in the transmitter, which is not affordable in portable wireless systems where terminals are battery powered. To avoid this problem, PTS approach is introduced by achieving high PAPR reduction. However, it causes high system complexity and computational complexity which make it difficult to employ OFDM system. So, the modified PTS technique [47] is proposed to lower the computational complexity while maintaining the similar PAPR reduction performance compared with the ordinary PTS technique. To reduce PAPR further, interleaving technique can be combined with modified PTS scheme. MIMO systems may be implemented in a number of different ways to obtain either diversity gain or capacity gain. A modified PTS combined with interleaving technique to improve PAPR reduction performance in OFDM and MIMO-OFDM is presented in this chapter. The performance of the modified PTS combined with interleaving technique is evaluated to maximise the PAPR reduction and is compared with modified PTS method.

3.2 PAPR IN OFDM SIGNAL

In OFDM modulation technique, a block of N data symbols, $\{X_n,\ n = 0, 1, \ldots, N-1\}$, is formed with each symbol modulating the corresponding subcarrier from a set $\{f_n,\ n = 0, 1, \ldots, N-1\}$ where N is the number of subcarriers.

The N subcarriers are chosen to be orthogonal, i.e. $f_n = n\Delta f$, where $\Delta f = 1/NT$ and T is the original symbol period.

The resulting baseband OFDM signal $x(t)$ of a block can be expressed as

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j2\pi f_n t}, 0 \le t \le NT \qquad (3.1)$$

The PAPR of the transmitted OFDM signal $x(t)$, is then given as the ratio of the maximum to the average power and is written as

$$PAPR = \frac{\max\limits_{0\le t\le NT} |x(t)|^2}{E\left[\left|x(t)^2\right|\right]} = \frac{\max\limits_{0\le t\le NT} |x(t)|^2}{\frac{1}{NT}\int_0^{NT} \left|x(t)^2\right| dt} \qquad (3.2)$$

The PAPR of the continuous-time OFDM signal cannot be precisely computed at the Nyquist sampling rate, which corresponds to N samples per OFDM symbol. So, in discrete-time systems, instead of reducing the peak of the continuous-time signal i.e. $\max|x(t)|$, it is better to reduce the maximum amplitude of LN samples of $x(t)$, where parameter L denotes the oversampling factor. This is due to the fact that the PAPR of a continuous time OFDM signal cannot be precisely described by sampling the signal using N samples per signal period where some of the signal peaks may be missed. So oversampling $(L > 1)$ is usually employed for better approximation of true PAPR. The case $L = 1$ is known as critical sampling or Nyquist rate sampling. Oversampling is implemented by LN-point IFFT of the data block with $(L-1)N$ zero padding. It was shown in [93] that $L = 4$ is sufficient to capture the peaks.

The continuous PAPR of $x(t)$ is approximated by its discrete LN samples i.e. $x\left(\frac{nT}{LN}\right)$, which is obtained from the LN –point IFFT of X_n with $(L-1)N$ zero-padding and can be represented as

$$x(n) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j2\pi kn/LN} \quad ,k = 0,1,...,NL-1 \tag{3.3}$$

To evaluate the PAPR reduction performance accurately from the statistical point of view, the CCDF of the PAPR is used. It denotes the probability that the PAPR of OFDM symbol exceeds a certain threshold $PAPR_0$ and can be expressed as [19]

$$CCDF(PAPR(x(n))) = \Pr(PAPR(x(n))) > PAPR_0 \tag{3.4}$$

Due to the independence of the *N* samples, the CCDF of the PAPR of a data block at Nyquist rate sampling is given by

$$CCDF(PAPR(x(n))) = 1-(1-e^{-PAPR_0})^N \tag{3.5}$$

Therefore, the CCDF of PAPR of *L*-times oversampled OFDM signal can be defined as

$$CCDF(PAPR(x(n))) = \Pr(PAPR(x(n)) > PAPR_0) = 1-(1-e^{-PAPR_0})^{LN} \tag{3.6}$$

3.2.1 PTS Scheme

In PTS scheme, the input data block is partitioned into multiple disjoint subblocks. Then, the phase of each subblock is modified by a weighting factor, which is obtained by the optimization algorithm to minimise the PAPR value. The input data vector *X* is divided into *V* disjoint sets, represented by the vector,

$$X_v \text{, } v=1, 2,...,V \tag{3.7}$$

In PTS approach, the input data vector *X* that is to be transmitted is divided into *V* subblocks, by using subblock partitioning schemes [30]. The subblocks are then combined to minimise the PAPR. There are three categories of subblock partitioning scheme viz., interleaved partitioning, pseudo-random partitioning and adjacent partitioning. In the interleaved partitioning scheme, the subcarriers spaced at intervals of *V* are assigned to the same subblock. If each subcarrier is assigned randomly to a subblock then it is called pseudo-random partitioning scheme.

Each subcarrier is distributed within a sequence in adjacent partitioning scheme. It can be noted that the PAPR reduction performance of the adjacent subblock partitioning scheme is improved extensively as compared to that of the interleaved and pseudo-random partitioning scheme. This arrangement reduces the envelope fluctuations considerably in the transmitted waveform. The peak value optimization minimises the PAPR of the OFDM signal by multiplying weighting factor. The input data vector *X* is partitioned into *V* subblocks by using adjacent method. The subblocks consist of a contiguous set of *N/V* subcarriers and all the subblocks are of equal size. Each subblock is then multiplied by a phase factor $b_v = e^{j\phi v}$.The objective is to optimally combine the *V* subblocks to obtain the time domain OFDM signals with the lowest PAPR, in which frequency domain is given by

$$X' = \sum_{v=1}^{V} b_v X_v \tag{3.8}$$

where $\{b_v, v = 1, 2, 3, ...V\}$ is a set of phase factors.

In other words, the time domain signal is given by

$$\mathrm{x} = IFFT\left[\sum_{v=1}^{V} b_v X_v\right] = \sum_{v=1}^{V} b_v \mathrm{x}_v \tag{3.9}$$

where x_v is the partial transmit sequence.

The phase factor vector b_v is chosen from an allowed set $\{+1, -1, +j, -j\}$ of phase factors that will result in a low PAPR OFDM signal. The set of phase factors $\{b_v, v = 1, 2, 3, ..., V\}$ is sent as side information to the receiver for recovery of the transmitted signals. The set of phase factors for V subblocks are optimized in the time domain so as to achieve a better PAPR performance. If the number of allowed phase factors is W, then W^{V-1} set of phase factors is to be searched to find the optimum set of phase factors. This search complexity increases exponentially with the number of subblocks V .Then the time domain signal with lowest PAPR is given by,

$$\tilde{x} = \sum_{v=1}^{V} \tilde{b}_v x_v \tag{3.10}$$

where $\tilde{b}_v$ is optimum set of phase factors which will produce a low PAPR OFDM signal.

The phase factor combination that meets the minimum PAPR in OFDM signal is given by

$$\{\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_v\} = \arg\min\left[\max\left|\sum_{v=1}^{V} b_v X_v\right|^2\right] \tag{3.11}$$

where $\arg\min(.)$ express the criteria that the function has achieved the minimum.

The phase weighting factors parameter set is chosen to minimise the PAPR. The computational complexity of PTS method depends on the number of phase rotation factors allowed. The phase rotation factors can be selected from an infinite number of phases $b_v \in (0, 2\pi)$. But finding the optimum set of phase factors is indeed a complex problem, because it requires an exhaustive search over all possible combinations of the allowed phase factors.

3.2.2 Modified PTS Scheme

In the conventional PTS, the computational complexity is usually too large for practical system to accept. In modified PTS [47], a modified neighbourhood search algorithm is used to find the optimum set of phase factors by using a threshold PAPR value with an objective to reduce this computational complexity. In the neighbourhood search algorithm, an initial value of solution is assumed. Then a search is made to obtain a better solution in the neighbourhood of the initial assumed value. Iteratively, if a solution exists, then the initial one is replaced with the recent solution. Thus an optimum solution is obtained when there is no better solution in the neighbourhood. In the practical OFDM, modified PTS using neighbourhood search algorithm can be used to find the optimum phase factor combination.

The PAPR of the OFDM signal is reduced to a linear range, so that the amplitude is always at the linear region of amplifier. For implementation, a threshold value $PAPR_0$ is set and the optimum phase factor combination is obtained by neighbourhood search algorithm until the $PAPR$ is less than the threshold $PAPR_0$. The region of neighbourhood search is defined to be a function of the current $PAPR$ value $\left(\overline{PAPR}\right)$ and the threshold $PAPR_0$ is defined as $\Delta b = f(\Delta E) = f(\overline{PAPR} - PAPR_0)$, where Δb is a vector of V phase factors. A random new combination of V phase factors is selected from the allowed set and the $PAPR$ of the OFDM signal is determined. The current value of PAPR is compared with the threshold value $PAPR_0$ and if it is less, then the threshold value is replaced with the current PAPR value and phase factor combination is considered as the optimum set. Thus the region shrinks with the reduction of PAPR due to dynamic adjusting of the neighbourhood region. This operation is performed for the specified number of iterations in order to reduce the computational complexity involved in the exhaustive search of optimum phase factors. Thus in the specified number of iterations, an optimum set of phase factors can be determined by using the neighbourhood search algorithm. The flow chart of the modified PTS for PAPR reduction is given in Figure 3.1.

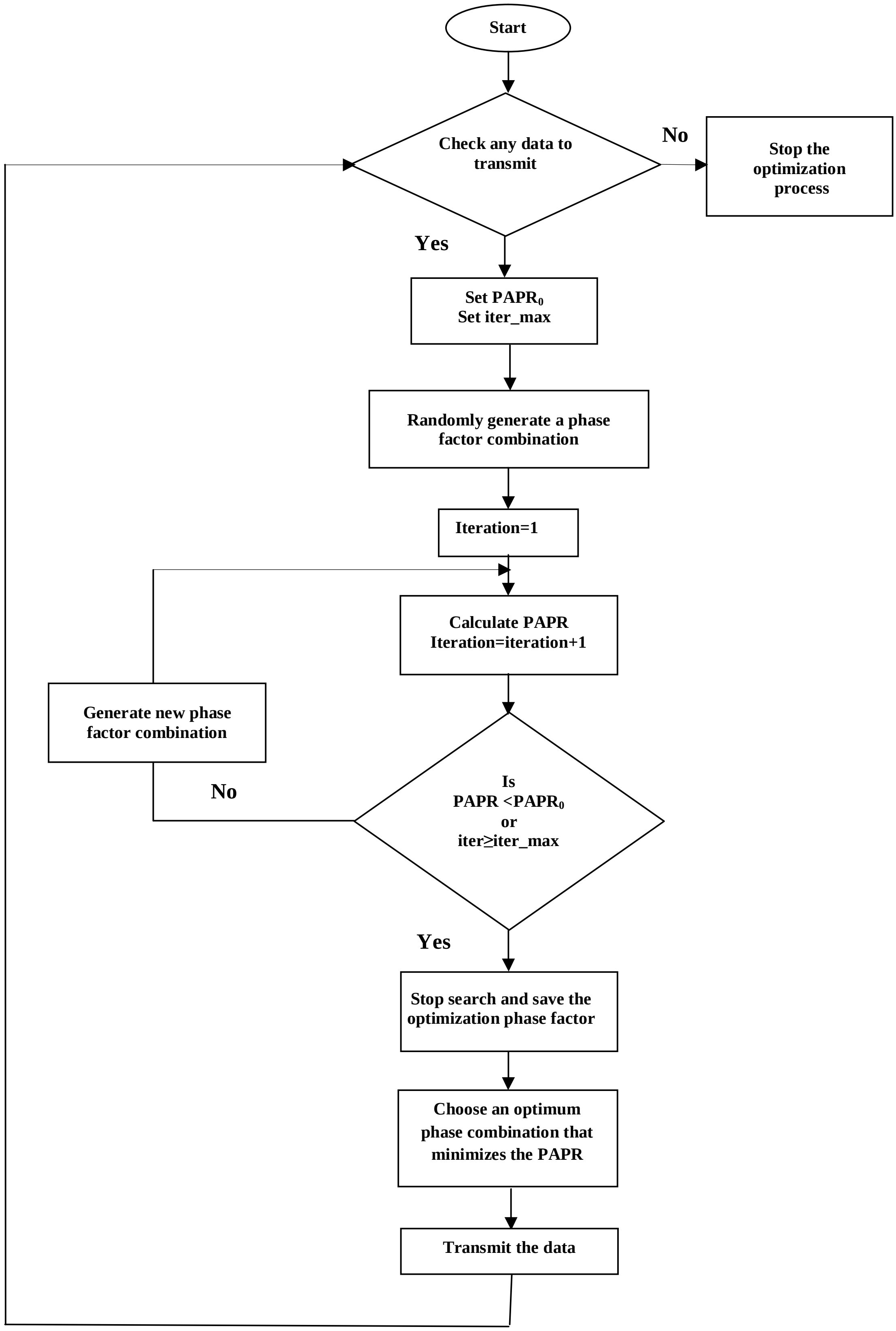

Figure 3.1 The flowchart for PAPR reduction by modified PTS scheme

3.3 MODIFIED PTS WITH INTERLEAVING TECHNIQUE FOR OFDM SYSTEM

The transmitter block diagram is illustrated in Figure 3.2 where the incoming data is QPSK modulated. The interleaving technique is based on the fact that highly correlated data frames have large PAPR values. The correlation patterns are broken down in order to achieve PAPR reduction by using interleaving technique [50]. In the proposed method, the correlation pattern of QPSK modulated symbols are interleaved with zeros by using a spreading factor of S defined as $S = \frac{N}{N_d}$, where N_d is the number of subcarriers allotted to a user. The interleaved symbols are then partitioned into V disjoint subblocks, using adjacent partitioning scheme. Then, oversampling $(L > 1)$ is employed for better approximation of true PAPR using LN-point IFFT of the data block with $(L-1)N$ zero padding. These subblocks are multiplied by a set of b_v phase factor selected from the allowed set of phase factors $\{+1, -1, +j, -j\}$ .In modified PTS, the b_v phase factors are selected from the allowed set and optimized by using neighbourhood search algorithm, such that the calculated *PAPR* is less than the threshold value $PAPR_0$.

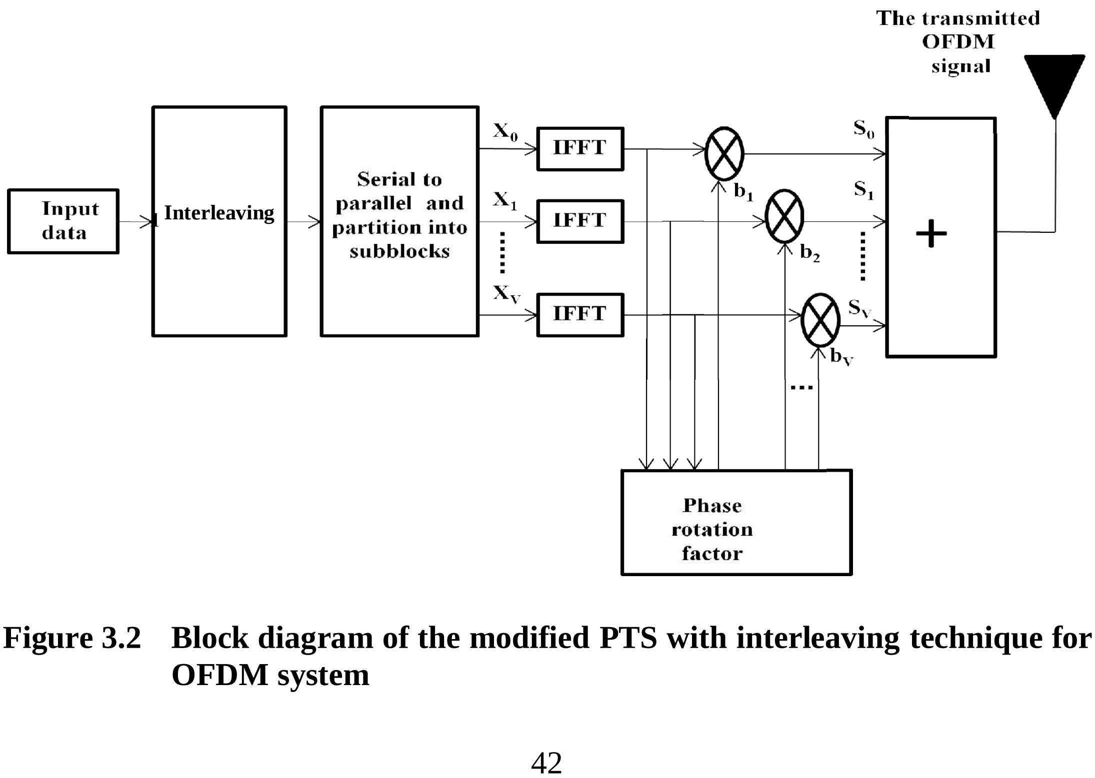

Figure 3.2 Block diagram of the modified PTS with interleaving technique for OFDM system

3.4 MODIFIED PTS WITH INTERLEAVING TECHNIQUE FOR MIMO-OFDM SYSTEM

A popular mechanism to achieve high data-rate transmission in frequency selective fading channels is MIMO-OFDM. For achieving high-data-rate transmission, the frequency-selective channel is transformed into a set of parallel frequency-flat MIMO channels by combining MIMO and OFDM techniques. But high peak-to-average power ratio is the major disadvantage of OFDM system as discussed earlier. So, modified PTS with interleaving technique for PAPR reduction in SISO-OFDM system can be extended to MIMO-OFDM systems.

MIMO-OFDM system [55] with M_t transmitting antennas that use N subcarriers is considered for analysis. In each of the M_t parallel OFDM transmitters a block of N data symbols $\{X_{mk}, m=1,2,...,M_t, k=0,1,....,N-1\}$ is transformed into time-domain by using IFFT after the process of interleaving to break the correlation pattern. The resulting baseband OFDM signal $x_{mk}(n)$ of a block can be expressed as

$$x_{mk}(n)=\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}X_{mk}e^{j2\pi kn/LN} \quad , m=1,2,...,M_t,\ k=0,1,...,N-1 \qquad (3.12)$$

where X_{mk} is the transmitted OFDM signal at the k^{th} subcarrier of the m^{th} transmitting antenna.

The PAPR of the transmitted signal $x_{nm}(t)$ with multiple transmit antennas is defined as

$$PAPR_m=\frac{\max_k |x_{mk}|^2}{E\left[|x_{mk}|^2\right]} \qquad (3.13)$$

where $E[.]$ denotes the expectation operator.

The PAPR of the continuous-time MIMO-OFDM signal cannot be precisely computed at the Nyquist sampling rate, which corresponds to *N* samples per OFDM symbol. When this is not the case, the achieved PAPR reduction might be lower and suboptimal [40-42]. To achieve effective PAPR reduction for these cases, the presented algorithms could be modified to apply oversampling in the algorithm. This can be implemented by *LN*-point IFFT of data block with *(L-1) N* zero-padding of the signal. To evaluate the PAPR reduction performance accurately from the statistical point of view, the CCDF of the PAPR of MIMO-OFDM can be rewritten as

$$CCDF(PAPR(x(n))) = \Pr(PAPR_{MIMO-OFDM} > PAPR_0) = 1-(1-e^{-PAPR_0})^{M_t LN} \tag{3.14}$$

In MIMO-OFDM [57], $M_t LN$ time domain samples are considered compared to LN in SISO-OFDM. Comparing equation(3.6) with equation (3.14), it is evident that MIMO-OFDM results in even worse PAPR performance than SISO-OFDM.

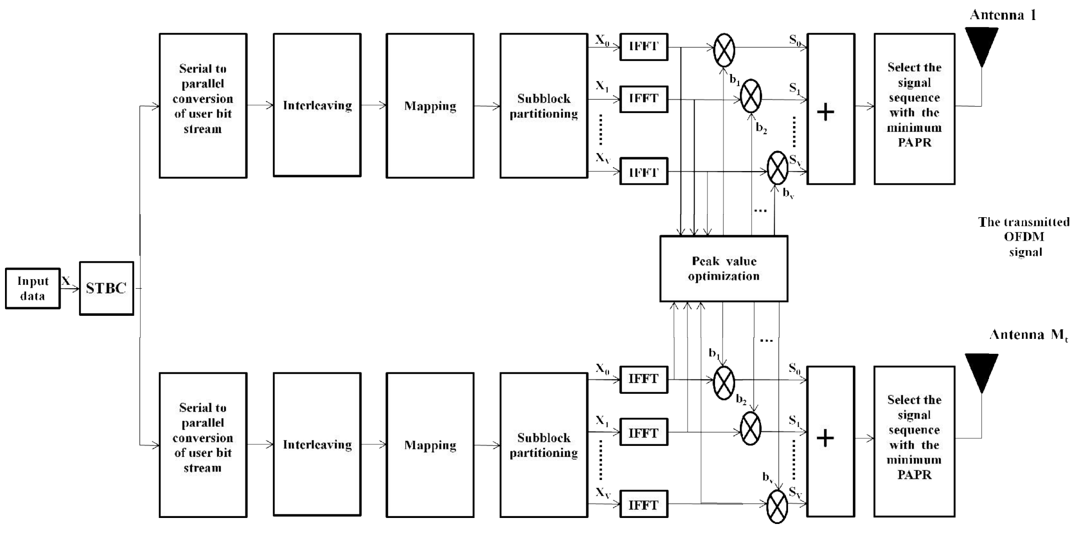

Figure 3.3 Block diagram of the modified PTS with interleaving technique for MIMO-OFDM system

The block diagram of modified PTS combined with interleaving method for PAPR reduction in STBC MIMO-OFDM system is shown in Figure 3.3. In this case, the subcarriers are encoded by a STBC encoder and the resulting encoded data is applied to Serial-to-Parallel (S/P) converter and passed to the IFFT block. A data symbol vector $X_{mk} = [X_{m0}, X_{m1}, ..., X_{mN-1}]$ is encoded with space-time encoder into two vectors as follows in [56].

$$X_{1n} = [X_{10}, -X^*_{11}, ...X_{1N-2}, -X^*_{1N-1}],$$

$$X_{2n} = [X_{21}, X^*_{20}, ...X_{2N-1}, X^*_{2N-2}]. \tag{3.15}$$

Each subcarrier is modulated by the data that is to be transmitted. In the proposed method, the correlation patterns of QPSK modulated symbols are interleaved with zeros by using a spreading factor S . The interleaved symbols are then partitioned into V disjoint subblocks such that LN-point IFFT is taken on the oversampled data block. The resulting subblocks are multiplied by the optimized set of b_v phase factor selected from the allowed set of phase factors, $\{+1, -1, +j, -j\}$ in order to obtain a reduced PAPR MIMO-OFDM signal.

