A NEW APPROACH FOR PERFORMANCE IMPROVEMENT OF OFDM SYSTEM USING PULSE SHAPING

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Technology

(Research)

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By

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ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation technique, in which a single high rate data-stream is divided into multiple low rate data-streams and is modulated using sub-carriers, which are orthogonal to each other. Some of its main advantages are multipath delay spread tolerance, high spectral efficiency, efficient modulation and demodulation process using computationally efficient Inverse Fast Fourier Transform and Fast Fourier Transform operation respectively. The peak to average power ratio of the time domain envelope is an important parameter at the physical layer of the communication system using OFDM signaling. The signals must maintain a specified average energy level in the channel to obtain the desired Bit-error-rate. The peak signal level relative to that average defines the maximum dynamic range that must be accommodated by the components in the signal flow path to support the desired average. A secondary concern is the carrier frequency offset which disturbs the orthogonality among the carriers and results ICI. The undesired ICI degrades the performance of the system.

This thesis work overviews some of the previously reported Peak-to-Average Power Ratio and Inter-Carrier-Interference reduction techniques. Extensive simulation study and comparisons are carried out to justify their applications. The thesis proposes an efficient pulse shaping technique for compensating both PAPR and ICI which in turn improves the performance of the OFDM system. Modification for conventional pulse shape is attempted in this research by including new design parameters to shape their spectral response. Some of the performance measures like Complementary Commutative Distribution Function of PAPR, ICI power, SIR, and BER are analyzed through simulation study to demonstrate the efficacy of the proposed scheme.

National Institute of Technology
Rourkela

CERTIFICATE

This is to certify that the thesis entitled "**A New Approach for Performance Improvement of OFDM System Using Pulse Shaping**" submitted by **Ms. Srabani Mohapatra**, in partial fulfillment of the requirements for the award of Master of Technology (Research) in Electrical Engineering, at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge, the matter presented her in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date:

Place: NIT Rourkela

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Finally, I am forever indebted to my parents and my sisters for their understanding and encouragement when it was most required.

I dedicate this thesis to my family and friends.

Srabani Mohapatra

CONTENTS

LIST OF ACRONYMS

AWGN	Additive White Gaussian Noise
PAPR	Peak-to-Average Power Ratio
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BTRC	Better Then Raised Cosine Pulse
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
DAB	Digital Audio Broadcast
DFT	Discrete Fourier Transform
DSL	Digital Subscriber Line
DSP	Digital Signal Processing
DVB	Digital Video Broadcast
FDMA	Frequency Division Multiple Access
GMSK	Gaussian Minimum Shift Keying
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
HDSL	High speed Digital Subscriber Line
HDTV	High Definition Television
IDFT	Inverse Discrete Fourier Transform
ICI	Inter Carrier Interference
ISI	Inter Symbol Interference
ISP	Improved Sinc Power Pulse
LAN	Local Area Network
MC	Multicarrier Communication
MCM	Multi Carrier Modulation
OFDM	Orthogonal Frequency Division Multiplexing
PSK	Phase Shift Keying
16PSK	16 Phase Shift Keying
PTS	Partial Transmit Sequence

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RC	Raised Cosine Pulse
REC	Rectangular Pulse
RF	Radio Frequency
SIR	Signal to Interference Ratio
SLM	Selected Mapping
SNR	Signal to Noise Ratio
SP	Sinc Power Pulse
TDMA	Time Division Multiple Access
VHDSL	Very High speed Digital Subscriber Line
VLSI	Very Large Scale Integration
WLAN	Wireless Local Area Network

LIST OF SYMBOLS

k	Discrete Frequency (0 to *N-1*)
n	Time Sample
N	Number of Subcarrier
T_s	Symbol Duration of the base band Modulated Signal
Δf	Sub-channel Spacing
f_c	Carrier Frequency
BW_{total}	Bandwidth Total
$X(k)$	the Transmitted Symbol for the k^{th} subcarrier
α	Roll-off Factor

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Chapter 1

INTRODUCTION

INTRODUCTION

1.1 Introduction

New Technologies and thereby various applications are emerging not only in wired environment but also in the wireless area in the last few years. The next generation mobile systems shall be able to handle a substantially high data rate to meet the requirements of future high performance multimedia applications. The minimum target data rate for the 4G system is expected to be at 10-20 Mbps and at least 2Mbps in the moving vehicles. To provide such a high spectral efficiency, an efficient modulation scheme is to be employed [1,2]. A promising modulation technique that is increasingly being considered for adoption by 4G community is Orthogonal Frequency Division Multiplexing (OFDM). In recent years, OFDM has emerged as the standard of choice in a number of important high data rate applications.

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation technique, in which a single high rate data-stream is divided into multiple low rate data-streams and is modulated using sub-carriers which are orthogonal to each other [3]. Major advantages of OFDM are its multi-path delay spread tolerance and efficient spectral usage by allowing overlapping in the frequency domain. Also another significant advantage is that the modulation and demodulation can be done using IFFT and FFT operations, which are computationally efficient [4]. In addition to above, OFDM has several favorable properties like high spectral efficiency, robustness to channel fading, immunity to impulse interference, uniform average spectral density, capacity to handle very strong echoes and non-linear distortion [5,6]. Hence, OFDM is a promising modulation technique which can be used in many new broadband communication systems.

Two major limitations of OFDM systems are Peak-to-Average Power Ratio (PAPR) and Inter Carrier Interference (ICI). PAPR is a measurement of waveform calculated from the peak amplitude of the waveform divided by the RMS value of the waveform and this large peak occurs due to the constructive superimposition with a number of subcarriers or the summation of a large number of subcarriers. This high PAPR demands high power amplifiers (HPA) at the transmitter. The non-linearity effects of HPA on the transmitted OFDM symbols are spectral spreading, inter modulation and changing the signal constellation. In other words, the non-linear distortion causes both in-band and out-of band interference to signals. Further OFDM system is vulnerable to frequency-offset errors between the transmitted & received signals, which may be caused by Doppler shift in the channel or by difference between the transmitter and receiver local oscillator frequencies. Hence orthogonality is lost between subcarriers resulting in intercarrier interference (ICI). If ICI in not properly compensated it results in power leakage among the subcarriers and orthogonality between them will be lost. Result in degradation of system performance is observed.

This chapter begins with an exposition of the principal motivation behind the work undertaken in the thesis followed by a literature survey as discussed in section 1.3. The contributions and layout of the thesis have been outlined in section 1.4.

1.2 Motivation for Work

Over the last decade a lot of research has been carried out in reducing the two major limitations of OFDM for improving the performance of the system. The large variation in envelope of OFDM signal, which causes high peak-to-average power ratio (PAPR) and the sensitivity of OFDM signal against carrier frequency offset which causes inter-carrier interference (ICI) are the focussed area of this research. Previously reported schemes like clipping and filtering, selected mapping, partial transmit sequence, tone reservation, and tone insertion provide PAPR reduction. Peak regrowth in clipping and filtering causes the transmitted signal to exceed the clipping level at some points. In case of selected mapping and partial transmit sequence technique; the transmitter needs some side information. Overall it is noticed that these techniques have large computational overhead. An ICI self-cancellation scheme causes reductions in bandwidth efficiency. So there is a need to develop new technique which can overcome those drawbacks of existing ones and also provide performance enhancement from practical implementation point of view.

1.3 Literature Survey

OFDM is a special form multicarrier (MC) that dates back to 1960s. The concept of multicarrier transmission was first explicitly proposed by Chang [1] in 1966. A detailed description of multicarrier can also be found in [2] and [3]. In 1971, Weinstin and Ebert [4] proposed time limited multicarrier transmission, which is what we call OFDM today. The implementation of MC systems with equalization was investigated by Hirosaki etal.[5] and [6] and Peled and Ruiz [7]. Zimmerman and Kirsch [8] published one of the earliest papers in the application of MC in HF radio in 1967. More materials on the HF application of MC can be found in [9]. In 1985, Cimini first applied OFDM in mobile wireless communications [10]. In [11], Casas and Leung discussed the application of MC over mobile radio FM channels. Bingham [12] studied the performance and complexity of MC modulation and concluded that MC has higher potential in future. The application of original OFDM, clustered OFDM, and MC code-division multiple access (CDMA) in mobile wireless systems can be found in [13]-[14]

The flexibility of OFDM provides opportunities to use advanced techniques, such as adaptive loading, transmit diversity, and receiver diversity, to improve transmission efficiency. Shannon’s classical paper in 1948 suggested that the highest data rate can be achieved for frequency-selective channels by using an MC system with an infinitely dense set of sub-channels and adapting transmission powers and data rates according to the signal-to-noise ratio (SNR) at different sub-channels. Based on his theory, a water-filling principle has been derived. Cioffi and his group have extensively investigated OFDM with performance optimization for asymmetric digital subcarrier line, which they discrete multiple tone (DMT). Some of their earlier inventions on practical loading algorithms for OFDM or DMT systems were in [15][16].

More recently, OFDM has been implemented in mobile wideband data transmission (IEEE 802.11a, Hyper LAN II), high-bit-rate digital subcarrier lines

(HDSL), asymmetric digital subcarrier lines (ADSL), very high-speed digital subscriber lines (VHDSL), digital audio broadcasting (DAB), digital television and high-definition television (HDTV), IEEE 802.16 Wi-MAX standard and its predecessor multicarrier multipoint distribution service (MMDS) [17] [18] [19].

Despite the widespread acceptance of OFDM, it has its drawbacks. One drawback is that OFDM systems are not robust in carrier frequency estimation errors. Even small carrier frequency offsets destroy the orthogonality between the subcarriers causing drastic error rate increases. The second drawback is that OFDM signals suffer from large envelope variations. Such variations are problematic because practical communication systems are peak power limited. Thus, envelope peaks require a system to accommodate an instantaneous signal power that require lager power efficiencies or power amplifier (PA) saturation. This problem is termed as Peak to Average Power Reduction.

PAPR reduction was required for radar and speech synthesis applications. In radar, PAPR reduction was important because radar systems are peak-power limited just like communications system. And for communication system a number of approaches have been proposed to deal with the PAPR problem. These techniques include Clipping, Clipping and Filtering, Tone Reservation, Tone injection; Selected Mapping and Partial Transmit Sequence.[20-27] Clipping is the most straight forward PAPR reduction technique but can lead to significant out-of-band distortion. In order to alleviate such effects filtering can be applied. However, this causes significant peak-regrowth. Distortion-less techniques such as Tone Reservation also requires the receiver to know the location of the reserved tones so as to disregard them when decoding the data signal. Selected Mapping (SLM) is implemented by generating a set of sufficiently different signals from the original data signal. The transmitter selects and submits the candidate signal having the lowest PAPR. Partial Transmit Sequencing (PTS) is a similar technique in which sub-blocks of the original signal are optimally combined at the transmitter to generate a transmitted signal with a low PAPR. Although SLM and PTS are effective at reducing the PAPR, they require the use of side information in order to decode the signal at the receiver.