3.5 RESULTS AND DISCUSSION

The analysis of PAPR reduction using modified PTS with interleaving technique in the OFDM and MIMO-OFDM systems has been carried out using MATLAB. The simulation parameters considered for the analysis is tabulated in Table 3.1. The performance evaluation is done in terms of CCDF of the PAPR, which is the probability that the PAPR of the signal exceeds the threshold $PAPR_0$.

Table 3.1 Simulation parameters for modified PTS with interleaving technique

Simulation parameters	**Type/Values**
Number of subcarriers (*N*)	64, 128, 256, 512, 1024
Number of subblocks (*V*)	2, 4, 8,16
Oversampling factor (*L*)	4
Subblock partitioning scheme	Adjacent
Number of antennas(*Mt*)	1 and 2
Modulation scheme	QPSK
Phase weighting factor (*b*)	+1, -1, +j, -j

3.5.1 PAPR Performance of Modified PTS with and without Interleaving Technique for OFDM System

The PAPR performance for OFDM system using modified PTS technique and modified PTS with interleaving technique are simulated with fixed subblocks V=4 and their performances are compared in Figure 3.4. It is observed that PAPR values of OFDM without any PAPR reduction technique (normal OFDM), modified PTS and modified PTS with interleaving technique are 10.8 dB, 9.4 dB and 7.6 dB respectively at CCDF of 10^{-3}. The PAPR reduction performance in modified PTS with interleaving technique increased by 19% when compared with modified PTS.

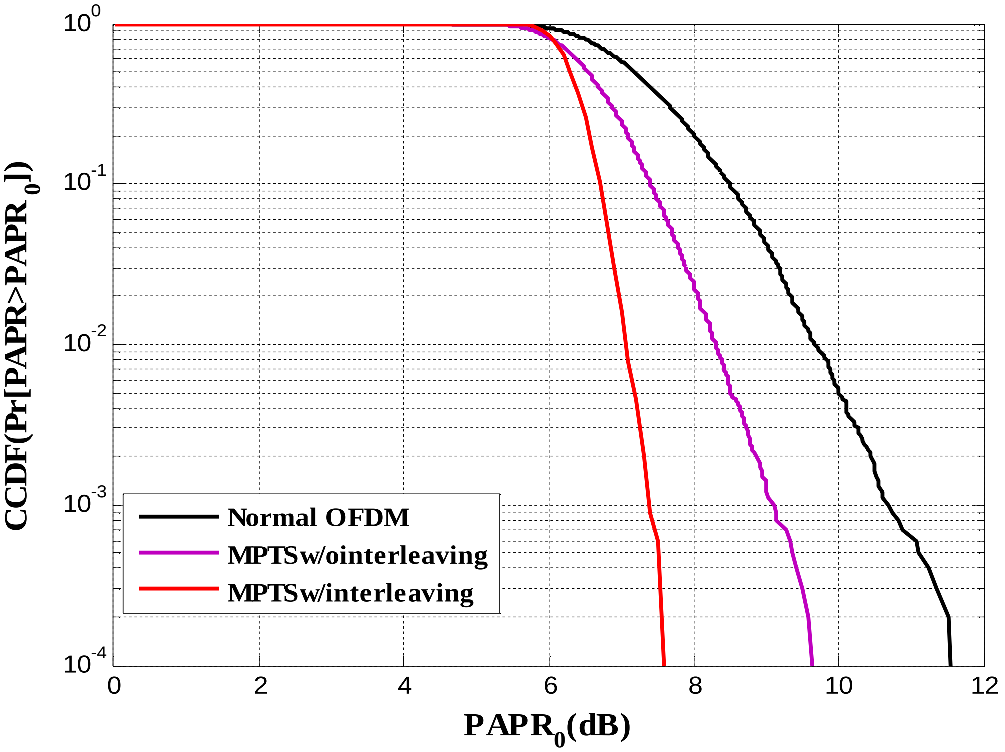

Figure 3.4 CCDF comparison of an OFDM system using modified PTS with and without interleaving technique

3.5.2 Different Subcarriers with Fixed Subblocks *V*=4 for OFDM System

Figure 3.5 shows that the PAPR performance of modified PTS with interleaving technique for different subcarriers of size 64, 128, 256, 512 and 1024 with subblocks *V*=4 in OFDM systems. It is evident that the PAPR values of 6.4 dB, 6.9 dB, 7.6 dB, 7.8 dB and 8.3 dB are obtained for different subcarriers of size 64, 128, 256, 512 and 1024 respectively at CCDF of 10^{-3}. This simulation result shows that with increase in the number of subcarriers, the PAPR reduction performance is degraded.

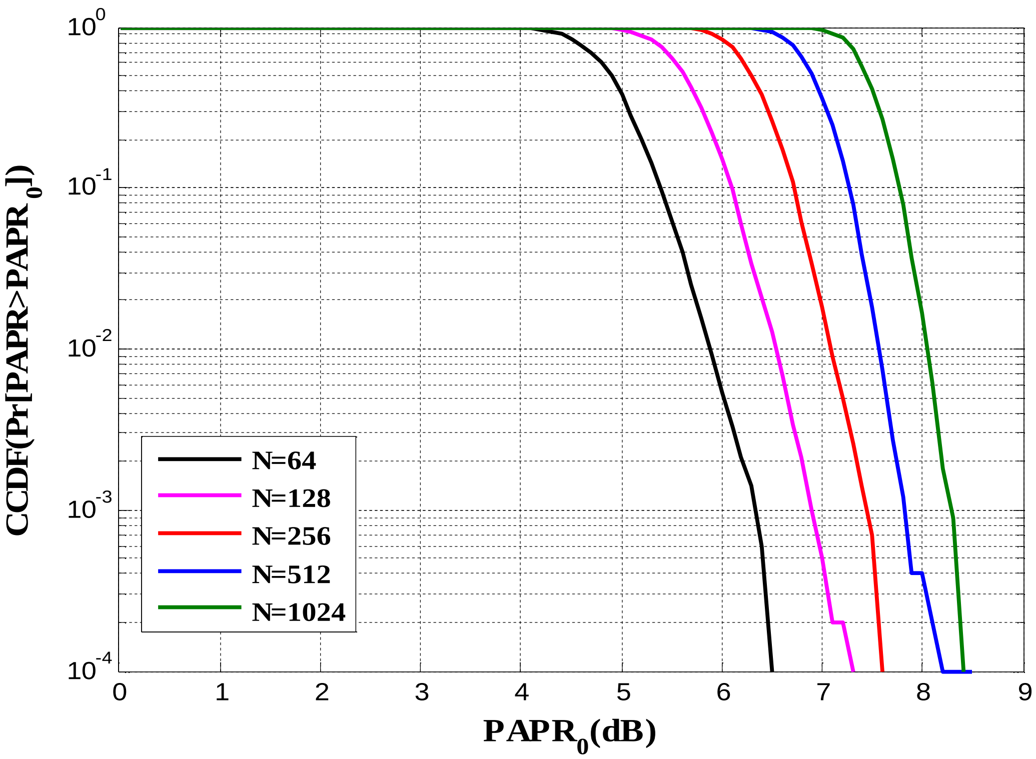

Figure 3.5 PAPR reduction performance of OFDM system for different subcarriers with *V*=4

3.5.3 Different Subblocks with Fixed Subcarriers *N*=256 for OFDM System

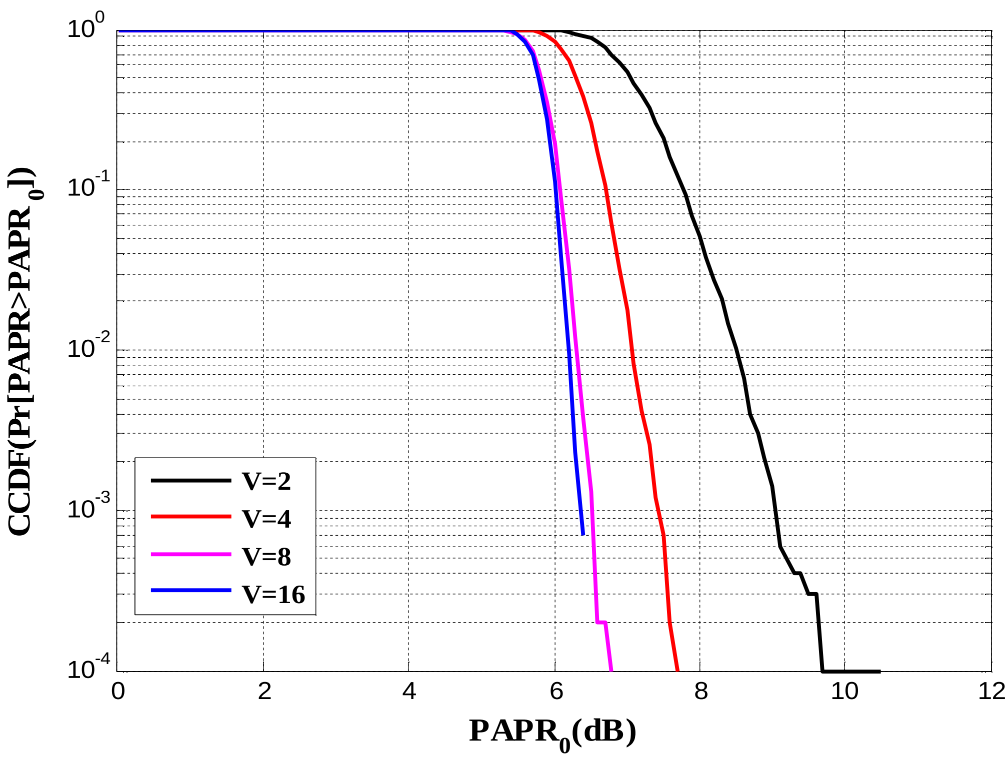

Figure 3.6 PAPR reduction performance of OFDM system for different subblocks with *N*=256

In order to obtain high data rate, large number of subcarriers are needed which in turn increases the PAPR and computational complexity. To overcome this limitation, the size of the subblocks can be varied with fixed moderate subcarrier size. The performance of modified PTS with interleaving technique in OFDM system for *N*=256 subcarriers is analyzed for various subblock sizes of 2, 4, 8 and 16 and it is illustrated in Figure 3.6. From this figure, it is found that the PAPR values for the various subblocks size of 2, 4, 8 and 16 are 9 dB, 7.6 dB, 6.5 dB and 6.3 dB respectively at CCDF of 10^{-3}. It shows that the performance of PAPR reduction is increased when the number of subblocks is increased.

3.5.4 PAPR Performance of Modified PTS with and without Interleaving Technique for MIMO-OFDM System

The PAPR performance of MIMO-OFDM system with two transmitting antennas is analysed using modified PTS without interleaving and with interleaving techniques by simulation with fixed subblocks *V*=4. The simulation results are depicted in Figure 3.7. From this figure it is found that PAPR values of MIMO-OFDM without any PAPR reduction, using modified PTS and modified PTS with interleaving techniques at CCDF of 10^{-3} are 10.8 dB, 9.4 dB and 7.6 dB respectively. Thus through simulation study it is verified that modified PTS with interleaving technique is beneficial providing considerable improvement of 19% in PAPR reduction compared to that of modified PTS. The advantage of the proposed scheme for STBC MIMO-OFDM is most suitable for fast fading channels and PAPR values are same in comparison to OFDM system.

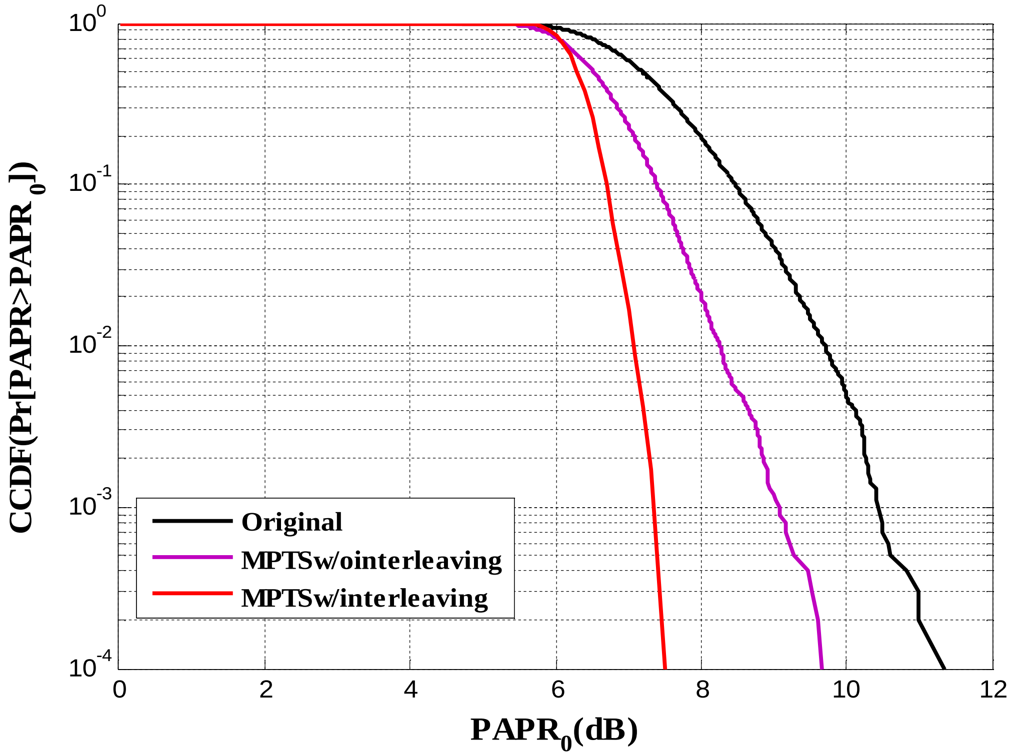

Figure 3.7 CCDF comparison of modified PTS with and without interleaving technique for MIMO-OFDM system

3.5.5 Different Subcarriers with Fixed Subblocks *V*=4 for MIMO-OFDM System

Figure 3.8 displays the PAPR reduction performance of modified PTS with interleaving technique for different subcarriers of size 64, 128, 256, 512 and 1024 keeping subblock *V*=4 in MIMO-OFDM with M_t = 2. It can be observed that the PAPR values of 6.4 dB, 6.9 dB, 7.6 dB, 7.8 dB and 8.3 dB are obtained for different subcarriers of size 64, 128, 256, 512 and 1024 respectively at CCDF of 10^{-3}.

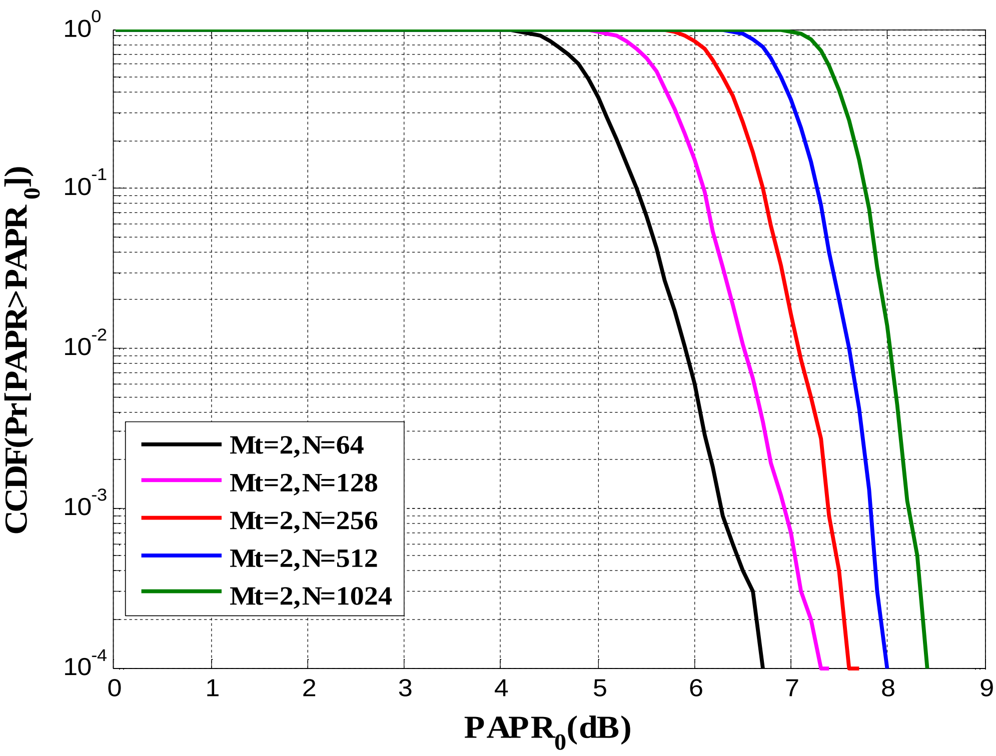

Figure 3.8 PAPR reduction performance of MIMO-OFDM system using modified PTS with interleaving technique for different subcarriers at *V*=4

3.5.6 Different Subblocks with Fixed Subcarriers *N*=256 for MIMO-OFDM System

To increase PAPR reduction at reduced computational complexity, fixed carrier size and different subblock sizes are considered. Figure 3.9 illustrates the performance of modified PTS with interleaving technique in MIMO-OFDM systems, considering the M_t=2 transmit antennas with number of subcarriers N=256 for different subblock sizes of 2, 4, 8 and 16. It can be seen that the PAPR reduction performance for the different subblocks size of 2, 4, 8 and 16 are 9 dB, 7.6 dB, 6.5 dB and 6.3 dB respectively at CCDF of 10^{-3}. It can be concluded that the PAPR values are further found to be decreased as the number of subblocks are increased.

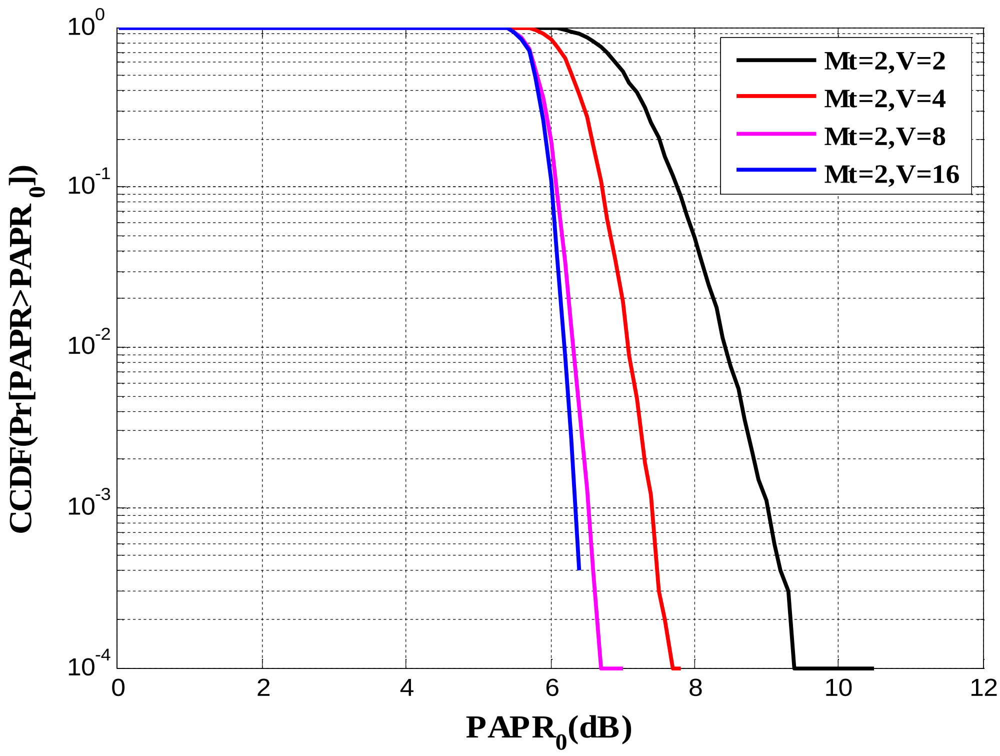

Figure 3.9 PAPR reduction performance of MIMO-OFDM system for different subblocks with *N*=256

3.6 SUMMARY

The modified PTS with interleaving technique has been analysed in this chapter to solve the high PAPR problem for OFDM and MIMO-OFDM systems. The efficient PAPR reduction performance is achieved by increasing the number of subblocks for fixed number of subcarriers. The problem of high computational complexity which increases with increase in the number of subblocks in ordinary PTS is reduced using modified PTS. This is due to the fact that neighbourhood search algorithm is used to find the optimum set of phase factor combination from the allowed set in order to obtain an OFDM signal with PAPR that is less than the threshold value. It can be observed that the PAPR performance of OFDM and MIMO-OFDM systems has improved by using interleaving technique. Simulation results prove that the PAPR reduction is around 19% using modified PTS with interleaving technique when compared to modified PTS in OFDM and MIMO-OFDM.

CHAPTER 4

MODIFIED PTS WITH FEC FOR OFDM AND MIMO-OFDM SYSTEMS

4.1 INTRODUCTION

The high PAPR of multicarrier signals is one of the major obstacles in implementing an OFDM system. The occurrence of large peaks in the signal seriously hampers the efficiency of a power amplifier. Hence, linear and consequently efficient amplifiers are required for the amplification of these signals to avoid distortion and spectral regrowth. The previous chapter dealt about the modified PTS combined with interleaving technique to improve PAPR reduction performance in OFDM and MIMO-OFDM systems. Another way to improve the PAPR reduction performance is the use of Forward Error Correction (FEC) codes. However, Hideki Ochiai and Hideki Imai [65] does mention the interesting fact that a large part of the codes found are Golay complementary sequences, which define a structured way of generating PAPR reduction codes. These coding techniques use a code that produces OFDM symbols with low PAPR. The redundancy present in these codes can be used for error correction to improve the BER performance. The coding technique is usually invoked before IFFT processing in an OFDM system for improvement in PAPR reduction performance [67]. This chapter proposes a modified PTS technique combined with FEC codes such as turbo codes and Golay complementary codes. These codes have the advantage of efficient encoding, good error-correcting capability and tightly controlled PAPR. It can operate without the need for any dedicated side information for channels under coded and uncoded scenarios and also provide similar PAPR reduction abilities compared to the ordinary PTS technique.