However, for inter carrier interference (ICI) reduction a few techniques like frequency domain equalization, time domain windowing, ICI self-cancellation are analyzed [28] [29] [30] [31]. It is found that the first two methods are not so efficient because they do not address the major cause of ICI which is due to the frequency mismatch between the transmitter and receiver, and the Doppler shift. But the drawback of the ICI self-cancellation method is that the same data is modulated into two or more carriers, thus reducing spectral efficiency.

1.4 Objective and Outline of Thesis

This thesis overviews some of the existing techniques through investigation. Extensive simulation study and comparisons are done to justify their applications. But the previously reported literatures have suggested individual schemes to reduce PAPR and ICI. Till now no scheme has been presented which can reduce both the drawbacks simultaneously. This thesis proposes an efficient technique having low implementation complexity which has the potential of compensating both PAPR and ICI problems significantly without affecting spectral efficiency of the system. This thesis is organized as follows:

Chapter 2: The basic principle of OFDM system is discussed in Chapter-2. OFDM communication system including its generation and reception, advantages, applications and two major limitations such as peak-to-average power ratio (PAPR) & inter-carrier interference (ICI) are briefly focussed in this chapter. Orthogonal Frequency Division Multiplexing (OFDM) as a transmission technique is known to possess a lot of strength, compared to any other transmission technique, such as high spectral efficiency, robustness to the channel fading and immune to impulse interference. Also Chapter 2 outlines the effect of several radio impairment factors like AWGN, delay spread, multipath fading etc on the BER performance.

Chapter 3: The chapter overviews the existing PAPR and ICI reduction techniques. For PAPR existing schemes like clipping and filtering, selected mapping, and partial transmit sequence are analyzed in detail. Simulation study is carried out in each PAPR reduction technique and their performances are compared. Also in case of inter carrier interference

(ICI), existing methods namely frequency domain equalization, time domain windowing and ICI self cancellation are analyzed. It is found that the first two methods are not so efficient, because they do not address to the major cause of ICI which is due to the frequency mismatch between the transmitter and receiver and the Doppler shift. The drawback of ICI self cancellation scheme is that the same data is modulated into two or more carriers, thus reducing the spectral efficiency. In Pulse shaping method there is no loss of spectral efficiency.

Chapter 4: An efficient technique to reduce peak to average power ratio is proposed in this chapter. This novel method based on pulse shaping technique is superior compared to existing methods in terms of performance and complexity. It is discussed in various literature that the PAPR of the OFDM signals can be reduced if the subcarrier waveforms have different shapes. With a proper selection of pulses to shape the subcarrier waveforms, significant improvement in PAPR reduction can be achieved. Hence simulation study has been carried out to implement this technique by incorporating the pulse shaping functions in the basic OFDM system.

A number of pulse shaping functions such as Rectangular pulse (REC), raised cosine pulse (RC), Modified raised cosine pulse (MRC), Sinc power pulse (SP) and Improved sinc power pulse (ISP) are considered for both PAPR and ICI reduction. Overcoming the inter carrier interference (ICI) using the proposed pulse shapes in OFDM system is also attempted. Simulation study, performance evaluation and results are discussed. Performance enhancement of pulse shaping OFDM system is analyzed.

Chapter 5: Chapter-5 summarizes and concludes the total research work in brief. Peak-to-average power ratio and inter carrier interference are major limitations of OFDM system which degrades the performance. Pulse shaping technique is found to be more efficient than other conventional ones like clipping and filtering, selected mapping, partial transmit sequence in terms of peak to average power ratio reduction. Simulation study and results show that utilizing improved sinc pulse (ISP) in OFDM system provides better performance in terms of PAPR. The proposed pulse shaping functions also provide the additional advantage of ICI reduction with ease.

Chapter 2

BASICS OF ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING SYSTEM

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2.1 Introduction

Orthogonal Frequency Division Multiplexing (OFDM) has grown to a popular communication technique for high speed communication in the last decade. Being an important member of the multicarrier modulation (MC) techniques, Orthogonal Frequency Division Multiplexing (OFDM), is also called Discrete Multitone Modulation (DMT) [2]. It is based upon the principle of frequency division multiplexing (FDM) where each frequency channel is modulated with simpler modulation scheme. It splits a high rate data stream into a number of lower rate streams that are transmitted simultaneously over a number of orthogonal subcarriers [3]. Orthogonality is achieved by ensuring that the carriers are placed exactly at the nulls in the modulation spectra of each other. The increase of symbol duration for the lower rate parallel subcarriers reduces the relative amount of dispersion in time caused by multipath delay spread. Therefore OFDM is an advanced modulation technique which is suitable for high-speed data transmission due to its advantages in dealing with the multipath propagation problem, high data rate and bandwidth efficiency [4]. Although OFDM principles have been developed over several decades, its implementation for high data rate communications has only recently become popular by the reduced cost and availability of suitable signal processing components which make it a competitive technology for commercial applications also.

2.2 Evolution of OFDM

The evolution of OFDM [2] can be divided into three parts. These consist of Frequency Division Multiplexing (FDM), Multicarrier Communication (MC) and Orthogonal Frequency Division Multiplexing.

2.2.1 Frequency Division Multiplexing (FDM)

Frequency Division Multiplexing (FDM) has been used for a long time to carry more than one signal over a telephone line. FDM is the concept of using different frequency channels to carry the information of different users. Each channel is identified by the central frequency of transmission. To ensure that the signal of one channel does not overlap with the signal from an adjacent one, some gap or guard band is left between different channels. This guard band leads to inefficiencies which were exaggerated in the early days since the lack of digital filtering made it difficult to filter closely packed adjacent channels.

2.2.2 Multicarrier Communication (MC)

Multicarrier (MC) is actually the concept of splitting a signal into a number of signals, modulating each of these new signals over its own frequency channels; multiplexing these different frequency channels together in an FDM manner; feeding the received signal via a receiving antenna into a de-multiplexer that feeds the different frequency channels to different receivers and combining the data output of the receivers to form the received signal.

2.2.3 Orthogonal Frequency Division Multiplexing

OFDM is derived from the concept of MC where the different carriers are orthogonal to each other. Orthogonal in this respect means that the signals are totally independent. It is achieved by ensuring that the carriers are placed exactly at the nulls in the modulation spectra of each other.

2.3 Orthogonal Frequency Division Multiplexing Technology

In OFDM system, the bit stream that is to be transmitted is split into several parallel bit streams. The available frequency spectrum is divided into sub-channels and each low rate bit stream is transmitted over one sub-channel by modulating a subcarrier using a standard modulation scheme, for example; PSK, QAM. The sub-carrier frequencies are chosen so that the modulated data streams are orthogonal to each other, ensuring that cross talk between the sub-channels is eliminated. Channel equalization is simplified by using many slowly modulated narrowband signals instead of one fastly modulated wideband signal. The primary advantage of OFDM is its ability to cope up with severe channel conditions, for example multipath and narrowband interference without complex equalization filters. The performance of OFDM system depends on several factors, such as the modulation schemes used, the amount of multipath, and the level of noise in the signal.

The performance of a single carrier transmission will degrade rapidly in the presence of multipath. Before equalizers are developed parallel transmission scheme was preferred for achieving high data rate despite its bandwidth inefficiency and high cost due to several modulators and demodulators.

Table2.1. Compares parallel transmission scheme with a single carrier transmission scheme.

Transmission method	**Parallel**	**Serial**
Symbol time	Ts	Ts/N
Rate	1/ Ts	N/Ts
Total BW required	2*N/ Ts + N*0.1/ Ts (Assume Guard band=0.1/Ts)	2*N/Ts
Susceptibility to ISI	Less	More

Table 2.1: Comparison of Parallel and Serial Transmission Schemes.

Although OFDM is a parallel transmission scheme, those problems are eliminated by using orthogonal sub-carriers ‘N’ instead of widely spaced sub-carriers (i.e., carriers with guard band between them). Applying, IFFT and FFT algorithms for implementing the modulation and demodulation operations.

Orthogonality can be achieved by carefully selecting carrier spacing, such as letting the carrier spacing be equal to the reciprocal of the useful symbol period. As the sub-carriers are orthogonal, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system. This results in no interference between the carriers, allowing them to be spaced as close as theoretically possible. Mathematically

$$\int_b^a X_p(t) X_q(t)^* dt = \begin{cases} k & for \quad p \neq q \\ 0 & for \quad p = q \end{cases} \tag{2.1}$$

Where * indicates the complex conjugate and interval [a, b], is a symbol period. Since the carriers are orthogonal to each other the nulls of one carrier coincides with the peak of another sub-carrier.

2.3.1 OFDM Modulation & Demodulation

The OFDM signal can, in general, be represented as the sum of '*N*' separately modulated orthogonal subcarriers

$$x(t) = \sum_{n=-\infty}^{\infty} \sum_{k=0}^{N-1} s_{n,k} \; g_k \; (t - nT_s) \tag{2.2}$$

Where $g_k(t)$, $k = 0,1,.......,N-1$ represent the '*N*' carriers and are given by,