4.2 FORWARD ERROR CORRECTION CODING SCHEME

Wireless communication channels are highly dynamic. The transmitted signals reach the receiver after undergoing many detrimental effects that corrupt the signal to degrade the performance of the system. The detrimental effects of the channel introduce errors in the data transmitted from the source to the destination. So, some form error control coding which includes error detection and error correction is used to ensure reliable delivery of data over these unreliable communication channels. Error detection allows detection of errors while error correction enables reconstruction of original data. In FEC codes parity check bits are added to the transmitted message in order to form a codeword based on the code used by the system. A decoding error is committed if the receiver either fails to detect the presence of errors or determine the exact location of the errors. When the receiving side detects the presence of errors in a received word, it attempts to locate and correct the errors. After the process of error correction, the decoded word is delivered to the destination. Subsequently, use of code words can result in high PAPR. The attractive way to deal with high PAPR is to use block coding across the subcarriers and the codeword with low PAPR is selected. The inherent redundancy in the code words can be exploited for error correction.

PAPR can be reduced by using a selected code to generate OFDM symbols for which the PAPR is below the desirable level. There exist a large number of codes suitable for PAPR reduction. But they require a structured way of generating these code words with requisite code properties. It is known that Golay complementary pair sequences [68] are power efficient since the PAPR of these codes is no more than 3 dB. Golay complementary sequences are the sequence pairs for which the sum of autocorrelation functions is zero for all delay shifts unequal to zero. This correlation property of complementary sequences relatively translates into a small PAPR of 3 dB when the codes are applied to modulate the OFDM signal [69].

4.2.1 Turbo Codes

The turbo codes are used to generate different sequences which are inserted at the beginning of the data. This will give maximum length sequences at the output of a turbo encoder [71]. These codes are used to increase the capability of PAPR reduction. Figure 4.1 shows the block diagram of a turbo encoder. A turbo encoder offers atleast two advantages viz, significant PAPR reduction and good bit error rate performance. Turbo codes [72] are parallel concatenated convolutional codes. Here the information bits are first encoded by a Recursive Systematic Convolutional (RSC) Code and then, they are passed through an interleaver and successively followed by the second RSC encoder. The purpose of interleaving is to transform burst error into independent errors. The result of interleaving makes error bursts to spread out over time, so that errors within a codeword appear to be independent. The turbo encoder generates different sequences and the sequence with lowest PAPR is selected for transmission. The role of puncture is to periodically delete the selected bits to reduce coding overhead. The turbo encoder generates different sequences and the sequence with lowest PAPR is selected for transmission. A turbo decoder is used to recover the transmitted signal at the receiver side.

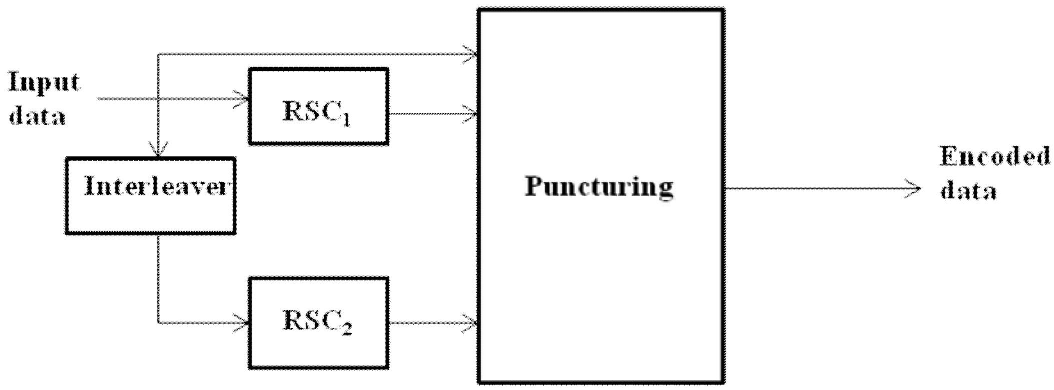

Figure 4.1 Turbo encoder

Pawan Sharma and Seema Verma [73] analysed the selective mapping scheme combined with turbo code for the PAPR reduction of OFDM signal. In this scheme, no side information is needed for reconstructing the original information and also there is no code rate loss at the receiver side. The turbo encoder is used for both error correction and PAPR reduction. However, turbo coding and SLM can be combined to reduce the PAPR of OFDM signal with quite moderate additional complexity. But, the PAPR of turbo coded OFDM symbols can be reduced by using modified PTS with reduced complexity.

4.2.2 Golay and Reed-Muller Codes

Binary complementary sequences were proposed by M.J.E. Golay in 1961 [94]. Golay complementary sequences are sequence pairs for which the sum of a periodic autocorrelation function is zero, for all delay shifts not equal to zero. It was mentioned that the autocorrelation properties of complementary sequences can be used to construct the OFDM signal with low PAPR. In an OFDM transmission, normally the IFFT is applied to the input sequence x. However, because the IFFT is equal to the conjugated FFT scaled by *1/N*, the conclusion that the PAPR has an upper bound of 2 is also valid when $X(f)$ is replaced by $x(t)$ for the sequence x. The PAPR is guaranteed not to exceed 3 dB by using a complementary code as input to generate an OFDM signal.

The sequence pairs x and y of length N, i.e., $x = [x_0, x_1, x_2, ...x_{N-1}]$ and $y = [y_0, y_1, y_2, ...y_{N-1}]$, are said to be complementary if the following condition holds on the sum of both autocorrelation functions [95].

$$\sum_{k=0}^{N-1} (x_k x_{k+i} + y_k y_{k+i}) = 2N; \; i = 0$$

$$= 0 \; ; \; i \neq 0 \tag{4.1}$$

After taking the Fourier transform on both sides of equation (4.1) the above condition translates into the following equation.

$$|X(f)|^2 + |Y(f)|^2 = 2N \tag{4.2}$$

where $X(f)$ and $Y(f)$ are the power spectrums of x and y respectively. From the spectral condition of equation (4.2), it is observed that the maximum value of the power spectrum is bound by $2N$.

$$|X(f)|^2 \leq 2N \tag{4.3}$$

Because the average power of x is equal to N, the PAPR of x is bounded as

$$PAPR \leq \frac{2N}{N} = 2 \quad (=3\text{ dB}) \tag{4.4}$$

The PAPR of a binary or polyphase sequence of length N can be as large as N, but if the sequence is constrained to be a member of a Golay complementary pair, then its PAPR is at most 2, as recognized in [77]. Hence, by using complementary sequences as input to generate an OFDM symbol, it is guaranteed that the maximum PAPR of 3 dB can be achieved.

Complementary sequences are encoded by the generator matrix $G_{n,k}$ and $b_{n,k}$ [95]. Let $A_{n,k}$ denotes the corresponding codeword sequences of length N_l and u is the integer sequence between [0, M-1] of length k. Then $A_{n,k}$ can be written as

$$A_{n,k} = u \cdot G_{n,k} + b_{n,k} \pmod{M}, \tag{4.5}$$

Where $G_{n,k}$ is a $n \times k$ matrix and $b_{n,k}$ is a phase shift sequence of length N_l while k is related to $N_l = 2^{k-1}$ for k = 3,4,5,….

Using M-ary PSK modulation the i^{th} phase sequence of $A_{n,k}$ can be given by

$$\phi_i = \frac{2\pi}{M} a_i + \Delta\phi, \tag{4.6}$$

where $\Delta\phi$ is the arbitrary phase offset, and a_i is the i^{th} sequence of $A_{n,k}$. Transforming the integer a_i to the phase sequence ϕ_i using equation (4.6), will not affect the complementary property.

4.3 MODIFIED PTS WITH FEC FOR OFDM SYSTEM

The block diagram of modified PTS with FEC for PAPR reduction in OFDM system is presented in Figure 4.2. The incoming data is encoded by using a coding scheme (turbo coding/ Golay coding). The encoded symbols are then QPSK modulated and are then partitioned into V disjoint blocks, using adjacent partitioning. Oversampling is employed for better approximation of PAPR. Then OFDM modulation is employed using IFFT on the oversampled data. Modified PTS is then applied on the OFDM symbols by multiplying each subblock with a optimum phase factor selected from the allowed set by using neighbourhood search algorithm. Applying modified PTS scheme achieves higher reduction in complexity with minimum PAPR value which is then transmitted. The PAPR of the signal is evaluated by finding the CCDF of PAPR by using equation (3.6).

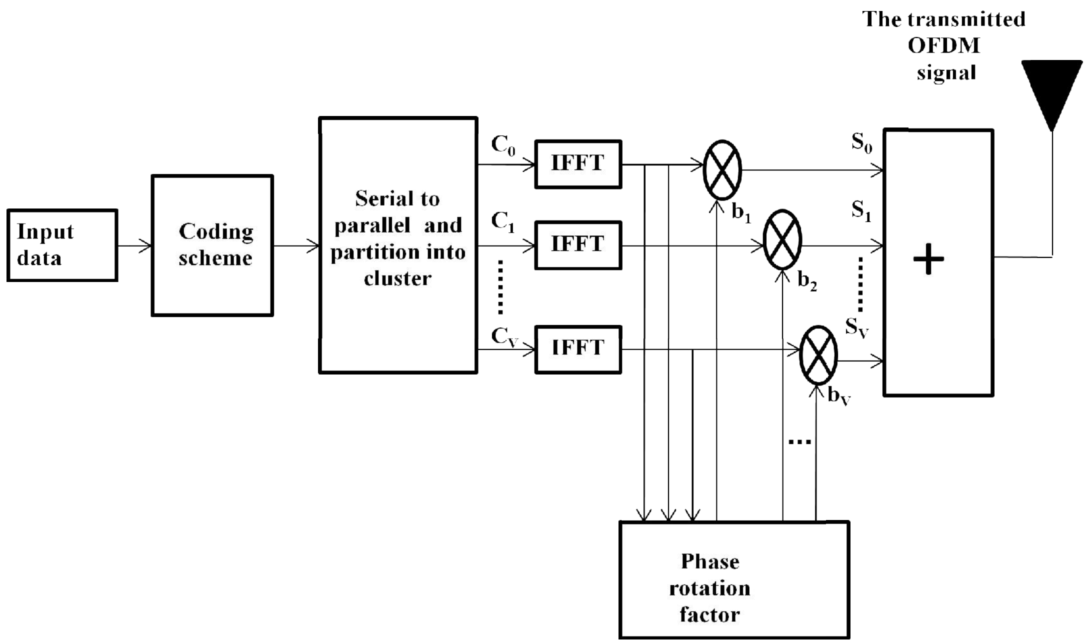

Figure 4.2 Block diagram of the modified PTS with FEC coding scheme for OFDM system

4.4 MODIFIED PTS WITH FEC FOR MIMO-OFDM SYSTEM

MIMO-OFDM is employed to achieve higher data rates. The concept of modified PTS with FEC coding (turbo coding/ Golay coding) has been extended to improve PAPR reduction in MIMO-OFDM system. The system model of modified PTS with FEC for PAPR reduction in MIMO-OFDM system model is shown in Figure 4.3. The implementation of a MIMO-OFDM system using a space time block coding scheme for 2 transmitter antennas is considered. The input data is STBC coded to divide them into two streams for the two transmitting antennas. The two input data streams are encoded using FEC coding scheme (turbo encoding/ Golay encoding). Each stream acts has separate input to a MIMO-OFDM system in which the data is converted from serial to parallel form for IFFT operation. Modified PTS is applied on the modulated data. In modified PTS, the modulated OFDM symbols are multiplied with optimum set of phase factors selected from the allowed set of phase factors, by using neighbourhood search algorithm. The CCDF of PAPR in MIMO-OFDM system is calculated by using equation (3.14).

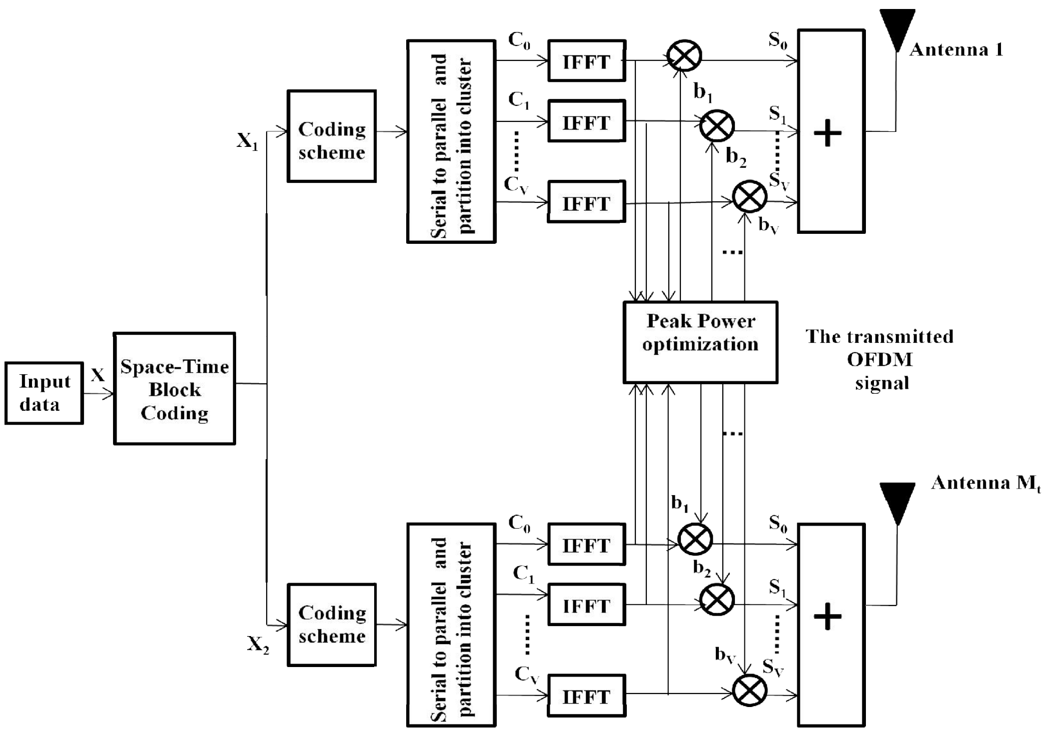

Figure 4.3 Block diagram of the modified PTS with FEC coding scheme for MIMO-OFDM system

4.5 RESULTS AND DISCUSSION

The analysis of the modified PTS with FEC codes such as Golay complementary sequences with Reed-Muller code and turbo code techniques has been carried out using MATLAB. The simulation parameters considered for this analysis are tabulated in Table 4.1. Using the proposed scheme, the PAPR reduction performance is evaluated for different number of subcarriers and subblocks. There is a significant improvement in PAPR reduction performance.

Table 4.1 Simulation parameters for modified PTS with FEC coding scheme

Simulation parameters	**Type/Values**
Forward error correction code	Turbo and Golay codes
Number of subcarriers (*N*)	64, 128, 256, 512, 1024
Number of subblocks (*V*)	2, 4,8,16
Oversampling factor (*L*)	4
Number of antennas (*Mt*)	1 and 2
Modulation Scheme	QPSK
Phase weighting factor (*b*)	+1, -1,+j, -j
Subblock partitioning scheme	Adjacent
Turbo code rate	1/2

4.5.1 PAPR Performance of Modified PTS with and without Turbo Codes for OFDM System

Figure 4.4 shows the comparison of PAPR reduction performance for normal OFDM, modified PTS and modified PTS with turbo coding. From this figure it is observed that the PAPR values for normal OFDM, modified PTS and modified PTS with turbo codes are 10.8 dB, 9.4 dB and 7.4 dB respectively at CCDF of 10^{-3} for N=256 subcarriers and V=4 subblocks. The PAPR reduction performance of modified PTS is increased by 13% compared to normal OFDM. Combining turbo coding with modified PTS will reduce the PAPR by about 21.27% when compared with modified PTS scheme.

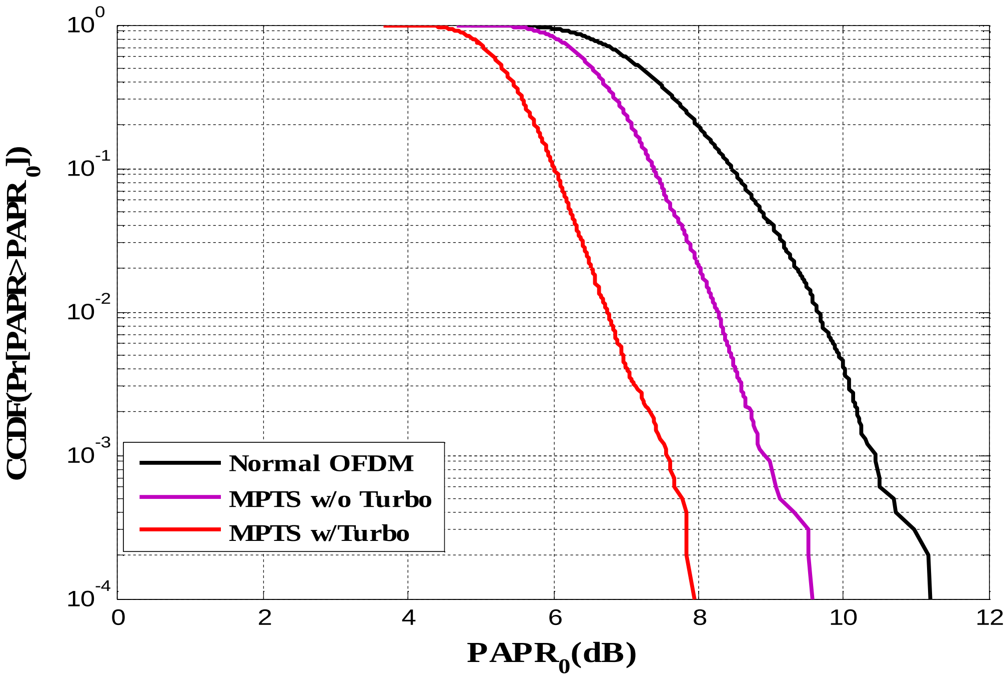

Figure 4.4 **CCDF comparison of an OFDM system using modified PTS with and without turbo codes**

4.5.2 Different Subcarriers with Fixed Subblocks *V*=4 for OFDM System

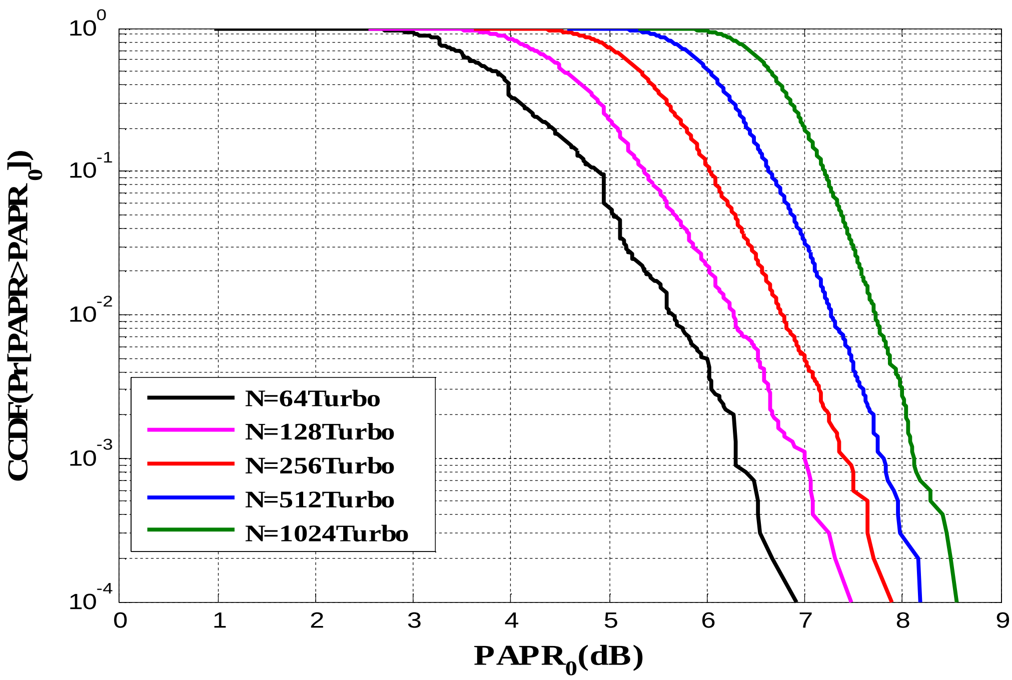

Figure 4.5 **PAPR reduction performance of OFDM system for different subcarriers with *V*=4**

The PAPR reduction performance of the modified PTS with turbo codes in OFDM system for different subcarriers N = 64, 128, 256, 512 and 1024 with subblock V=4 is displayed in Figure 4.5. The PAPR values are 6.3 dB, 7 dB, 7.4 dB, 7.8 dB and 8.2 dB respectively for N=64, 128, 256, 512 and 1024 subcarriers at CCDF of 10^{-3}. The inference is that with increase in the number of subcarriers there is degradation in the PAPR reduction performance.

4.5.3 Different Subblocks with Fixed Subcarriers *N*=256 for OFDM System

In Figure 4.6 the PAPR reduction performance is considered for an OFDM system with N = 256 for different subblock sizes V = 2, 4, 8 and 16. This approach provides an improvement in PAPR values of 9 dB, 7.4 dB, 6 dB and 4.8 dB at CCDF of 10^{-3}. It is clearly observed that the PAPR is significantly reduced as the number of subblock size increases.

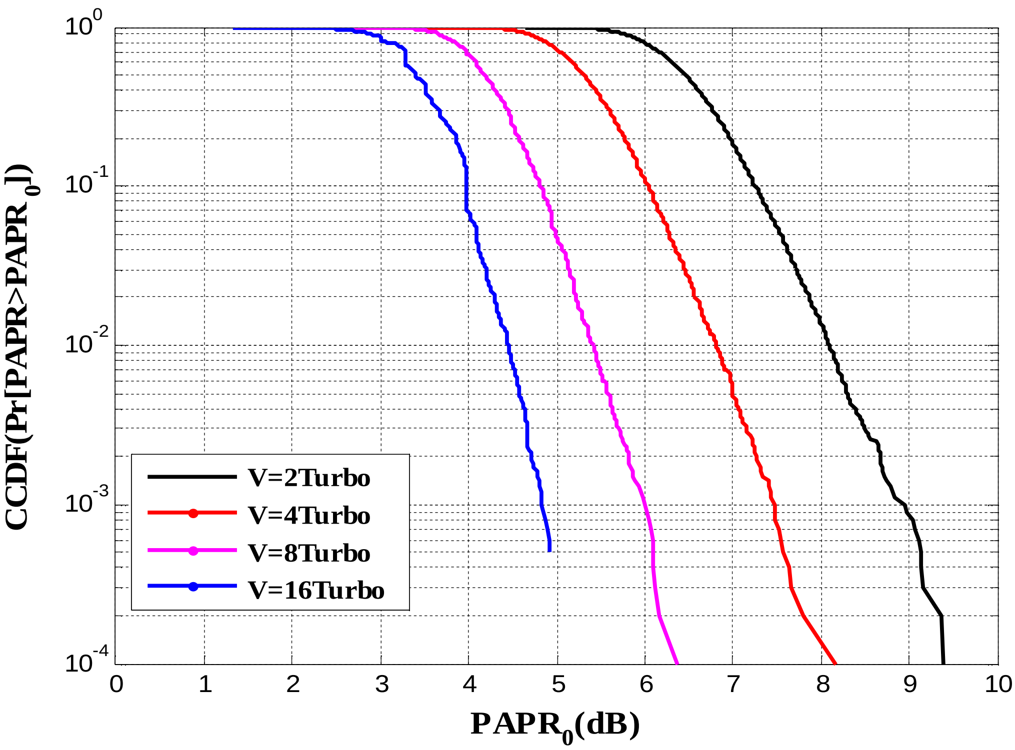

Figure 4.6 PAPR reduction performance of OFDM system for different subblocks with *N*=256

4.5.4 PAPR Performance of Modified PTS with and without FEC for OFDM System

Figure 4.7 presents the PAPR reduction performance of a normal OFDM, modified PTS, modified PTS with turbo codes and modified PTS with Golay codes. The PAPR values at CCDF of 10^{-3} are 10.8 dB, 9.4 dB, 7.4 dB and 3 dB respectively for normal OFDM, modified PTS, modified PTS with turbo coding and modified PTS with Golay codes. This shows that modified PTS with Golay codes improves the PAPR perforamnce by 60% as compared to modified PTS with turbo coding. Futhermore, the number of subcarriers and subblocks are increased for modified PTS with FEC to achieve better PAPR reduction performance.

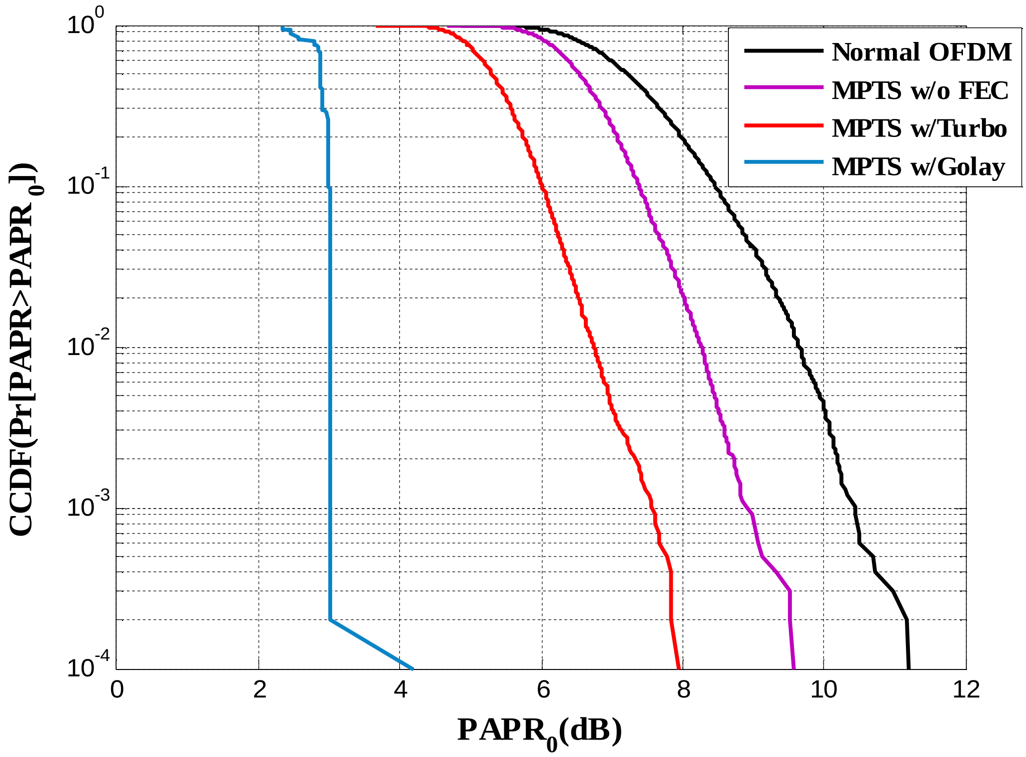

Figure 4.7 CCDF comparison of an OFDM system using modified PTS with and without FEC coding scheme

4.5.5 PAPR Performance of Modified PTS with and without Turbo Codes for MIMO-OFDM system

Figure 4.8 represents the CCDF of the PAPR reduction performance for original MIMO-OFDM, modified PTS and modified PTS with turbo codes in MIMO-OFDM system whose PAPR values are given by 10.8 dB, 9.4 dB, and 7.4 dB respectively at CCDF of 10^{-3} for two transmitter antennas.

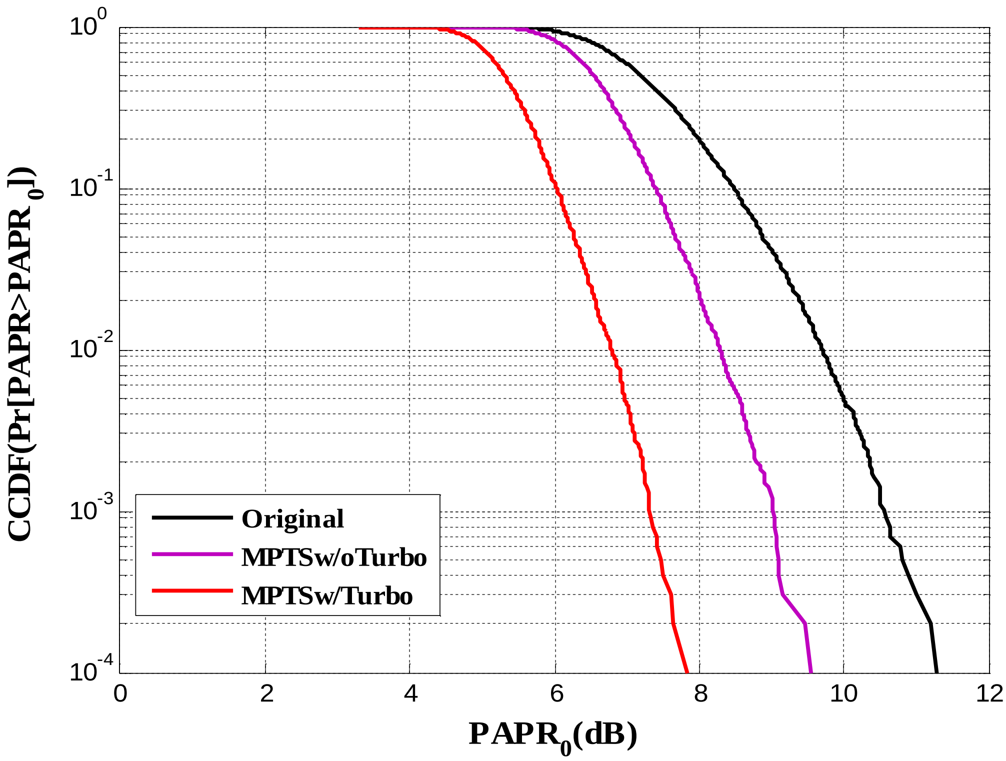

Figure 4.8 CCDF comparison of modified PTS with and without turbo codes for MIMO-OFDM system

4.5.6 Different Subcarriers with Fixed Subblocks *V*=4 for MIMO-OFDM System

Figure 4.9 shows the PAPR reduction performance of modified PTS with turbo coding for a subblock size *V*=4 for the different number of subcarriers in MIMO-OFDM. It gives better PAPR reduction at *N*=64 compared to all other subcarriers. From this figure it is noted that the values of PAPR are obtained as 6.4 dB, 7 dB, 7.4 dB, 8 dB and 8.3 dB for 64, 128, 256, 512 and 1024 at CCDF of 10^{-3} respectively.

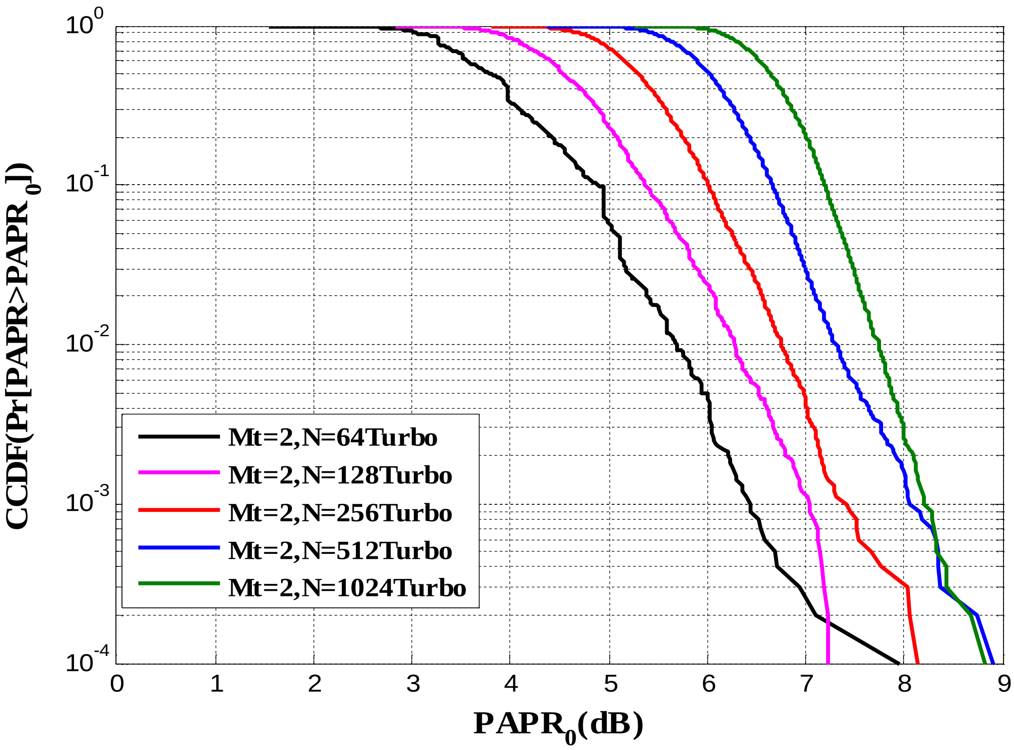

Figure 4.9 PAPR reduction performance of MIMO-OFDM system using modified PTS with turbo codes for different subcarriers at *V*=4

4.5.7 Different Subblocks with Fixed Subcarriers *N*=256 for MIMO-OFDM System

From Figure 4.9, the conclusion is that there is degradation in PAPR reduction performance with increase in the number of subcarriers. Figure 4.10 depicts the CCDF of PAPR of MIMO-OFDM system with N = 256 carriers and for different subblock sizes of V = 2, 4, 8 and 16. It can be concluded that when the subblock size increases better PAPR reduction performance can be achieved for modified PTS with turbo coding scheme, in the case of MIMO-OFDM system with two transmitting antennas.

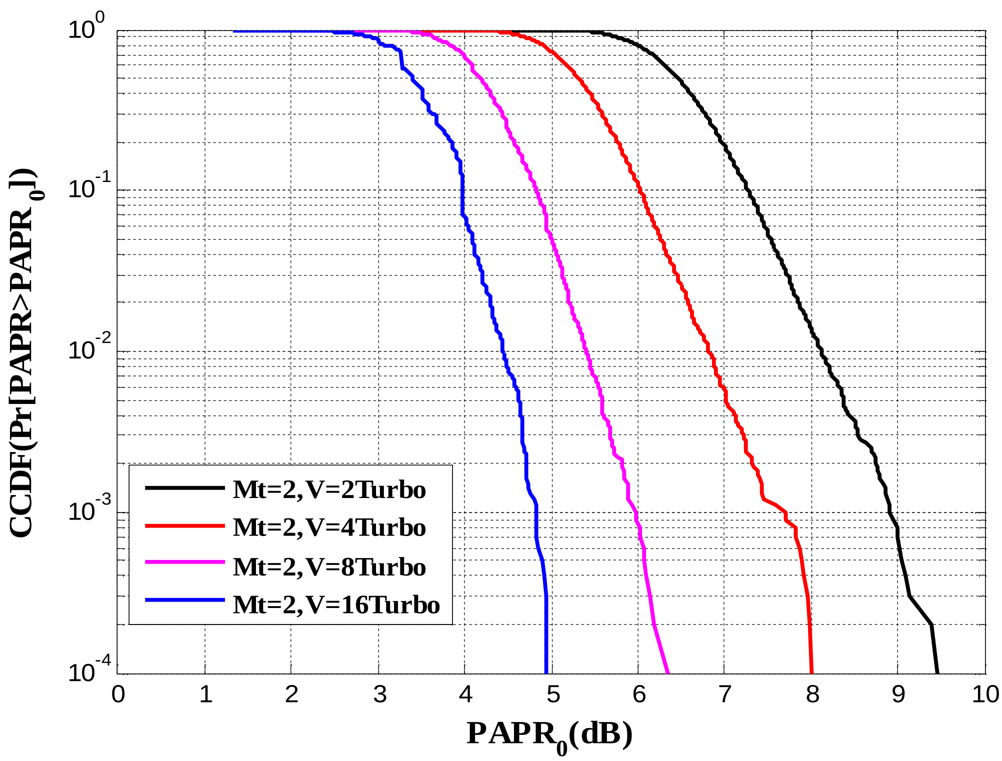

Figure 4.10 PAPR reduction performance of MIMO-OFDM system for different subblocks with *N*=256

4.5.8 PAPR Performance of Modified PTS with and without FEC for MIMO-OFDM System

Figure 4.11 gives the PAPR of original MIMO-OFDM system with M_t =2, *V*=4 subblocks and *N*=256 subcarriers is 10.8 dB, modified PTS is 9.4 dB, modified PTS with turbo code is 7.4 dB and modified PTS with Golay codes is 3 dB at CCDF of 10^{-3}. From this figure it is concluded that the modified PTS with Golay code has significant improvement in PAPR reduction performance of 60% as compared to modified PTS with turbo code.

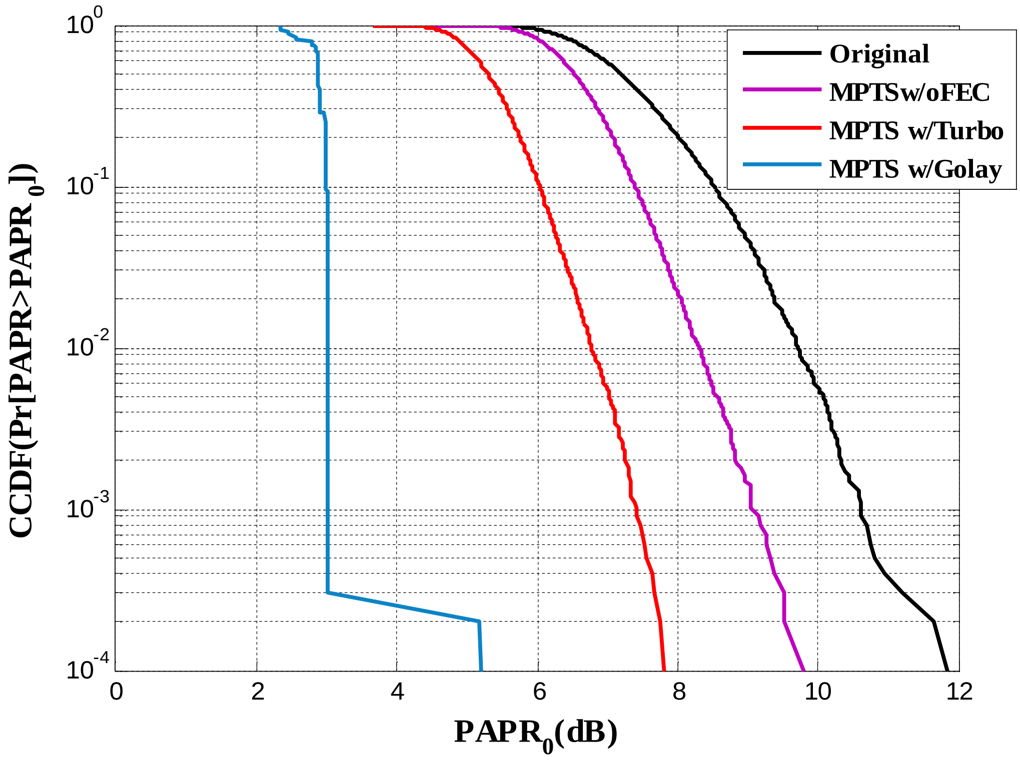

Figure 4.11 CCDF comparison of modified PTS with and without FEC for MIMO-OFDM system

4.6 SUMMARY

In this chapter, the PAPR of OFDM and MIMO-OFDM system based on modified PTS with FEC such as turbo codes and Golay complementary sequences code is evaluated. In general, significant improvement in PAPR reduction performance can be achieved when the subcarriers are divided into several disjoint subblocks. Modified PTS with turbo code provides good PAPR performance but the performance has been degraded as the number of subcarrier increases. Modified PTS with Golay codes restricted the PAPR values upto 3 dB. Moreover, Golay code provides error correction and increases the overall performance of MIMO-OFDM system. The simulation results indicate that the proposed technique has a better PAPR reduction capability compared to that of the modified PTS technique with different subcarriers and subblocks. In the case of modified PTS with Golay code, there is about 60% PAPR reduction performance as compared to modified PTS with turbo code.

CHAPTER 5

MODIFIED PTS WITH SUPERIMPOSED TRAINING SEQUENCE METHOD FOR OFDM AND MIMO-OFDM SYSTEMS

5.1 INTRODUCTION

In the previous chapter, the modified PTS with FEC coding scheme has shown excellent performance on PAPR reduction but it requires extra hardware for the process of encoding and decoding in OFDM and MIMO-OFDM systems. If the number of subcarriers is significantly large, the required computational load and hardware complexity can become prohibitively high. These drawbacks can be overcome by the superimposed training method and this method incurs no loss in information transfer rate. PAPR reduction requires the use of a perfect training sequence. Certain power has to be allocated to the Superimposed Training (ST) sequence which could otherwise be allocated to the information signal. Therefore, the foremost requirement in this method of PAPR reduction is the judicial selection of the superimposed training sequence so that a little power is wasted in it [80]. In this chapter, the PAPR reduction performance of OFDM and MIMO-OFDM systems are to be improved by using modified PTS with superimposed training sequence method.

5.2 SUPERIMPOSED TRAINING SEQUENCE METHOD

The superimposed training sequences hold an important place in wireless technologies. Initially, it has been used in channel estimation and synchronization of OFDM systems. The superimposed training sequence can be combined with PTS scheme to achieve PAPR reduction which results in the increase of the average power of the transmitted OFDM signal without the increase of peak power, rendering efficient utilization of power amplifiers [81]. The time domain OFDM signal $s[n]$ is obtained by taking the normalized IFFT of $S[k]$.

$$s[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S[k] e^{j2\pi kn/N} \tag{5.1}$$

Then, a known pilot sequence $b[n]$ is added onto $s[n]$ to obtain $x[n] = s[n] + b[n]$. A length of G symbols is added onto $x[n]$ as cyclic prefix and the resulting signal is passed through a linear power amplifier to yield $\tilde{x}[n]$, the equivalent baseband transmitted signal is given as follows

$$\tilde{x}[n] = \zeta\, x[n + N - G]_N \,,\; 0 \le n \le N + G - 1, \tag{5.2}$$

where ζ is the linear gain of the power amplifier, $[n]_N$ is the residue of n divided by N. Assume that the gain of the power amplifier to be unity; i.e., $\zeta = 1$.

The signal $x[n]$ is independent complex Gaussian distributed with time-varying mean and variance σ_S^2, since $\{S[k]\}_{k=0}^{N-1}$ is independent and identically distributed and N is assumed to be large. The distribution of PAPR of $x[n]$ depends on the number of subcarriers, the average power of the information signal σ_P^2 and the magnitude of the superimposed pilot sequence $|b(n)|$. The PAPR depends on the specific sequence $|b(n)|$.

The CCDF of the continuous-time PAPR and that of the Nyquist-rate sampled PAPR of an OFDM symbol $\{x[n]\}_{n=0}^{N-1}$ should be defined as

$$PAPR(x[n]) = \frac{\max\limits_{0 \le n \le N-1} \left\{ |x[n]|^2 \right\}}{\frac{1}{N} \sum_{n=0}^{N-1} |x[n]|^2} \tag{5.3}$$

For large values of N,

$$\frac{1}{N}\sum_{n=0}^{N-1}\left|x[n]\right|^2 \rightarrow \tilde{E}\left[\left|x[n]\right|^2\right] \equiv \frac{1}{N}\sum_{n=0}^{N-1}E\left[\left|x[n]\right|^2\right], \tag{5.4}$$

The PAPR of $x[n]$ is generally written as:

$$PAPR(x[n]) = \frac{\max\limits_{0\le n\le N-1}\left\{\left|x[n]\right|^2\right\}}{E\left[\left|x[n]\right|^2\right]} \tag{5.5}$$

The quantity in Equation (5.5) is easier to handle since the denominator is now a constant. Youngseok Oh *et al.* [82] evaluated the distribution of the so-called symbol-wise PAPR in equation (5.4) using a numerical method. To get an optimum closed form expression for the CCDF of the PAPR with the superimposed training sequence of constant amplitude for larger values of N subcarriers in equation (5.3). Periodic pilots are added to data symbols in time domain before transmission, and first order statistics [83] are exploited to identify the larger peaks. As adding pilots can increase the PAPR, the superimposed pilots must be carefully chosen to mitigate this problem.