$$g_k(t) = e^{j2\pi f_k t}, \quad t \in [0, T_s] \tag{2.3}$$

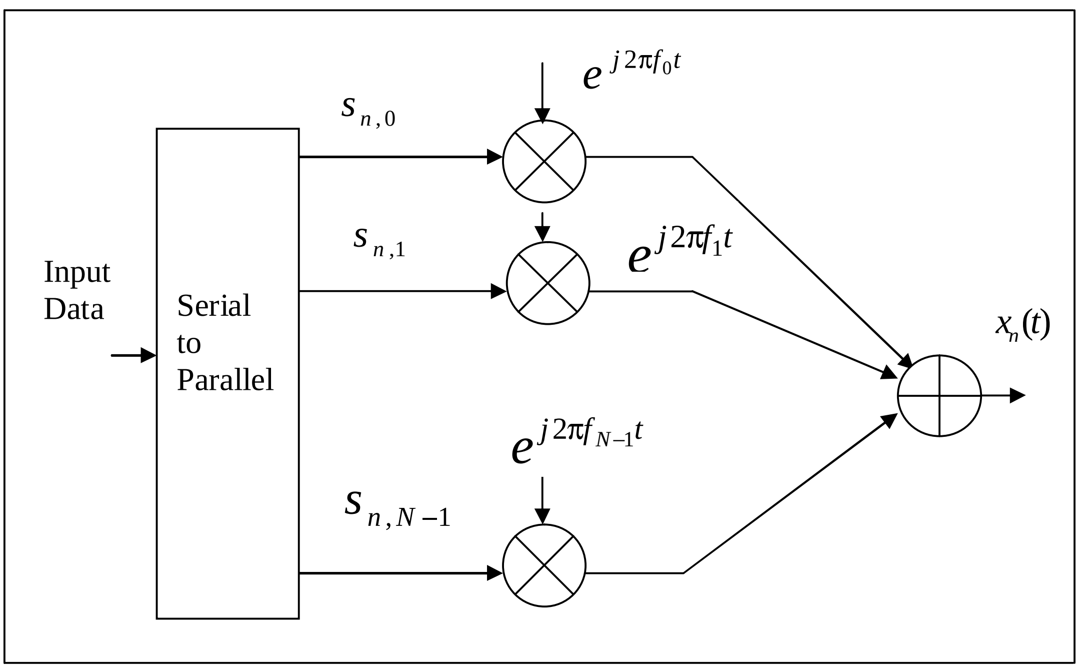

Fig 2.1 OFDM Modulation

In equation (2.2), $s_{n,k}$ stands for the symbol that modulates the k^{th} carrier in the n^{th} signaling intervals and each signaling interval is of duration T_s. From equation (2.2), we see that 'N' symbols are transmitted in Ts time interval. The symbol sequence $s_{n,k}$ is obtained by converting a serial symbol sequence of rate N/T_s (symbol duration=T_s/N) into 'N' parallel symbol sequences of rate $1/T_s$ (each with symbol duration T_s).

As mentioned previously, the subcarrier frequencies satisfy the following requirement

$$f_k = f_0 + \frac{k}{T_s},\ k = 1,2,.........,N-1 \qquad (2.4)$$
$$= f_0 + k\Delta_f$$

The signal transmitted in the n^{th} signaling interval (of duration Ts) is defined as the n^{th} OFDM frame, i.e.,

$$x_n(t) = \sum_{k=0}^{N-1} s_{n,k}\, g_k(t - nT_s) \qquad (2.5)$$

Thus it is observed that the n^{th} OFDM frame $x_n(t)$ consists of *'N'* symbols, each modulating one of the 'N' orthogonal sub-carriers. Since the carriers are orthogonal with each other, it follows that the scalar product

$$< g_k(t), g_i(t) > T_s = \int_{T_s} g_k(t) g_i^*(t)\, dt = T_s \delta(k-i) \qquad (2.6)$$

Fig 2.2 illustrates the N orthogonal subcarriers used in n^{th} OFDM frame. Thus, the orthogonality of the carriers can be used to demodulated each of the sub-carriers (without inter-carrier interference) as follows

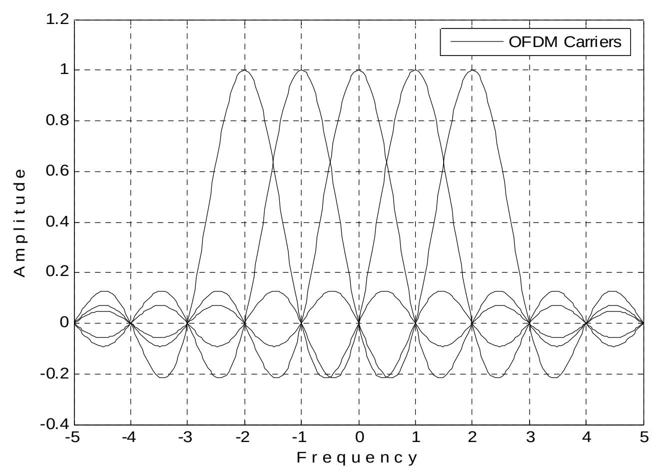

Fig. 2.2 Sub-carriers in the OFDM spectrum

$$s'_{n,k} = \frac{1}{T_s} \int_{nT_s}^{(n+1)T_s} x(t)\, g_k(t)\, dt \tag{2.7}$$

If there is zero inter-frame interference, then the above expression reduces to

$$s'_{n,k} = \frac{1}{T_s} \int_{nT_s}^{(n+1)T_s} x_n(t)\, g_k(t)\, dt = s_{n,k} \tag{2.8}$$

Thus we are able to perfectly demodulate each sub-carrier in the transmitted signal and get back the transmitted symbol sequence.

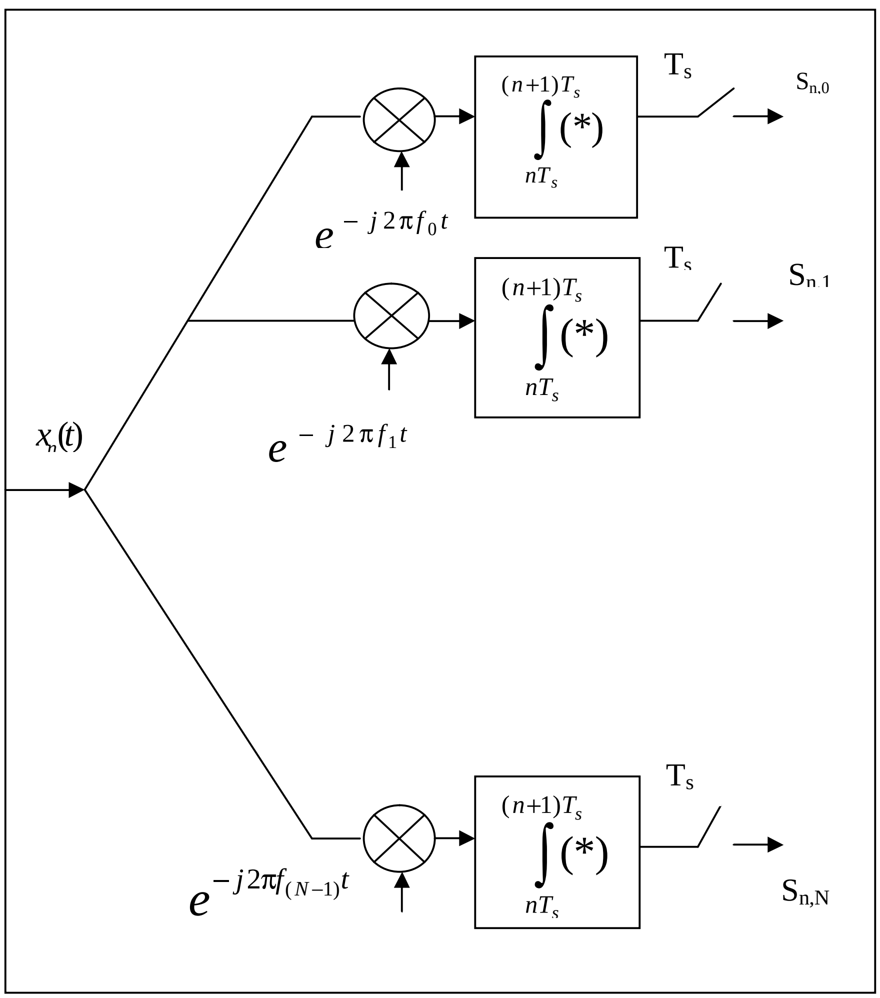

Fig 2.3 OFDM Demodulation

2.3.2 OFDM Modulation as IFFT

The number of sub-carriers '*N*' in OFDM systems is usually of the order of 100's; it implies that the transmitter and receiver blocks become bulky and expensive to build. Also the oscillators (for generating the carrier frequencies) have temperature instability. In [6], the Discrete Fourier Transform (IDFT) is used to solve the modulation and demodulation complexities discussed above. In the following, the modulation process can be achieved by the IFFT operation as explained below.

If the OFDM frame represented by equation (2.5) is sampled at a rate 'N/T_s', the resulting discrete-time signal is

$$x_n^m = \sum_{k=0}^{N-1} s_{n,k}\, g_k(t - nT_s)dt = (n + \frac{m}{N})T_s,\ m = 0,1,\ldots\ldots,N-1 \tag{2.9}$$

After expanding the above equation

$$x_n^m = e^{j2\pi f_0 \frac{m}{N} T_s} \sum_{k=0}^{N-1} s_{n,k}\, e^{j2\pi \frac{mk}{N}}, \qquad m = 0,1,\ldots\ldots\ldots,N-1 \tag{2.10}$$

If we assume f_0=0, then the above equation reduces to

$$x_n^m = \sum_{k=0}^{N-1} s_{n,k}\, e^{j2\pi \frac{mk}{N}}, \qquad m = 0,1,\ldots\ldots\ldots,N-1 \tag{2.11}$$

The above equation can be expressed in terms of the IFFT as,

$$x_n^m = N\,.\,IFFT\ (s_{n,k}) \tag{2.12}$$

Applying the FFT operation on both sides of the above equation,

$$FFT\,(x_n^m) = N.FFT\,(IFFT\,(s_{n,k})) = s_{n,k} \tag{2.13}$$

Thus the OFDM modulation and demodulation can be accomplished using the computationally efficient operations- IFFT and FFT respectively.

2.3.3 Guard Time and Cyclic Extension

One of the main advantages of OFDM is its immunity to multi-path delay spread that causes Inter-symbol Interference (ISI) in wireless channels. Since the symbol duration is made larger (by converting a high data rate signal into 'N' low rate signals), the effect of delay spread is reduced by the same factor. Guard Time is introduced in-order to eliminate the ISI almost completely. If the guard time duration is made larger than that of the estimated delay spread in the channel it is achieved. If the guard period is left empty, the orthogonality of the subcarriers no longer holds and Inter Carrier Interference (ICI) comes into picture. In order to eliminate both ISI as well as the ICI, the OFDM symbol is cyclically extended into the guard period as illustrated in fig 2.4. This preserves the orthogonality of the subcarriers by ensuring that the delayed versions of the OFDM symbol always have an integer number of samples within the FFT interval [16].

Thus both ISI and ICI can be eliminated by cyclically extending the OFDM symbol into the guard period and making sure that the guard time duration is larger than the delay spread.