5.3 MODIFIED PTS WITH SUPERIMPOSED TRAINING SEQUENCE METHOD FOR OFDM SYSTEM

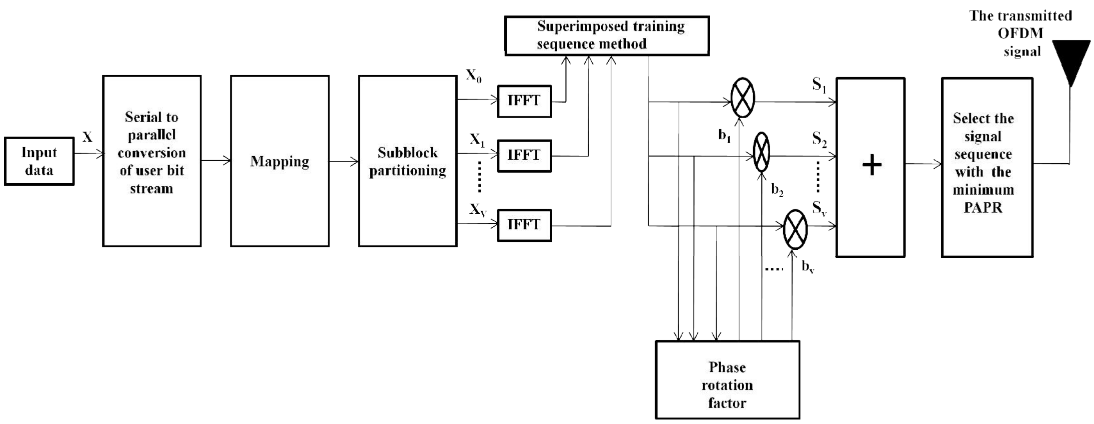

Figure 5.1 Block diagram of the modified PTS with superimposed training sequence method for OFDM system

The block diagram of modified PTS with the superimposed training sequence method for PAPR reduction in OFDM system is shown in Figure 5.1. Initially, the peak windowing technique is used to obtain low values of PAPR through minimising the large peaks which introduce the undesired effects resulting in signal regrowth. To eliminate this problem, an alternative approach does not reduce the maximum of signal amplitude peak but reduce the probability of appearance of peak. For that, periodic pilots are added to data symbols for improving the average power of the OFDM signal. PAPR of the system is minimised by increasing the average power to be transmitted for a fixed peak power. This is achieved by using superimposed training sequence. In this system modified PTS is combined with superimposed training sequence method for PAPR reduction. It is based on optimum phase factor selection for which the PAPR of the OFDM signal is low. The optimum phase factors for phase rotation are selected by using a neighbourhood search algorithm. This system has the advantage of inhibiting high PAPR of OFDM signals and improving the efficiency of linear power amplifier. The PAPR of the signal is evaluated by finding the CCDF of PAPR and by using equation (3.6).

5.4 MODIFIED PTS WITH SUPERIMPOSED TRAINING SEQUENCE METHOD FOR MIMO-OFDM SYSTEM

Figure 5.2 illustrates the block diagram of modified PTS with superimposed training sequence for PAPR reduction in MIMO-OFDM with multiple transmit antennas. The input data is applied to the space time encoders where it is divided into two streams and resulting encoded data is converted into serial to parallel format and then it passes through the IFFT block. Again the same superimposed training sequence process has been followed by optimized phase rotation factor (with two transmit antennas) to produce the minimum PAPR. The CCDF of the PAPR in MIMO-OFDM system is calculated by using equation (3.14).

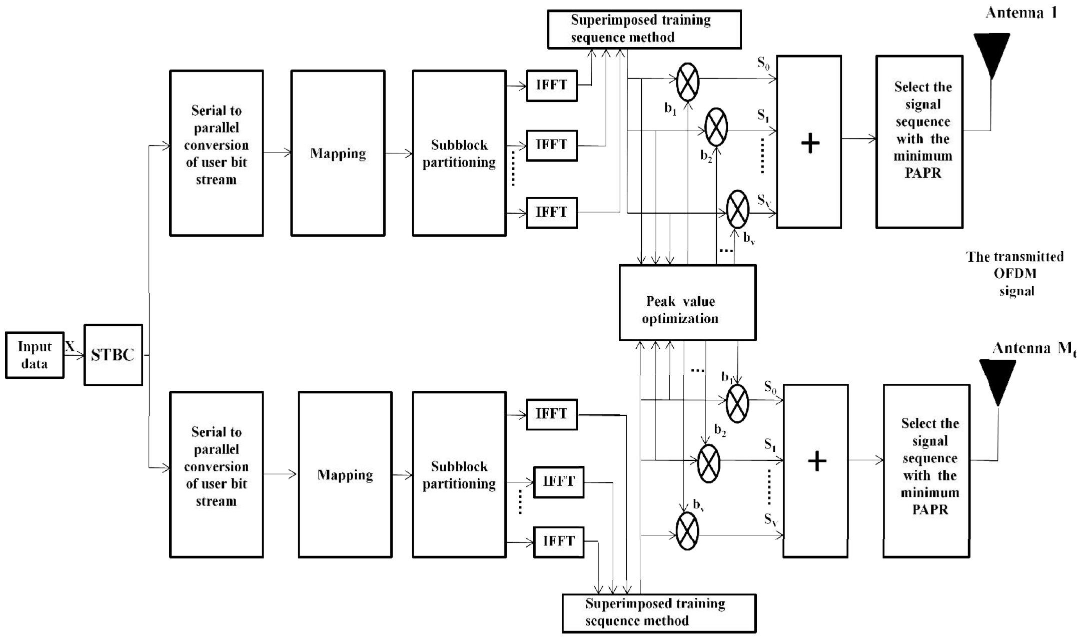

Figure 5.2 Block diagram of the modified PTS with superimposed training sequence method for MIMO-OFDM system

5.5 RESULTS AND DISCUSSION

The analysis of the modified PTS with superimposed training sequence method has been carried out using MATLAB. The simulation parameters used are shown in Table 5.1.

Table 5.1 Simulation parameters for modified PTS with superimposed training sequence method

Simulation parameters	Type/Value
Number of subcarriers (*N*)	64, 128, 256, 512, 1024
Number of subblocks (*V*)	2, 4,8,16
Oversampling factor (*L*)	4
Number of antennas (*Mt*)	1 and 2
Modulation scheme	QPSK
Phase weighting factor(*b*)	+1, -1, +j, -j
Subblock partitioning scheme	Adjacent
PN sequence	Superimposed training sequence

5.5.1 PAPR Performance of Modified PTS with and without Superimposed Training Sequence Method for OFDM System

In Figure 5.3 shows the CCDF of PAPR of the normal OFDM, modified PTS, and modified PTS with superimposed training sequence method. The corresponding values of PAPR are 10.8 dB, 9.4 dB and 6.4 dB at CCDF of 10^{-3} when N=256 subcarriers and V=4 subblocks. It can be inferred that the PAPR reduction performance of modified PTS compared to normal OFDM increases. The percentage of increase in PAPR reduction performance is around 13%. The performance of PAPR reduction with modified PTS combined with the superimposed training sequence is better and is about 31.92% increase when compared to modified PTS.

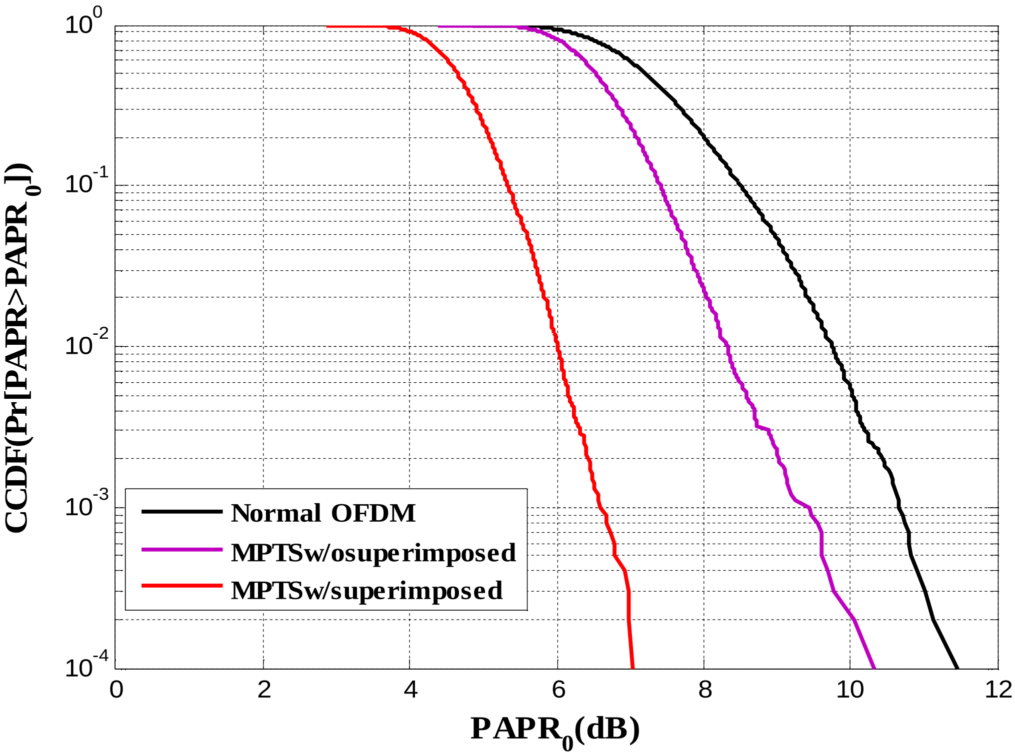

Figure 5.3 CCDF comparison of an OFDM system using modified PTS with and without superimposed training sequence method

5.5.2 Different Subcarriers with Fixed Subblocks *V*=4 for OFDM System

Figure 5.4 shows that the PAPR reduction performance is degraded with increase in the number of subcarriers with *V*=4 subblocks for the modified PTS with superimposed training sequence method. From the result it is observed that the PAPR values of different subcarriers *N*=64, 128, 256, 512 and 1024 are 7.3 dB, 6.8 dB, 6.4 dB, 6.2 dB and 5.6 dB respectively at CCDF of 10^{-3}.

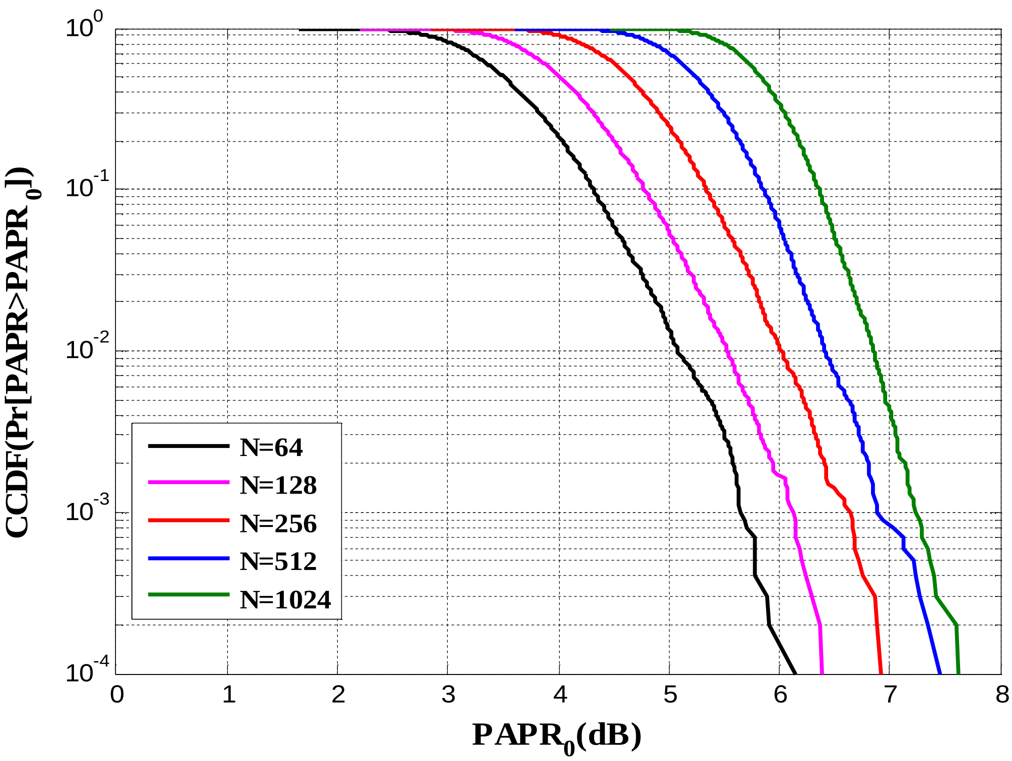

Figure 5.4 PAPR reduction performance of OFDM system for different subcarriers with *V*=4

5.5.3 Different Subblocks with Fixed Subcarriers *N*=256 for OFDM System

From Figure 5.4 it can be concluded that PAPR reduction performance degrades for large number of subcarriers. To overcome this drawback, PAPR reduction performance is increased by keeping the number of subcarriers as fixed and varying the number of subblocks. The CCDF of PAPR values for different subblocks such as 2, 4, 8, and 16 are 7.6 dB, 6.4 dB, 5 dB and 4.5 dB respectively at CCDF of 10^{-3} and to shown in Figure 5.5. These values show that the PAPR decreases significantly as the number of subblocks increases.

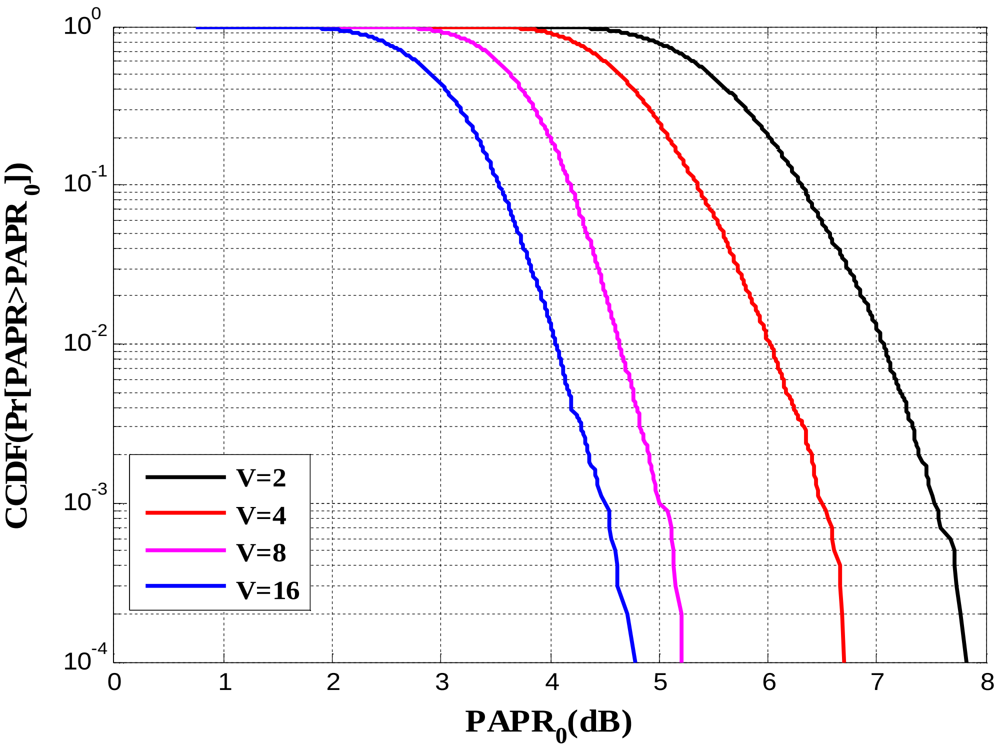

Figure 5.5 PAPR reduction performance of OFDM system for different subblocks with *N*=256

5.5.4 PAPR Performance of Modified PTS with and without Superimposed Training Sequence Method for MIMO-OFDM System

From this Figure 5.6, it is clear that the PAPR values of original MIMO-OFDM signal are 10.8 dB, modified PTS is 9.4 dB, modified PTS with the superimposed training sequence is 6.4 dB at CCDF of 10^{-3}. Overall result shows that the modified PTS has significant improvement in PAPR reduction performance which is around 13% than original MIMO-OFDM. It is also observed that modified PTS with the superimposed training sequence method results in better PAPR performance of around 31.92% compared to modified PTS.

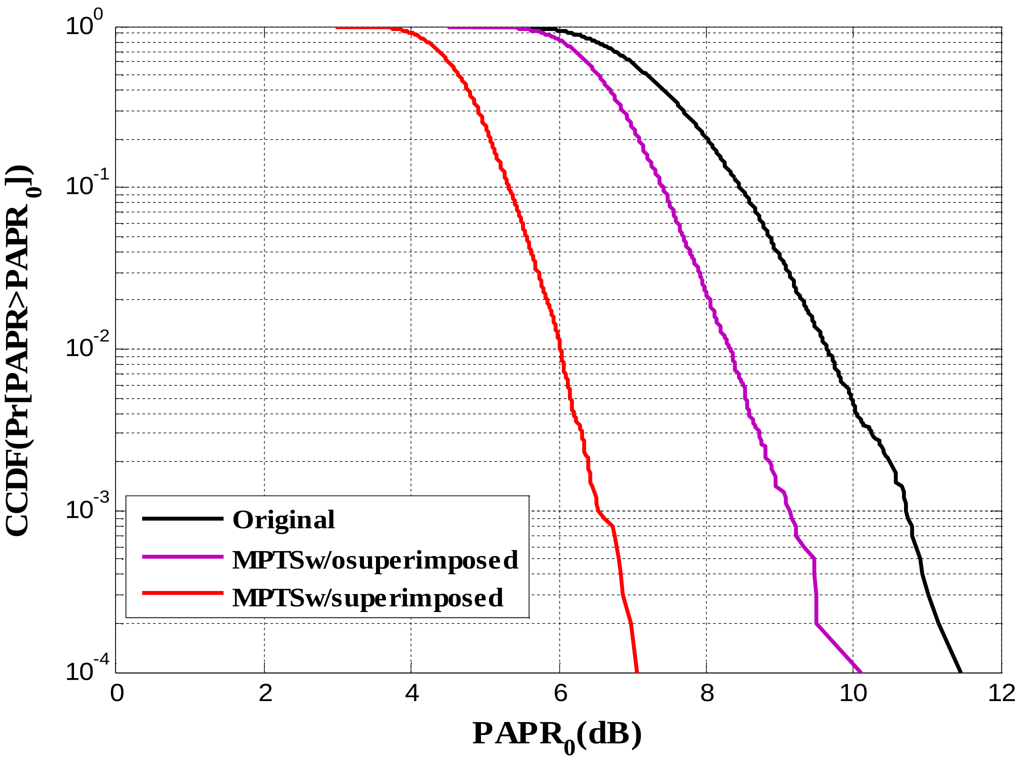

Figure 5.6 CCDF comparison of modified PTS with and without superimposed training sequence method for MIMO-OFDM system

5.5.5 Different Subcarriers with Fixed Subblocks *V*=4 for MIMO-OFDM System

It can be seen from the Figure 5.7 that the PAPR values of 7.4 dB, 6.9 dB, 6.6 dB, 6.2 dB and 5.7 dB are obtained for different numbers of subcarriers sizes N = 64, 128, 256, 512 and 1024, respectively at CCDF of 10^{-3}. Thus the increase in the number of subcarriers results in the degradation of PAPR reduction performance for modified PTS with superimposed training sequence method in MIMO-OFDM system.

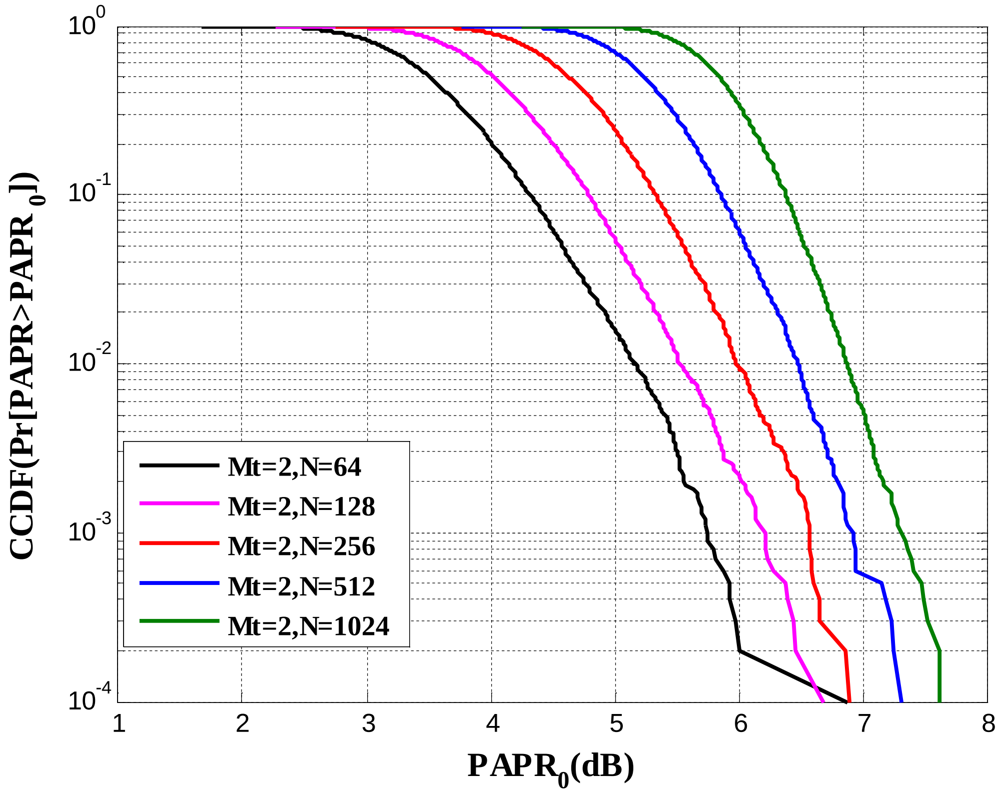

Figure 5.7 PAPR reduction performance of MIMO-OFDM system using modified PTS with superimposed training sequence method for different subcarriers at *V*=4

5.5.6 Different Subblocks with Fixed Subcarriers *N*=256 for MIMO-OFDM System

From the Figure 5.8 it is implicit that the PAPR values of modified PTS with superimposed training sequence method for different subblocks V = 2, 4, 8 and 16 are 8 dB, 6.6 dB, 5 dB, and 4.4 dB respectively at CCDF of 10^{-3}. Therefore, the subblock size should be chosen carefully to significantly reduce the PAPR for MIMO-OFDM system.