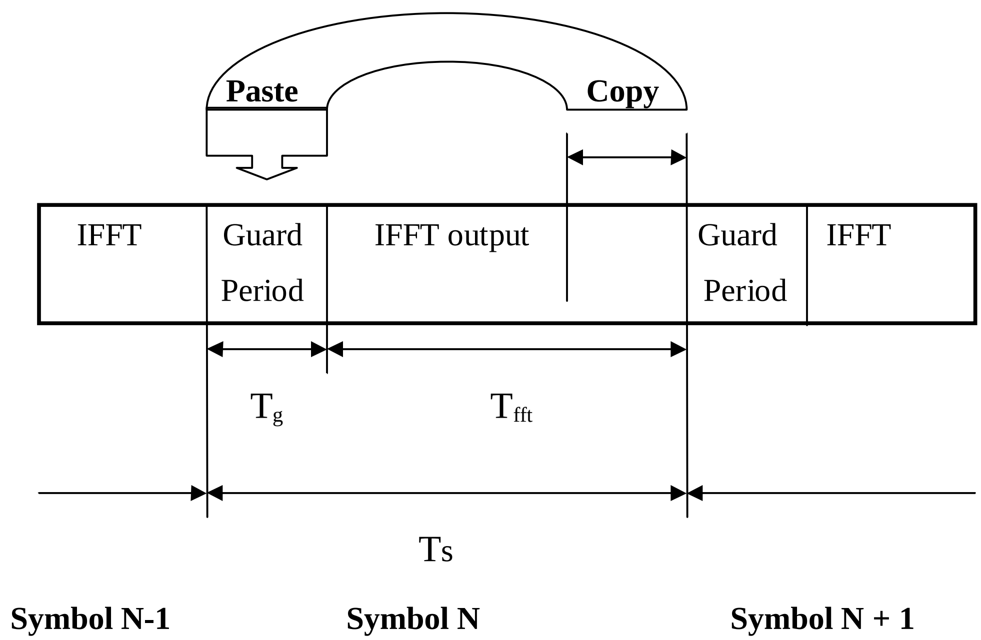

Fig. 2.4 - Guard Period Insertion in OFDM

2.3.4 Block Diagram of an OFDM system

After giving a brief introduction of OFDM system, this section provides the block diagram and which briefly describes the system details.

At the transmitter, the user information bit sequence is first subjected to channel encoding to reduce the probability of error at the receiver due to the channel effects. Usually, convolution encoding is preferred. Then the bits are mapped to symbols of either 16-QAM or QPSK. The symbol sequence is converted to parallel format and IFFT (OFDM modulation) is applied and the sequence is once again converted to the serial format. Guard time provided between the OFDM symbols and the guard time filled with the cyclic extension of the OFDM symbol. Windowing is applied to the OFDM symbols to make the fall-off rate of the spectrum steeper. The resulting sequence is converted to an analog signal using a DAC and passed on to the RF modulation stage. The resulting RF modulated signal is, then, transmitted to the receiver using the transmit antennas. Here, directional beam-forming can be achieved using antenna array, which allows for spectrum reuse by providing spatial diversity.

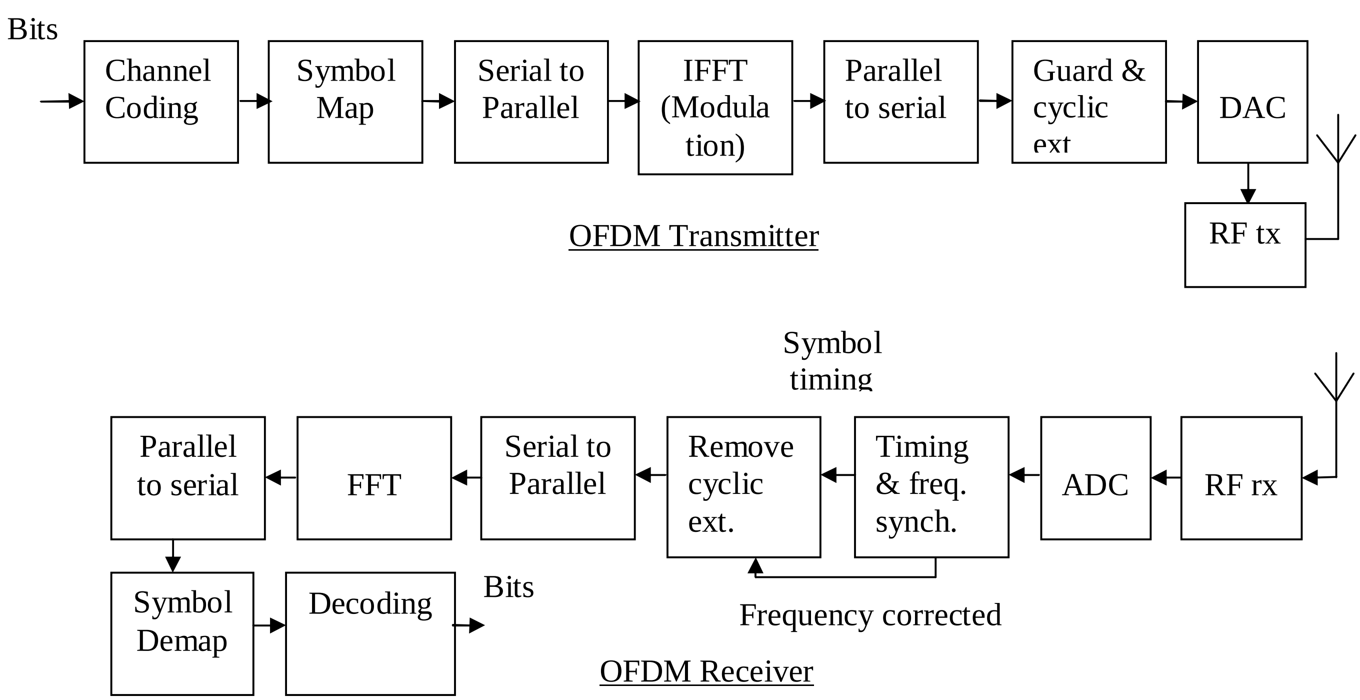

Fig 2.5 OFDM System Block Diagram

At the receiver, first RF demodulation is performed. Then, the signal is digitized using an ADC and timing and frequency synchronization are performed. The guard time is removed from each OFDM symbol and the sequence is converted to parallel format and FFT (OFDM demodulation) is applied. The output is then serialized and symbol de-mapping is done to get back the coded bit sequence. Channel decoding is, then, done to get the user bit sequence.

Time and frequency synchronization are very important for the OFDM based communication system. Without correct frequency synchronization the orthogonality will not exist among the carrier which leads to an increase in BER. Without correct timing synchronization it is not possible to identify start of frames.