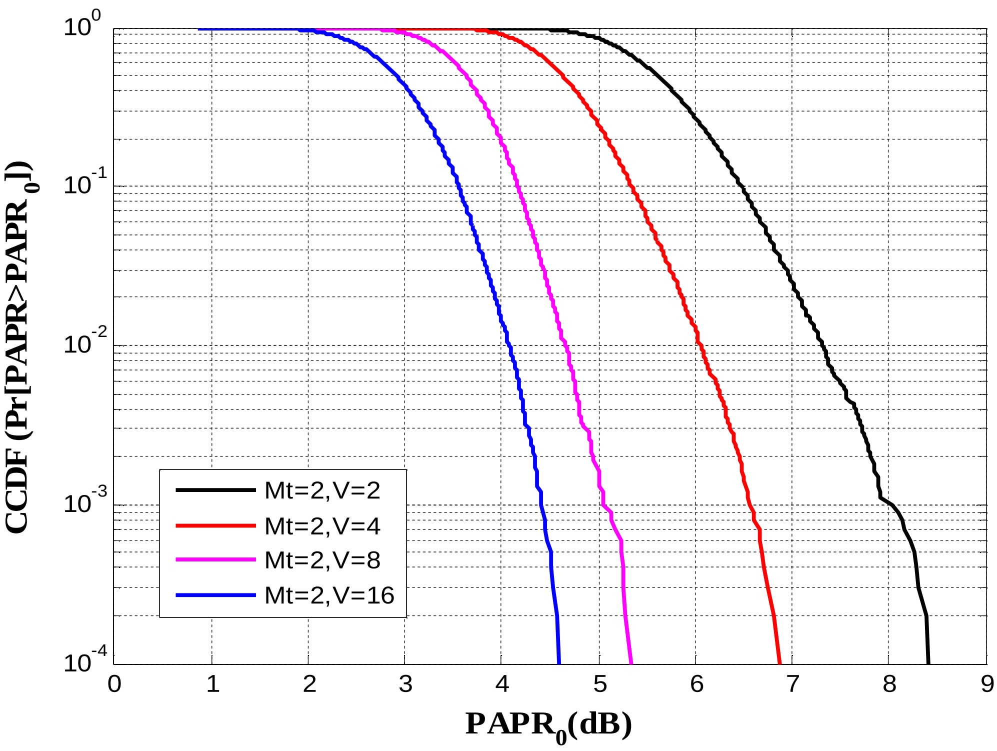

Figure 5.8 PAPR reduction performance of MIMO-OFDM system for different subblocks with *N*=256

5.6 SUMMARY

The proposed scheme includes a predefined superimposed training sequence which is added to the OFDM symbol block for the purpose of PAPR reduction without any loss in information transfer rate. The modified PTS with the superimposed training sequence method achieves better PAPR reduction performance for a fixed number of subcarriers with increase in the number of subblocks. Simulation results show that the modified PTS with superimposed training sequence method for OFDM and MIMO-OFDM systems. This method is an effective method of PAPR reduction as it compromises and achieves a better trade-off between PAPR reduction and computational complexity.

CHAPTER 6

MODIFIED PTS WITH INTERLEAVING AND PULSE SHAPING METHOD FOR OFDM AND MIMO-OFDM SYSTEMS

6.1 INTRODUCTION

Analytical results concluded that modified PTS with interleaving technique gives a better performance of PAPR reduction. Pulse shaping of the OFDM signal is a technique that has been proposed for PAPR reduction. It is based on a proper selection of the time-limited waveforms for different subcarriers. Pulse shaping method of PAPR reduction is an effective method as it avoids the use of extra IFFTs, resulting in low computational complexity [85]. Furthermore, since pulse shaping introduces controlled ICI, optimum detectors can be designed without any loss in bandwidth efficiency and with very good performance in frequency selective fading channels. In this chapter, the modified PTS with interleaving technique is combined with the pulse shaping method to achieve better PAPR reduction in OFDM and MIMO-OFDM systems without addition of much computational complexity. The performance of the modified PTS combined with interleaving and pulse shaping method is analysed and is compared with that of modified PTS method.

6.2 PULSE SHAPING METHOD

The pulse shaping method is an efficient and flexible approach for reducing the PAPR of OFDM signals. This technique is based on a proper selection of the time-limited waveforms of the different subcarriers [86]. This method of PAPR reduction uses only one IFFT/FFT operation in the transceiver. Since, the pulse shaping introduces controlled inter-channel interference, optimum detectors can be designed without any loss in bandwidth efficiency and with very good performance in frequency selective fading channels [96]. Consider a time waveform with constant energy (Es=1) and uncorrelated symbols within each OFDM block. The maximum PAPR is obtained as follows:

$$PAPR \leq PAPR_{\max} = \frac{1}{N} \max_{0 \leq t \leq T} \left(\sum_{n=0}^{N-1} \left| P_m(t) \right| \right)^2 \tag{6.1}$$

The above is a function of the number of subcarriers N and the pulse shape $P_m(t)$ of each subcarrier. Pulse shaping the different subcarrier signals using the same pulse shape will only increase the peak amplitude of the transmitted signal without affecting the correlation properties between the different samples of an OFDM block. A possible solution to reduce the PAPR of the OFDM signals is then to create some correlation between the different OFDM samples of the same block. The new set of pulse shapes indicates that each subcarrier pulse of the OFDM scheme has a different shape and all these pulse shapes are derived from the same pulse (cyclic shifts of the same pulse). This will also reduce the PAPR of the OFDM transmitted signal since the peak amplitude of the different pulse shapes never occurs at the same time unless time waveform is a rectangular pulse. A raised cosine pulse, which is a widely used pulse shape in wireless communication, is considered for the analysis of PAPR performance using pulse shaping method, combined with modified PTS and interleaving technique.

The impulse response of a raised cosine filter is,

$$r(t) = \sin c(\pi \frac{t}{\tilde{T}}) \frac{\cos(\frac{\pi \alpha t}{\tilde{T}})}{1 - \frac{4\alpha^2 t^2}{\tilde{T}^2}} \tag{6.2}$$

where the parameter α is the roll-off factor which ranges between 0 and 1.

The lower values of α introduce more pulse shaping and more suppression of out-of-band-signal components. The pulse shapes are very flexible and can control the correlation between the OFDM block samples without destroying the orthogonality property between the subcarriers of the OFDM modulated signal.

6.3 MODIFIED PTS WITH INTERLEAVING AND PULSE SHAPING METHOD FOR OFDM SYSTEM

Figure 6.1 shows the system model for modified PTS with interleaving and pulse shaping method for PAPR reduction in OFDM system. The baseband operation at transmitter includes mapping the information data bit stream to symbols according to a QPSK modulation scheme. These serial data bit streams are converted into parallel data bit stream using serial to parallel converter. Then these data streams are real-valued time domain sequences sets are constructed that correspond to the IFFT of the phase sequences sets, then used to directly generate the real valued baseband OFDM signals is more deteriorative than of complex-valued baseband OFDM signals. The modulated symbols are then interleaved and partitioned into V disjoint sub blocks for applying modified PTS. Each subblocks are independently rotated by optimum set of V phase factors selected from the allowed set of phase factors $\{+1,-1,+j,-j\}$. The optimum set of V phase factors are selected from the allowed set by using neighbourhood search algorithm, such that the calculated *PAPR* of the OFDM signal is less than the threshold value $PAPR_0$. The PAPR of the OFDM signal is further reduced by using raised cosine pulse defined by equation (6.2) by the process of convolution. The PAPR of the signal is evaluated by finding the CCDF of PAPR by using equation (3.6).

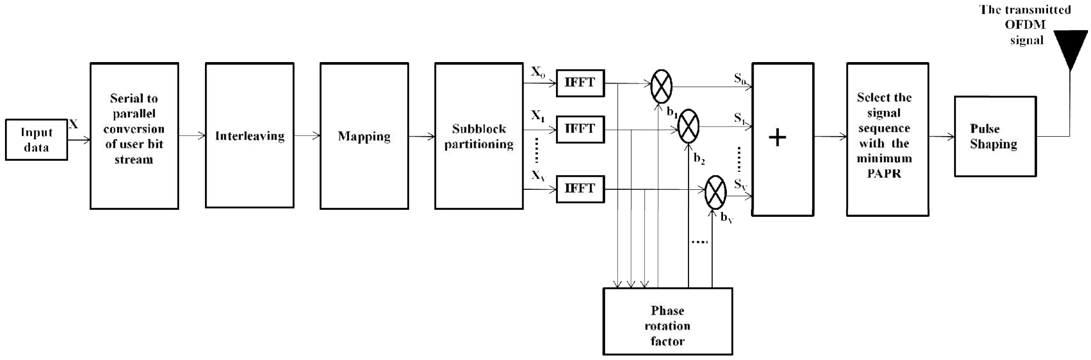

Figure 6.1 Block diagram of the modified PTS with interleaving and pulse shaping method for OFDM system

The pulse shaping process controls the correlation between the OFDM block samples without destroying the orthogonality property among the subcarriers of the OFDM modulator signal. As a result, the pulse shaping process reduces the PAPR of the OFDM signal.

6.4 MODIFIED PTS WITH INTERLEAVING AND PULSE SHAPING METHOD FOR MIMO-OFDM SYSTEM

The MIMO-OFDM combination provides capability of mitigating frequency dependent distortion across the channel bandwidth and simplifies the process of equalization in a multipath fading environment.

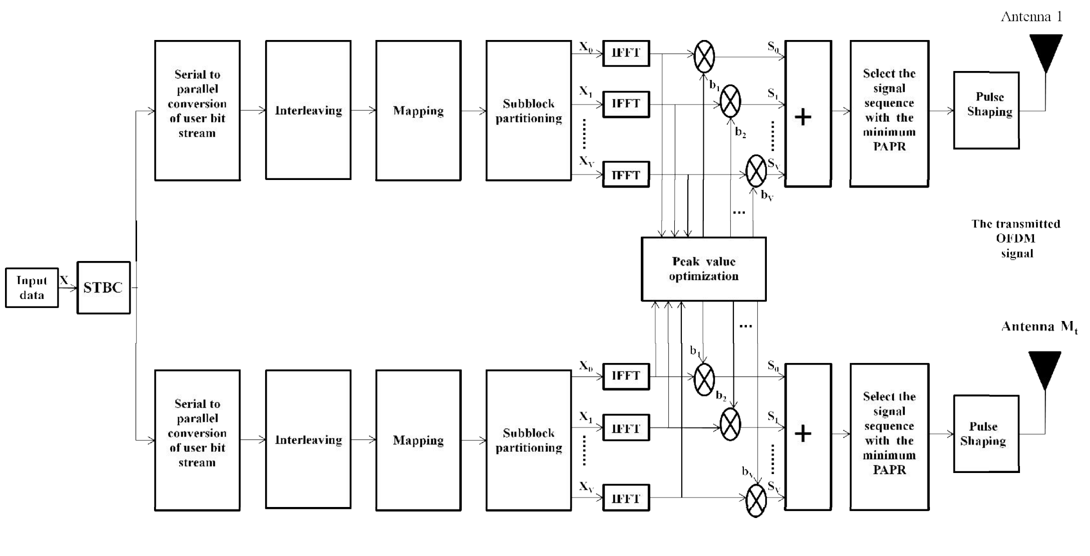

Figure 6.2 Block diagram of the modified PTS with interleaving and pulse shaping method for MIMO-OFDM system

Figure 6.2 is the block diagram of the modified PTS with interleaving and pulse shaping method for MIMO-OFDM system with M_t transmitting antennas. The STBC coded data for M_t = 2 transmitting antenna is divided into two streams. Each stream is then interleaved and divided into *V* subblocks using adjacent partitioning schemes. Then the subblocks are transformed into time domain by IFFT operation. The optimum set of phase factors required for phase rotation of the *V* subblocks is obtained by neighbourhood search algorithm, lesser than the threshold value in order to produce a low PAPR signal. The resulting signal is then convolved with the raised cosine filter for pulse shaping. The CCDF of PAPR of the MIMO-OFDM is calculated by using equation (3.14).

6.5 RESULTS AND DISCUSSION

The analysis of the modified PTS with interleaving and the pulse shaping method are evaluated using MATLAB. The simulation parameters are listed in Table 6.1.

Table 6.1 Simulation parameters for modified PTS with interleaving and pulse shaping method

Simulation parameters	Type/Values
Number of subcarriers (*N*)	64, 128, 256, 512, 1024
Number of subblocks (*V*)	2, 4,8,16
Oversampling factor (*L*)	4
Number of antennas (*Mt*)	1 and 2
Modulation scheme	QPSK
Phase weighting factor (*b*)	+1, -1, +j, -j
Subblock partitioning scheme	Adjacent
Type of pulse shaping	Raised-cosine filter

6.5.1 PAPR Performance of Modified PTS with and without Interleaving and Pulse Shaping Method for OFDM System

Figure 6.3 elucidates the comparison of the modified PTS, modified PTS with interleaving and modified PTS with interleaving and pulse shaping for *N*=256 subcarriers and *V*=4 subblocks. It can be seen that the PAPR of modified PTS is 9.4 dB, modified PTS with interleaving is 7.6 dB and modified PTS with interleaving and pulse shaping is 4.8 dB at CCDF of 10^{-3}. From this figure it is evident that the modified PTS with interleaving and pulse shaping provide 36.84% and 50% decrease in PAPR reduction performance compared to modified PTS with interleaving and modified PTS respectively.

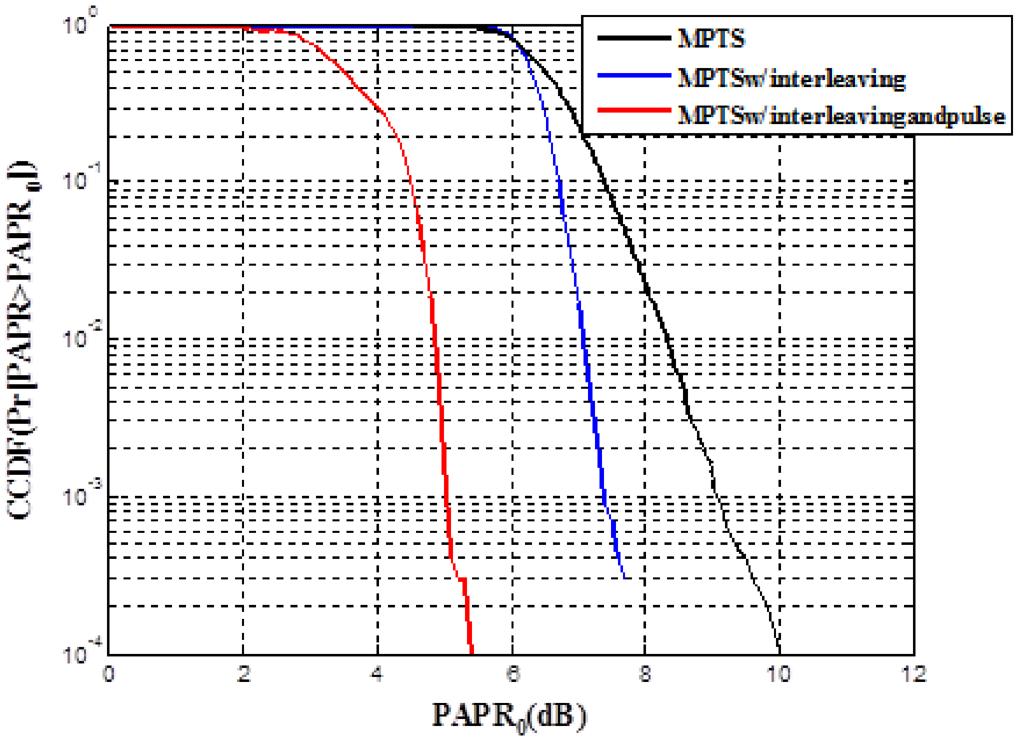

Figure 6.3 CCDF comparison of an OFDM system using modified PTS, modified PTS with interleaving and modified PTS with interleaving and pulse shaping method

6.5.2 Different Subcarriers with Fixed Subblocks *V*=4 for OFDM System

Figure 6.4 illustrates the PAPR reduction performance using modified PTS with interleaving and pulse shaping method for OFDM system with different number of subcarriers. The observation is that the values of PAPR for *N*= 64, 128, 256, 512, and 1024 become 1.3 dB, 2.7 dB, 4.8 dB, 6.8 dB and 7.8 dB respectively at CCDF of 10^{-3}. The increase in PAPR is significant with increase in the number of subcarriers of OFDM transmission system.

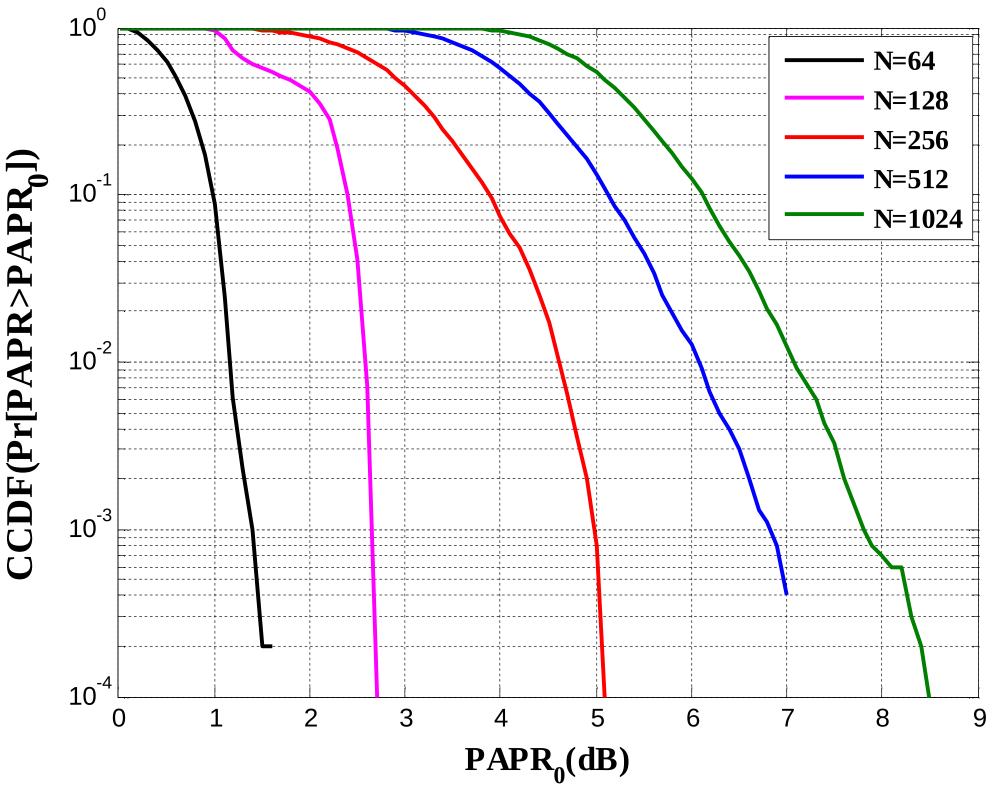

Figure 6.4 PAPR reduction performance of OFDM system for different subcarriers with *V*=4

6.5.3 Different Subblocks with Fixed Subcarriers *N*=256 for OFDM System

Figure 6.4 shows the CCDF of the PAPR increases as the number of subcarriers increases. A fixed number of subcarrier *N*=256 is assumed and the PAPR reduction performance is analysed for different number of subblocks. From Figure 6.5, it is visualized that the PAPR reduction performance is improved with increase in subblock sizes and the PAPR values are 6.8 dB, 4.8 dB, 1.8 dB, and 0.5 dB at CCDF of 10^{-3} for *V*=2, 4, 8 and 16 respectively.

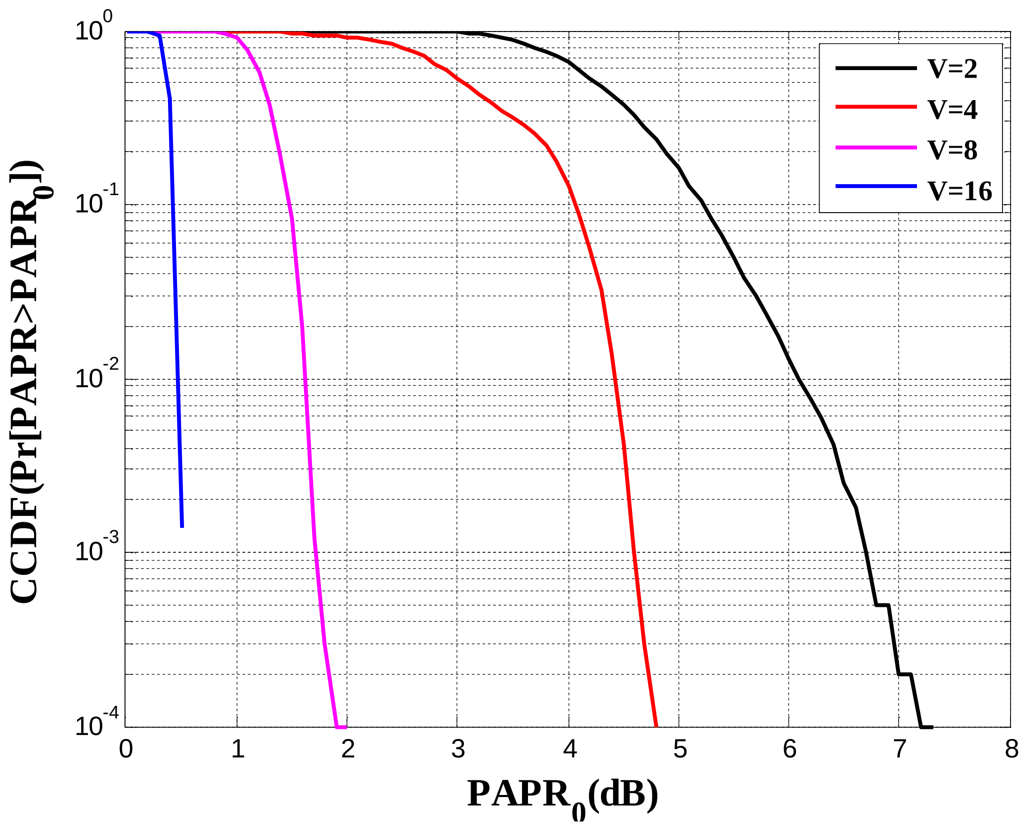

Figure 6.5 PAPR reduction performance of OFDM system for different subblocks with *N*=256

6.5.4 PAPR Performance of Modified PTS with and without Interleaving and Pulse Shaping Method for MIMO-OFDM System

In Figure 6.6, the PAPR reduction performance of MIMO-OFDM system by using modified PTS, modified PTS with interleaving and modified PTS with interleaving and pulse shaping are compared. It can be seen that the PAPR of modified PTS is 9.4 dB, the modified PTS with interleaving is 7.6 dB and the modified PTS with interleaving and pulse shaping method is 4.8 dB at CCDF of 10^{-3}. From Figure 6.6 it is observed that the maximum PAPR reduction performance of 36.84% is achieved by the modified PTS with interleaving and pulse shaping method when compared to modified PTS with interleaving technique. Also 50% decrease in the PAPR reduction performance is obtained as compared to modified PTS.

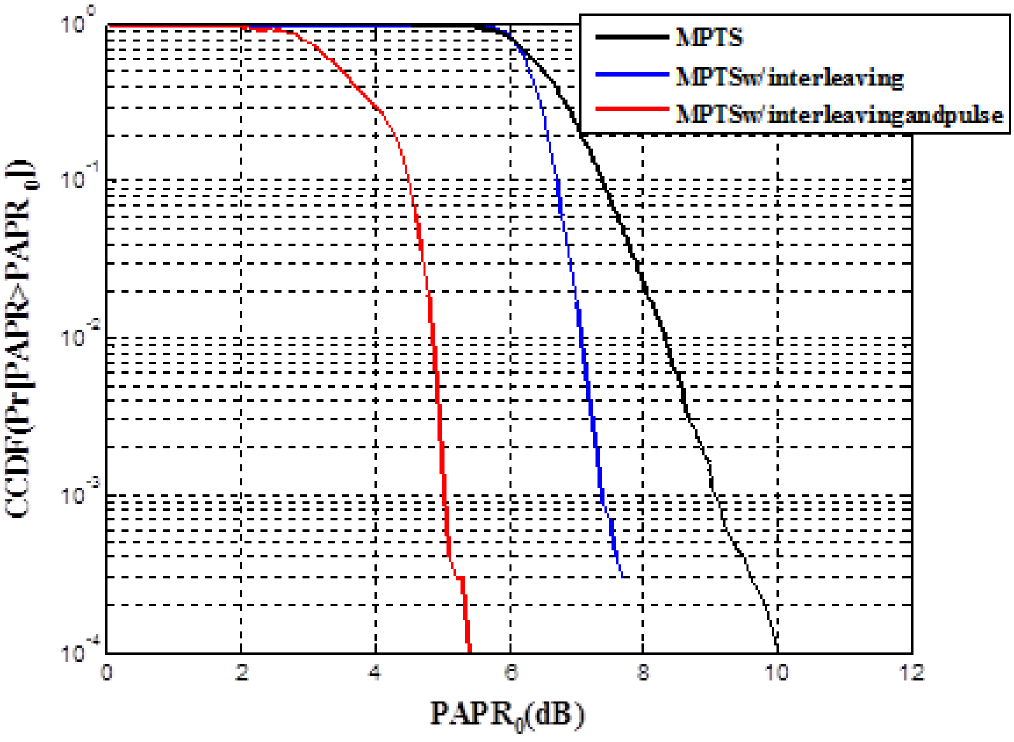

Figure 6.6 CCDF comparison of modified PTS, modified PTS with interleaving, modified PTS with interleaving and pulse shaping method for MIMO- OFDM system

6.5.5 Different Subcarriers with Fixed Subblocks V=4 for MIMO-OFDM System

Figure 6.7 shows that the performance of the modified PTS technique with interleaving and pulse shaping method for MIMO-OFDM system with different number of subcarriers. From this figure it is noted that the values of PAPR for *N*= 64, 128, 256, 512, and 1024 becomes 1.3 dB, 2.7 dB, 4.8 dB, 6.8 dB and 7.8 dB respectively at CCDF of 10^{-3}.

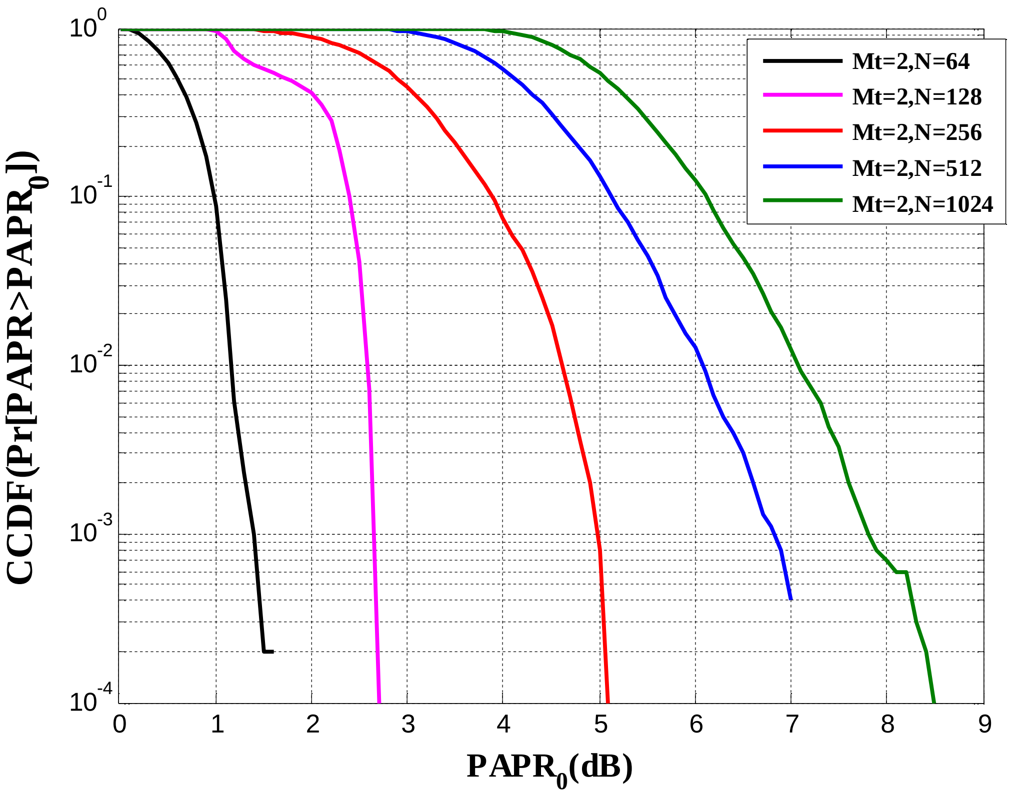

Figure 6.7 PAPR reduction performance of MIMO-OFDM system using modified PTS with interleaving and pulse shaping method for different subcarriers at *V*=4

6.5.6 Different Subblocks with Fixed Subcarriers *N*=256 for MIMO-OFDM System

The PAPR value increases significantly as the number of subcarriers used in the MIMO-OFDM transmission increases as shown in Figure 6.7. To mitigate the degradation of PAPR reduction performance modified PTS with interleaving and pulse shaping method in MIMO-OFDM system is considered for fixed number of subcarriers with different sizes of subblocks. In the Figure 6.8, it can be noted that, as the subblock size is increased from V = 2 to 16 the PAPR is reduced to 0.5 dB from 6.7 dB at CCDF of 10^{-3}. For V = 4 and 8, the CCDF values at 10^{-3} are 4.8 dB and 1.8 dB respectively. Thus, it can be concluded that by using modified PTS combined with interleaving and pulse shaping techniques, better PAPR reduction performance is achieved with increase in the number of subblocks.

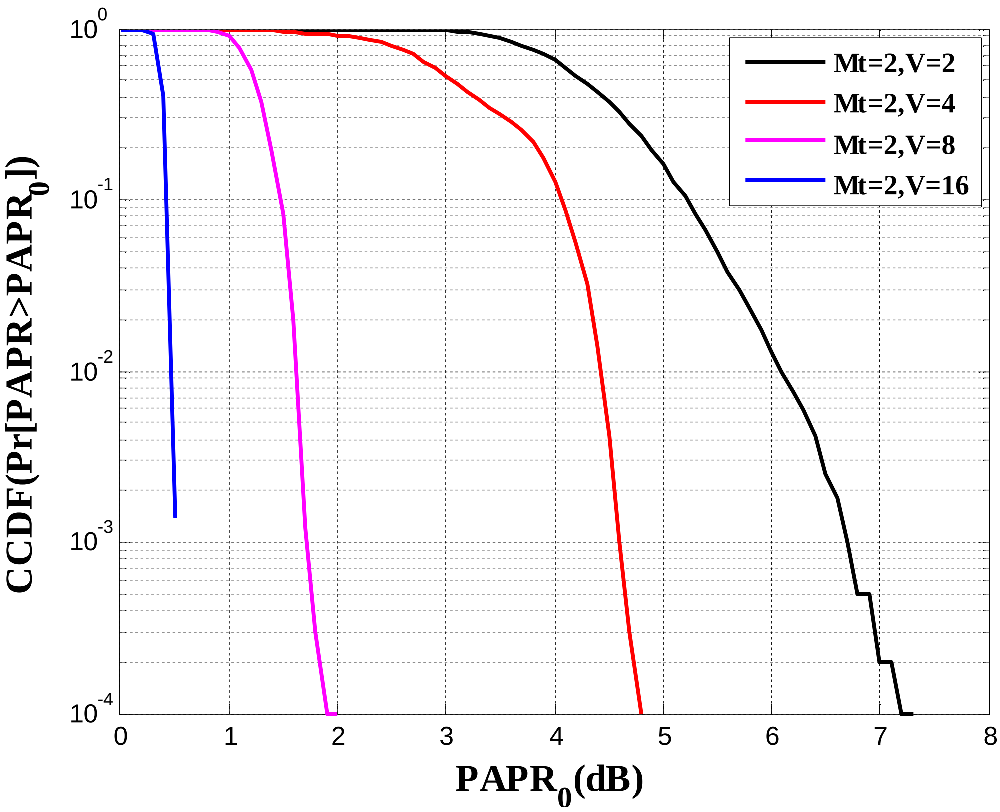

Figure 6.8 PAPR reduction performance of MIMO-OFDM system for different subblocks with *N*=256

6.6 SUMMARY

The approach employed for PAPR reduction in OFDM and MIMO-OFDM system is modified PTS with interleaving and pulse shaping method. The pulse shaping method avoids the use of any extra IFFTs and is based on a proper selection of the different subcarriers and subblocks. Simulation results illustrate the performance of the modified PTS with interleaving and pulse shaping method for OFDM and MIMO-OFDM systems. This method is an effective scheme to achieve a better trade-off between PAPR reduction and computational complexity. The computational complexity reduction ratio increases as the number of subcarriers increases and the proposed scheme becomes more suitable for the high data rate MIMO-OFDM system such as a digital multimedia wireless broadband mobile communication system. It has been shown that the PAPR performance can be improved 36.84% by using a modified PTS with interleaving and pulse shaping method compared with the modified PTS with interleaving method and also 50% PAPR reduction performance is achieved when compared to the modified PTS method.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 GENERAL

An attempt has been made in the present work to improve the PAPR reduction performance based on the combination of distortionless methods such as modified PTS, interleaving, coding techniques, superimposed training sequence and pulse shaping. The summary, salient conclusions and scope for further research work are presented in this chapter.

7.2 SUMMARY

Today, the modern wireless communication is facing a lot of challenges and researches for achieving reasonable data rate without sacrificing the bandwidth efficiency. The principle deliberation of OFDM system has been to prevent spectral growth and improve the efficiency of the power amplifier at the transmitter side.

In this work, an attempt has been made to combine modified PTS with interleaving to improve the PAPR reduction performance and minimise the computational complexity without degradation in BER performance. This approach has reasonable PAPR reduction and computational complexity increases exponentially with increase in the subblocks. Moreover, when large numbers of subcarriers are used, there exist high PAPR. So significant improvement is needed for PAPR reduction and this can be achieved using modified PTS combined with forward error correction coding such as turbo codes and Golay codes. Eventhough, both these techniques provide acceptable PAPR reduction it invokes unacceptable complexity and affects bandwidth efficiency. Yet there has not been a satisfying solution.

Furthermore, to get an excellent PAPR reduction performance, modified PTS has been combined with superimposed training sequence method. The superimposed training sequence, avoids the use of any extra IFFTs block. A better trade-off between PAPR reduction and computational complexity are achieved. This system will be suitable to medium and high mobility scenarios. However, modified PTS combined with interleaving and pulse shaping method has the potential of reducing the PAPR of the OFDM signal without affecting the bandwidth efficiency of the system. All above mentioned techniques have been incorporated to optimize the PAPR reduction in OFDM and MIMO-OFDM system.

7.3 CONCLUSIONS

Modified PTS with Interleaving Technique for OFDM and MIMO-OFDM Systems

The PAPR reduction performance of the proposed modified PTS combined with interleaving technique was examined through simulation analysis and compared with the modified PTS technique.

- Results show that the PAPR values of normal OFDM (without PAPR reduction) and modified PTS (with PAPR reduction) is 10.8 dB and 9.4 dB respectively when 256 subcarriers and 4 subblocks are used at CCDF to 10^{-3}.

- An improvement in PAPR reduction performance of around 13% is obtained for modified PTS compared to normal OFDM.

- When the subblocks are varied as 4, 8 and 16 with 256 subcarriers, the modified PTS with interleaving technique can achieve the PAPR values of 7.6 dB, 6.6 dB and 6.4 dB respectively at CCDF of 10^{-3}, thereby providing 19% PAPR reduction performance compared to the modified PTS technique. Similar conclusions are obtained for MIMO-OFDM systems.

- The modified PTS method reduces the computational complexity but the PAPR reduction performance is degraded. But in the case of modified PTS combined with interleaving method the PAPR performance is improved and computational complexity is reduced.

Modified PTS with FEC for OFDM and MIMO-OFDM Systems

Various error-control codes are usually invoked before the IFFT processing to deal with the loss in diversity. FEC scheme such as turbo codes and Golay complementary codes have been analysed.

- The simulation has been carried out and it has been observed that for the modified PTS with turbo codes when the number of subcarriers is 256 and the subblocks size is varied as 4, 8, and 16, the PAPR is reduced to 7.4 dB, 6 dB and 4.8 dB respectively at CCDF of 10^{-3}.

- From the above results, it is quantified that around 2.6% improvement in PAPR reduction performance is obtained compared to the modified PTS technique with interleaving method.

- Also, it is found that the modified PTS with Golay sequence achieves 60.5% improvement in PAPR reduction performance compared to the modified PTS with interleaving method.

- Golay complementary sequences define a structured way of generating PAPR reduction codes and they are sequence pairs for which the sum of autocorrelation functions is zero for all delay shifts not equal to zero. PAPR value of 3 dB is obtained for modified PTS based on Golay complementary sets eventhough the number of subcarriers is varied. These codes enjoy efficient encoding, good error-correcting capability, tightly controlled PAPR, and significantly extend the range of coding options.

Modified PTS with Superimposed Training Sequence Method for OFDM and MIMO-OFDM Systems

Furthermore, PAPR reduction performance of the modified PTS combined with superimposed training sequence method was evaluated for OFDM and also in MIMO-OFDM systems.

- The modified PTS with superimposed training sequence method are evaluated and PAPR values are 6.4 dB, 5 dB and 4.5 dB when 256 subcarriers and the subblocks size are increased from 4, 8, and 16 respectively at CCDF of 10^{-3}.
- The PAPR of the modified PTS with superimposed training sequence method result in 6.4 dB under same circumstances and thus provides 31.92% improvement in PAPR reduction performance compared to modified PTS.
- Similarly, the results as say that the modified PTS with superimposed training sequence method achieve 13.5% better PAPR reduction performance than modified PTS with turbo codes for OFDM and MIMO-OFDM systems.
- The superimposed training sequence has better correlation properties and lower PAPR due to its polyphase nature. A pre-defined pseudo noise sequence is super-imposed onto the data at a low power (in time domain) before transmission, thus avoiding the need for additional time slots for training. With the help of extra information provided by the training sequence, computational complexity is greatly reduced without sacrificing the PAPR reducing capability.

Modified PTS with Interleaving and Pulse Shaping Method for OFDM and MIMO-OFDM Systems

Finally, the modified PTS combined with interleaving and pulse shaping method for PAPR reduction have been analysed.

- When the sizes of subblocks are 4, 8, and 16 for 256 subcarriers, the modified PTS with interleaving and pulse shaping method provides PAPR of 4.6 dB, 1.8 dB and 0.5 dB respectively at CCDF of 10^{-3}.
- The modified PTS with interleaving and pulse shaping method has 25% improvement in PAPR reduction performance compared to modified PTS with superimposed training sequence method. And it can also been seen that 36.84% PAPR reduction performance is obtained than the modified PTS with interleaving technique.

7.4 SCOPE FOR FURTHER WORK

The following potential areas that might be interesting for researchers to pursue and explore in future are mentioned below.

i. Efforts can be made to provide a power control technique based on PAPR reduction using water filling algorithm in the channel estimation approach.

ii. Developing a Channel Dependent Scheduling (CDS) algorithm for the system to monitor the channel quality as a function of frequency for the each terminal and adapt subcarrier assignments to change in the channel frequency response of all the terminals.

iii. It would be necessary to investigate the performance of PAPR reduction using various modulation techniques, where the PAPR problem may not have been considered when optimizing the system parameters.

REFERENCES

[1] D. Tse and P.Viswanath, "*Fundamentals of Wireless Communication*", Cambridge University Press, Cambridge, UK, 2005.

[2] R. V. Nee and R. Prasad,"*OFDM for Wireless Multimedia Communications*", London, Artech House, 2000.

[3] V.Tarokh and H.Jafarkhani, "On the computation and reduction of the peak-to-average power ratio in multicarrier communications", *IEEE Transactions on Communications*, vol.48, no.1, pp.37-44, January 2000.

[4] Lin Yang, "*Link-level enhancement schemes utilizing multiple symbol representation for Multicarrier communication*", Ph.D. thesis, University of Manchester, September 2008.

[5] Haitham J.Taha and M.F.M. Salleh, "Multi-carrier transmission techniques for wireless communication systems: A survey", *WSEAS Transactions on Communications*, vol. 8, no. 5, pp. 457-472, May 2009.

[6] Zhiqiang Liu, Yan Xin and Georgios B.Giannakis, "Space-time-frequency coded OFDM over frequency-selective fading channels", *IEEE Transactions on Signal Processing*, vol. 50, no. 10, pp. 2465-2476, October 2002.

[7] M.Haridim, H.Matzner, V.Neder and D.Ezri, "Analysis of a fixed-complexity sphere decoding method for spatial multiplexing MIMO", *WSEAS Transactions on Communications*, vol. 8, no. 3, pp. 353-362, March 2009.

[8] S. M. Alamouti, "A simple transmit diversity technique for wireless communications", *IEEE Journal on Selected Areas in Communications,* vol. 16, no. 8, pp. 1451-1458, October 1998.

[9] Vahid Tarokh and A. R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction", *IEEE Transactions on Information Theory*, vol.44, no.2, pp. 744-765, March 1998.

[10] Pawan Sharma and Seema verma, "Performance analysis of peak-to-average power ratio reduction techniques for wireless communication using OFDM signals", *International Journal of Computer Science Issues*, vol.7, no.6, pp.261-268, November 2010.

[11] Suverna Sengar, and Partha Pratim Bhattacharya, "Performance improvement in OFDM system by PAPR reduction", *An International Journal of Signal and Image processing*, vol. 3, no.2, pp. 157-169, April 2012.

[12] T. Jiang and Y. Wu, "An Overview: Peak-to-average power ratio reduction techniques for OFDM signals", *IEEE Transactions on Broadcasting*, vol.54, no.2, pp.257-267, June 2008.

[13] T. Pollet, M. Van Bladel and M. Moeneclaey, "BER Sensitivity of OFDM Systems to Carrier Frequency Offset and Wiener Phase Noise", *IEEE Transactions on Communications*, vol. 43, no. 2/3/4, pp. 191-193, February 1995.

[14] M.Pauli and H.P.Kuchenbecher, "On the reduction of the out of band radiation of OFDM signals", *Proceedings of IEEE International Conference on Communications*, Atlanta, vol.3, pp. 1304-1308, June 1998.

[15] L. J. Cimini, "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing", *IEEE Transactions on Communication*, vol. 33, pp.665-675, July 1985.

[16] L. J. Cimini andX. D. Li, "Effects of clipping and filtering on the performance of OFDM", *IEEE Transactions on Communication Letters*, vol.2, no.5, pp.131-133, May 1998.

[17] H.Saeedi, M.Sharif and F.Marvasti, "Clipping noise cancellation in OFDM system using oversampled signal reconstruction", *IEEE Communications Letters*, vol. 6, no.2, pp. 73-75, Febuary 2002.

[18] Shang-Kang Deng and Mao-Chao Lin, "Recursive Clipping and Filtering with bounded distortion for PAPR reduction," *IEEE Transactions on Communication*, vol. 55, no. 1, pp. 227-230, January 2007.

[19] R. Van Nee and A. de. Wild, "Reducing the peak to average power ratio of OFDM", *Proceedings of IEEE Vehicular Technology Conference*, Ottawa, vol.3, pp. 2072-2076, May 1998.

[20] X.Huang, J.Lu, J.Zheng and J.Chuang, "Reduction of peak-to-average power ratio of OFDM signals with companding transform", *IEEE Transactions on Electronics Letters*, vol. 37, no.8, pp. 506-507, April 2001.

[21] X. Huang and J. Lu,J. Zheng, “Companding transform for reduction in peak-to-average power of OFDM signals”, *IEEE Transactions on Wireless Communications,* vol.3, no.6, pp. 2030–2039, November 2004.

[22] B. S. Krongold and D. L. Jones, “PAPR reduction in OFDM via active constellation extension”, *IEEE Transactions on Broadcasting*, vol.49, no.3, pp.258-268, September 2003.

[23] B. S. Krongold and D. L. Jones, “ An active –set approach for OFDM PAPR reduction via Tone Reservation”, *IEEE Transactions on Signal Processing*, vol.52, no.2, pp. 495-508, February 2004.

[24] R. W. Bauml, R. F. H. Fischer, and J. B. Huber, “Reducing the peak-to-average power ratio of multicarrier modulation by selective mapping”, *IEEE Transactions on Electronics Letters*, vol.32, no. 22, pp. 2056-2057, October 1996.

[25] Chin-Liang Wang, Sheng-Ju Ku, and Chun-Ju Yang, “A low complexity PAPR estimation scheme for OFDM signals and its application to SLM based PAPR reduction”, *IEEE Journal of Selected Topics in Signal Processing,* Taiwan, vol. 4, Issue 3, pp. 637-645, June 2010.

[26] M.Breiling, S.H.Muller and J.B.Huber, “SLM peak-power reduction without explicit side information”, *IEEE Transactions on Communications Letters*, vol. 5, no. 6, pp. 239-241, June 2001.

[27] Lei Wang, Kyongkuk Cho, Dongweon Yoon, and Sang Kyu Park, **“**PAPR reduction of OFDM signals using deliberate clipping and pre-scrambling technique”, *Proceedings of 4th International Conference on Signal Processing and Communication Systems*, Gold Coast, Australia, December 2010.

[28] S.H. Muller and J.B. Huber, “OFDM with reduced peak- to- average power ratio by optimum combination of partial transmit sequences”, *IEEE Transactions on Electronics Letters*, vol.33, no.5, pp.368-369, February 1997.

[29] S.H. Muller and J.B. Huber, “A novel peak power reduction scheme for OFDM”, *Proceedings of International Symposium on Personal, Indoor, and Mobile Radio Communication*,Finland, vol.3, pp.1090–1094, September 1997.

[30] S. G. Kang, J. G. Kim and E. K. Joo, “A novel subblock partition scheme for partial transmit sequence OFDM”, *IEEE Transactions on Broadcasting*, vol. 45, no.3, pp. 333-338, September 1999.

[31] H.G.Ryu, "PAPR reduction using subblock phase weighting method in OFDM communication system", *Proceedings of IEEE International Conference on Wireless Communications, Networking and Mobile Computing,* China, vol.1, pp.249-252, September 2005.

[32] C.Tellambura, "Phase optimization criterion for reducing peak-to-average power ratio of an OFDM signal", *IEEE Transactions on Electronics Letters*, vol. 34, no.2, pp. 169-170, January 1998.

[33] C. Tellambura, "Improved phase factor computation for the PAPR reduction of an OFDM signal using PTS", *IEEE Transactions on Communications Letters*, vol. 5, no. 4, pp. 135-137, April 2001.

[34] P.Boonsrimuang, B. Kriengkriwat, T. Paungma and H. Kobayashi, "Proposal of D-PTS method with non-uniform weighting factor for PAPR reduction in OFDM system", *Proceedings of IEEE 6thInternational Conference on Electrical Engineering / Electronics, Computer, Telecommunications and Information Technology,* Pattaya, vol. 2, pp. 954-957, May 2009.

[35] P. Liu, W. P. Zhu and M. O. Ahmad, "A phase adjustment based partial transmit sequence scheme for PAPR reduction", *Proceedings of Circuits System and Signal Processing*, vol. 24, no. 3, pp. 329-337, August 2004.

[36] S. K. Yusof, N. Fisal and T. S. Yin, "Reducing PAPR of OFDM signal using Partial Transmit sequences", *Proceedings of IEEE 9th Asia-Pacific Conference on Communications*, vol.1, pp. 411-414, September 2003.

[37] S. H. Han and J. H. Lee, "PAPR reduction of OFDM signals using a reduced complexity PTS technique", *IEEE Transactions on Signal Processing Letter*, vol.11, no. 11, pp. 887-890, November 2004.

[38] Y. Xin and I. J. Fair, "Low complexity PTS approaches for PAPR reduction of OFDM signals", *Proceedings of IEEE International Conference on Communications,* Seoul Korea, vol. 3, pp. 1991-1995, May 2005.

[39] L.J.Cimini and N.R.Sollenberger, "Peak-to-average power ratio reduction of an OFDM signal using partial transmit sequences", *IEEE Transactions on Communication Letters*, vol.4, no.3, pp.86-88, March 2000.

[40] J.H. Wen, S.H. Lee, Y.F. huang and H.L. Hung, "A suboptimal PTS algorithm based on particle swarm optimization technique for PAPR reduction in OFDM systems", *EURASIP Journal on Wireless Communications and Networking,* vol. 2008, Article ID 601346, pp. 1-8, DOI:10.1155/2008/601346.

[41] Le Hu, C. Li and G. Wan, “A modified sub-optimal algorithm for reducing PAR of multicarrier communication systems”, *Proceedings of IEEE International Conference on Innovative Computing, Information and Control,* Beijing, China, vol. 1, pp. 175-178, September 2006.

[42] K Srinivasarao, B Prabhakararao, and M V S Sairam, “Peak-to-average power reduction in MIMO-OFDM systems using sub-optimal algorithm”, *International Journal of Distributed and Parallel Systems,* vol. 3, no. 3, May 2012.

[43] Yuh-Ren Tsai and Sin-Jhih Huang, “PTS with non-uniform phase factors for PAPR reduction in OFDM systems”, *IEEE Transactions on Communications Letters,* vol. 12, no.1, pp. 20-22, January 2009.

[44] G. Lu, P. Wu and C. Carlemalm-Logothetis, “Peak-to-average power ratio reduction in OFDM based on transformation of partial transmit sequences”, *IEEE Transactions on Electronics Letters*, vol. 42, no. 2, pp.105-106, January 2006.

[45] Zi-Bin Zhao and Young-Hwan Kim, “A study on the PAPR reduction by hybrid algorithm based on the PTS and Guided Scrambling technique”, *Journal of Korea Information and Communication Socity*, vol.31, no.2A, pp.187-193, 2006.

[46] Q-S. Wen, Y. Xiao and H. Kayama, “The implement of Low-PAPR OFDM system”, *Proceedings of IEEE International Conference on Communications, Circuits and Systems,* Guilin, China, vol. 2, pp. 1226-1229, June 2006.

[47] Tian Ya-fei, Ding Rong-hua, Yao Xiao-an and Tang Hai-wei, “PAPR reduction of OFDM signals using modified partial transmit sequences”, *Proceedings of IEEE 2nd International Congress on Image and Signal Processing*, Tianjin, pp.1-4, October 2009.

[48] M.Sharif, M.Gharavi-Alkhansari, and B.H. Khalaj, “On the peak-to-average power of OFDM signals based on oversampling”, *IEEE Transactions on Communications*, vol.51, no.1, pp.72-78, January 2003.

[49] A.D.S.Jayalath and C.Tellambura, “Adaptive PTS approach for reduction of peak-to-average power ratio of OFDM signals”, *IEEE Transactions on Electronics Letters*, vol. 36, no. 14, pp. 1226–1228, July 2000.

[50] A.D.S, Jayalath and C.Tellambura, “The use of Interleaving to reduce the peak- to-average power ratio of an OFDM signal”, *Proceedings of IEEE Global Telecommunications Conference*, San Francisco, CA, pp. 82-86, December 2000.

[51] Roman Marsalex, "On the reduced complexity interleaving method for OFDM PAPR redcution", *Jounals on Radio Engineering*, vol. 1, no. 3, pp. 49-52, September 2006.

[52] Heung-Gyoon Ryu, Sang-Kyun Kim and Sang-Burm Ryu, "Interleaving method with outside information for the PAPR reduction of OFDM system", *Proceedings of International Symposium on Communications and Information Technologies*, Sydney, pp.72-76, October 2007.

[53] Jin Chuan-xue and Li Shao-qian, "Iterative random interleaver design for OFDM system", *Proceedings of Pacific-Asia Conference on Circuits, Communications and System*, Chengdu, pp. 85-87, May 2009.

[54] H. Sakran, M. Shokair, and A. Abou Elazm, "Combined Interleaving and Companding for PAPR reduction in OFDM systems", *Progress in Electromagnetics Research* , vol. 6, pp. 67–78, 2009.

[55] G.Jing,W.Jinkuan and W.Wang, "A low complexity PAPR reduction technique for STBC MIMO-OFDM system", *Proceedings of International Conference on Wireless Communications, Networking and Mobile Computing*, Shanghai, pp.109-112, September 2007.

[56] G.Jing, W. Jinkuan and X. Zhibin, "A new concurrent SLM algorithm for STBC MIMO-OFDM systems", *Proceedings of International Symposium on Intelligent Signal Processing and Communication Systems*, China, pp.132-135, December 2007.

[57] Harish Reddy and Tolga M.Duman, "Space-time coded OFDM with low PAPR", *Proceedings of Global Telecommunications Conference*, San Francisco, USA, vol.2, pp.799-803, December 2003.

[58] Z.Xiuyan, D.Yubo, and T.Guobin, "The research of peak-to-averagepower ratio performance by optimum combination of partial transmit sequences in MIMO-OFDM system", *Proceedings of the 3rd International Congress on Image and Signal Processing*, Yantai, China, vol. 9, pp. 4476- 4479, October 2010.

[59] Ben Lu and Xiaodong Wang, "Space-time code design in OFDM systems", *Proceedings of IEEE Global Telecommunications Conference*, San Francisco, USA, vol.2, pp.1000-1004, December 2000.

[60] Rick. S. Blum, Ye(Geoffrey) Li, Jack H. Winters, and Qing Yan, "Improved Space-Time Coding for MIMO-OFDM Wireless Communications", *IEEE Transactions on Communications*, vol.49, no.11, pp.1873–1878, November 2001.

[61] T. Mata, P. Boonsrimuang and H. Kobayashi, "A new weighting facotr with concurrrent PAPR reduction algorithm for STBC MIMO-OFDM", *Proceedings of IEEE 9th Malaysia International Conference on Communications*, Kuala Lumpur, Malaysia, pp. 136-140, December 2009.

[62] Dong Guo-fang, Gao Fei, FAN Jing and Zhao Zi-bin, "Enhancement of PAPR reduction using dynamic PTS algorithm in multiple antennas system", *Proceedings of 8th IEEE International Conference on Computer and Information Technology*, Sydney, pp. 613-617, July 2008.

[63] D.Phetsomphou, S. Yoshizawa and Y.Miyanaga, "A partial transmit sequence technique for PAPR reduction in MIMO-OFDM systems", *Proceedings of 10th International Symposium on Communications and Information Technologies*, Tokyo, Japan, pp.672-676, October 2010.

[64] Xu Yan, Wang Chunli, and Wang Qi, "Research of peak-to-average power ratio reduction improved algorithm for MIMO-OFDM system", *Proceedings of World Congress on Computer Science and Information Engineering*, Los Angeles, USA, vol.1, pp.171-175, April 2009.

[65] H. Ochiai and H. Imai, "Forward error correction with reduction of peak to average power ratio of QPSK multicarrier signals", *Proceedings of IEEE International Symposium on Information Theory*, Ulm, Germany, pp.120, June 1997.

[66] C. Tellambura, "A coding technique for reducing peak-to-average power ratio in OFDM", *Proceedings of Global Telecommunications Conference*, Sydney, vol. 5, pp. 2783-2787, November 1998.

[67] Kenneth G. Paterson and Vahid Tarokh, "Coding techniques for power controlled OFDM", *Proceedings of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Boston, vol.2, pp.801-805, September 1998.

[68] Kenneth G.Paterson, "Generalised Reed-Muller codes and power control in OFDM modulation", *IEEE Transactions on Information Theory*, vol. 46, no. 1, pp.104–120, January 2000.

[69] S. Uppal, "Codes with low peak-to-average power ratio for OFDM system", *International Journal of Engineering Science and Technology*, vol. 2, no.7, pp.3030-3037, 2010.

[70] Abolfazl Ghassemi and T. Aaron Gulliver, "PAPR reduction of OFDM using PTS and error-correcting code subblocking", *IEEE Transactions on Wireless Communications*, pp. 980-989, March 2010.

[71] Mao-Chao Lin, Kuan-Cheng Chen and Sherg-Lung Li, “Turbo coded OFDM system with peak power reduction”, *Proceedings of IEEE Vehicular Technology Conference,* Orlando, Florida, USA, vol.4, pp.2282-2286, October 2003.

[72] Yung-Chih Tsai, Shang-Kang Deng and Kuan-Cheng Chen, “ Turbo coded OFDM for reducing PAPR and error rates”, *IEEE Transactions on Wireless Communications*, vol.7, no.1, pp.84-89, January 2008.

[73] Pawan Sharma and Seema Verma, “PAPR reduction of OFDM signals using selective mapping with turbo codes”, *International Journal of Wireless and Mobile Networks*, vol.3, no.4, pp. 217-223, August 2011.

[74] Houshou Che and Hsinying Liang, “A modified seletive mapping with PAPR reduction and error correction in OFDM systems”, *Proceedings of IEEE Wireless Communications, and Networking Conference*, Kowloon, pp.1329-1333, March 2007.

[75] T. A. Wilkinson and A. E. Jones, “Minimisation of the peak-to-mean envelope power ratio of multicarrier transmission schemes by block coding”, *Proceedings of 45thIEEE Vehicular Technology Conference*, Chicago, vol. 2, pp. 825–829, July 1995.

[76] Tao Jiang and Guangxi Zhu, “Complement block coding for reduction in peak to average power ratio of OFDM signals”, *IEEE Radio Communications,* vol. 43,no. 9, pp.517-522, September 2005.

[77] J.A.Davis and J.Jedwab, “Peak-to-mean power control in OFDM, Golay complementary sequences, and Reed-Muller codes”, *IEEE Transactions on Information Theory*, vol. 45, no.7, pp. 2397–2417, November 1999.

[78] Fangling PU, Jianya Gong and Liangcai Gan, “OFDM peak-to-average power ratio reduction by combining the PTS with Golay complementary sequences and Reed-Muller codes”, *Proceedings of International Conference on Advanced Communication Technology*, Phoenix Park, vol. 2, pp. 845-848, 2005.

[79] Hamidreza Bakhshi and Mohammadamin Shirvani, “Peak-to-average power reduction by combining selective mapping and Golay complementary sequences”, *Proceedings of IEEE International Conference on Wireless Communications, Networking and Mobile Computing*, Beijing, pp.1-4, September 2009.

[80] Ning Chen and G. Tong Zhou, “Superimposed traning for OFDM: A peak-to-average power ratio analysis”, *IEEE Transcations on Signal Processing*, vol. 54, no. 6, pp. 2277-2287, June 2006.

[81] Luo ren-ze, WU Xiao-qiong, and Dang Yu-pu, "An estimation rotation factor PTS scheme with superimposed training sequence for PAPR reduction in OFDM system", P*roceedings of IEEE 7th International Conference on Wireless Communications, Networking and Mobile Computing*, Chengdu, China, pp. 1-4, September 2011.

[82] Youngseok Oh, Eui-Rim Jeong, Sungho Choi, Wooseok Nam, and Yong H. Lee, "Side information-free PTS-PAPR reduction via pilot assisted estimation of phase factors in an OFDM frame with a preamble", P*roceedings of IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications*, Daejeon, South Korea, pp. 41-45, September 2010.

[83] G. Tong Zhou, Mats Viberg and Tomas McKelvey, "A first-order statistical method for channel estimation", *IEEE Transactions on Signal Processing Letters*, vol. 10, no.3, pp. 57-60, March 2003.

[84] Tae-Young Han, Nam Kim, Jung-Hun Choi and JaeHwan Lee, "A PTS-OFDM phase-superimposed over pilot symbols", *Proceedings of 10th International Conference on Advanced Communication Technology*, Cheongju, South Korea, vol.7, pp.17-20, February 2008.

[85] S. Ben Slimane, "Peak-to-average power ratio reduction of OFDM signals using pulse shaping", *Proceedings of Vehicular Technology Conference*, USA, vol. 4, pp.889-893, September 2002.

[86] Hyung G Myung, Junsung Lim and Davide J Goodman, "Peak to average power ratio of single carrier FDMA signals with pulse shaping", *Proceedings of the 17th annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Helsinki, pp.1-5, September 2006.

[87] S. Zid and R. Bouallegue, "Low-complexity PAPR reduction schemes using SLM and PTS approaches for Interleaved OFDMA", *Proceedings of International Conference on Ultra Modern Telecommunications and Workshops*, Saint Petersburg, Russia, pp.1-5, October 2009.

[88] Lei Xia, Xiao Yue, Tang Youxi and Li Shaoqian, "A novel method to design phase factor for PTS based on pseudo-random subblock partition in OFDM system", *Proceedings of IEEE 66th International Conferenceon Vehicular Technology*, Baltimore, pp. 1269-1273, October 2007.

[89] Jae-kwon Lee Jeong-Sang Park and Jin-Up Kim, "An enhanced adjacent partitioning PTS technique with low computational complexity", *Proceedings of IEEE International Conferenceon Mobile and Wireless Communications*, Budapest, pp. 1-3, July 2007.

[90] G.Lu, P. Wu and C. Carlemalm-Logothetis, “Enhanced Interleaved partitioning PTS for peak-to-average power ratio reduction in OFDM systems”, *IEEE Transactions on Electronics Letters*, vol. 42, no. 17, pp. 983-984, August 2006.

[91] J.Sarawong, T.Mata, P.Boonsrimuang and H.Kobayashi, “Interleaved partitioning PTS with new phase factors for PAPR reduction in OFDM systems”, *Proceedings of 8th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, Khon Kaen, Thailand, pp. 361-364, May 2011.

[92] Shukla, R.Sapra, V. Goyal and M.Shukla, “Performance analysis of PAPR reduction in helical Interleaved OFDM system”, *Proceedings of IEEE International Conference on Communication Systems and Network Technologies*, GLA University, Mathura, India, pp.639-642, May 2012.

[93] C.Tellambura, “Computation of the continuous –time PAPR of an OFDM signal with BPSK subcarriers”, *IEEE Transactions on Communications Letters*, vol. 5, no. 5, pp. 185-187, May 2001.

[94] M.J.E.Golay, “Complementary series”, *Institute of Radio Engineers Transaction on Information Theory*, vol.7, pp.82-87, April 1961.

[95] T. Inada, T.Hattori, K.Nakamura and K.Obara, “Spectrum suppression and BER improvement in non-linear OFDM systems using complementary sequences with error correction”, *Proceedings of 10th Asia-Pacific Conference on Communications and 5th International Symposium on Multi-dimensional Mobile Communications*, Beijing, China, vol.2, pp.843-847, September 2004.

[96] S.Ben Slimane, “Performance of OFDM systems with time-limited waveforms over multipath radio channels”, *Proceedings of IEEE Global Telecommunications Conference*, Sydney, Australia, vol. 2, pp. 962-967, November 1998.

LIST OF PUBLICATIONS

International Journals

1. **P.Mukunthan** and P. Dananjayan, “Modified PTS with FECs for PAPR reduction of OFDM signals”, ***International Journal of Computer Applications***, vol. 11, no. 3, pp. 38-43, December 2010, ISBN: 978-93-80746-37-1, DOI: 10.5120/776-1095.

2. **P.Mukunthan** and P. Dananjayan, “Modified PTS with FECs for PAPR reduction in MIMO-OFDM systems with different subcarriers and subblocks”, ***International Journal of Computer Science Issues***, vol. 8, Issue 4, no. 2, pp. 444-452, July 2011, ISSN online: 1694-0814.

3. **P.Mukunthan** and P. Dananjayan, “PAPR reduction of an OFDM signal using modified PTS combined with interleaving and pulse shaping method”, ***European Journal of Scientific Research***, vol.74, no.4, pp. 475-486, April 2012, ISSN online: 1450-216X.

4. **P. Mukunthan** and P. Dananjayan, “Modified PTS combined with interleaving technique for PAPR reduction in MIMO-OFDM system with different subblocks and subcarriers”, ***International Association of Engineers – International Journal of Computer Science***, vol.39, Issue 4, no. 2, November 2012.

5. **P.Mukunthan** and P. Dananjayan, “A modified PTS combined with interleaving and pulse shaping method based on PAPR reduction for STBC MIMO-OFDM system”, ***World Scientific and Engineering Academy and Society International Journal of Transactions on Communications,*** vol. 12, Issue 3, pp. 121-131, March 2013, E-ISSN: 2224-2864.

6. **P.Mukunthan** and P. Dananjayan, “Modified PTS with interleaving for PAPR reduction of OFDM signal with QPSK subblocks”, ***International Journal of Future Computer and Communication***, vol. 3, no. 1, pp. 22- 25, February 2014.

International Conferences

7. **P.Mukunthan** and P. Dananjayan, “Modified PTS with FECs for PAPR reduction in MIMO-OFDM system with different subcarriers”, ***Proceedings of IEEE International Symposium on Humanities, Science and Engineering Research – Advanced Computation &Communications Technology***, Kuala Lumpur, Malaysia, pp.89-94, June 2011.

8. **P.Mukunthan** and P. Dananjayan, "Modified PTS with interleaving and pulse shaping method for PAPR reduction of OFDM signal with QPSK subcarriers", ***Proceedings of Second International Conference on Information and Communication Technology***, Chennai, India, pp.65-71, December 2011, Organised by Interscience Research Network.

9. **P.Mukunthan** and P. Dananjayan, "PAPR reduction by modified PTS combined with interleaving technique for OFDM system with QPSK subcarriers", ***Proceedings of second IEEE International Conference on Advances in Engineering, Science and Management***, Nagapattinam, India, pp. 410-415, March 2012.

10. **P.Mukunthan** and P. Dananjayan, "Modified PTS with interleaving for PAPR reduction of OFDM signal with QPSK subblocks", ***Proceedings of fourth IEEE International Conference on Electronics Computer Technology***, Kanyakumari, India, vol. 3, pp.262-265, April 2012.

11. **P.Mukunthan** and P. Dananjayan,"PAPR reduction based on a modified PTS with interleaving and pulse shaping method for STBC MIMO-OFDM system", ***Proceedings of third IEEE International Conference on Computing, Communication and Networking Technologies***, Coimbatore, India, pp. 1-6, July 2012, DOI:10.1109/ICCCNT.2012.6396082.

12. **P.Mukunthan** and P. Dananjayan, "PAPR reduction by modified PTS combined with superimposed training sequence method for MIMO-OFDM system with different subcarriers", ***Proceedings of IEEE International Conference on Radar, Communication and Computing***, Tiruvannamalai, India, pp. 59-65, December 2012.

13. **P.Mukunthan** and P. Dananjayan, "Modified PTS based on superimposed training sequence method for PAPR reduction of OFDM signals with different subblocks", ***Proceedings of International Association of Science and Technology for Development Conference on Engineering and Applied Science***, Colombo, Sri Lanka, pp.443-449, December 2012, DOI:10.2316/P.2012.785-134.

Communicated

14. **P.Mukunthan** and P. Dananjayan, "Modified PTS based on superimposed training sequence method for PAPR reduction in OFDM system with different subblocks and subcarriers", ***Iranian Journal of Electrical and Electronic Engineering.***

VITAE

P. Mukunthan received B.E degree in Electronics and Communication Engineering from University of Madras, Chennai, India in 1998 and M.E degree in Applied Electronics from University of Madras, Chennai, India in 2000. He has thirteen years of teaching experience. He is currently working as Assistant Professor in the Department of Computer Science and Engineering at Adhiparasakthi Engineering College affiliated to Anna University, Chennai, India. He is a full time Research Scholar in the Department of Electronics and Communication Engineering, Pondicherry Engineering College, Puducherry, India. He presented his research papers in International Conference held at Kuala Lumpur (Malaysia) and Colombo (Sri Lanka). He has published six papers in International Journals and seven papers in International Conferences. His research interests include computer networks, wireless communication and Mobile Computing.