2.4 Advantages of OFDM

Orthogonal Frequency Division Multiplexing (OFDM) has several advantages over single carrier modulation systems and these make it a viable alternative for CDMA in future wireless networks. In this section, these advantages are discussed.

2.4.1 Multipath Delay Spread Tolerance

OFDM is highly immune to multipath delay spread that causes inter-symbol interference in wireless channels. Since the symbol duration is made larger (by converting a high data rate signal into *'N'* low rate signals), the effect of delay spread is reduced by the same factor. Also by introducing the concepts of guard time and cyclic extension, the effects of inter-symbol interference (ISI) and inter carrier interference (ICI) are removed completely.

2.4.2 Immunity to Frequency Selective Fading Channels

If the channel undergoes frequency selective fading, then complex equalization techniques are required at the receiver for single carrier modulation techniques. But in the case of OFDM the available bandwidth is split among many orthogonal narrowly spaced sub-carriers. Thus the available channel bandwidth is converted into many narrow flat-fading sub-channels. Hence it can be assumed that the sub-carriers experience flat fading only, though the channel gain/phase associated with the sub-carriers may vary. In the receiver, each sub-carrier just needs to be weighted according to the channel gain/phase encountered by it. Even if some sub-carriers are completely lost due to fading, proper coding and interleaving at the transmitter can recover the user data.

2.4.3 High Spectral Efficiency

OFDM achieves high spectral efficiency by allowing the sub-carriers to overlap in frequency domain. At the same time, to facilitate inter-carrier interference free demodulation of the sub-carriers, the sub-carriers are made orthogonal to each other. If the number of sub-carriers in 'N', the total bandwidth required is

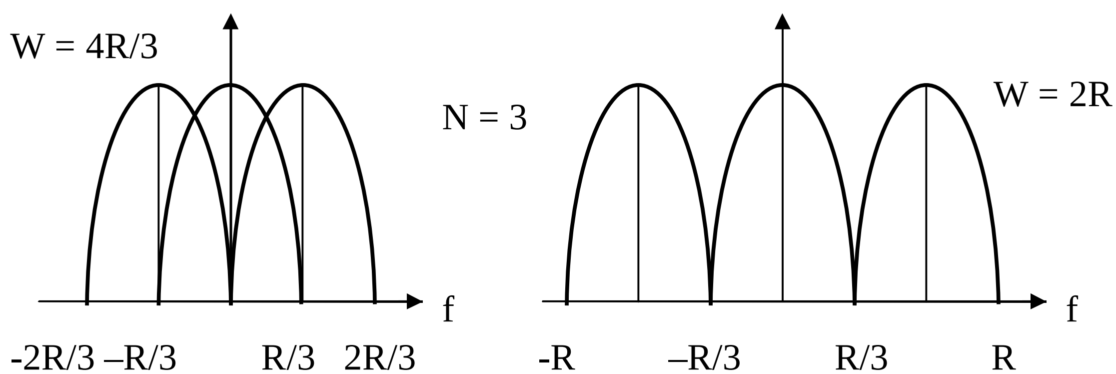

Fig. 2.6 - Spectrum Efficiency of OFDM Compared to FDM

$$BW_{total} = \frac{(N+1)}{T_s} \tag{2.14}$$

For large values of N, the total bandwidth required can be approximated as

$$BW_{total} \approx \frac{N}{T_s}$$

On the other hand, the bandwidth required for serial transmission of the same data is

$$BW_{total} = \frac{2N}{T_s} \tag{2.15}$$

Because no guard-band is needed between the adjacent sub-channels, OFDM can achieve spectrum efficiency close to Nyquist limit. Achieve a spectral gain of nearly 100% in OFDM compared to the single carrier serial transmission case.

2.4.4 Efficient Modulation and Demodulation

Modulation and Demodulation of the sub-carriers are done using computationally efficient IFFT and FFT methods respectively [4]. By performing the modulation and demodulation in the digital domain, the need for highly frequency stable oscillators is avoided.

2.4.5 Robust to Impulse Noise

The duration of OFDM symbols is much longer than that of single carrier system for a channel with strong impulse noise; the transmitted symbols can still be largely recovered since only a small fraction of each symbol is interfered by noise. Thus OFDM is more robust to impulse noise than single carrier systems.

2.5 Applications of OFDM

The primary applications of Orthogonal Frequency Division Multiplexing (OFDM) are discussed below.

2.5.1 Wireless LAN Applications

Data rates in wireless applications are mainly limited because of multipath fading channel. HiperLAN2 (European standard) and IEEE 802.11a pushes the performance of WLAN systems, allowing a data rate of 6Mbps to 54 Mbps. User location is achieved using TDM, and subcarriers are allocated using a range of modulation schemes, from

BPSK up to 64 QAM , depending on the link quality. The table 2.2 describes the physical layer parameters for IEEE 802.11a standard.

Parameter	**Value**
Data Subcarriers	48
Pilot Subcarriers	4
Channel Spacing	20MHz
Carrier Shaping	312.5kHz
Normal Bandwidth	16.25MHz=(312.5kHz.52)
Useful Symbol Period	$3.2\ \mu\sec\ (=1/\Delta_f)$
Guard Period	0.8μ sec
Modulation Schemes	BPSK,QPSK,16 QAM,64 QAM
IFFT	64
Coding Rate	½, 2/3, 3/4

Table 2.2 Physical Layer Parameters for the IEEE 802.11a Standard

2.5.2 Digital Subscriber Loop (xDSL)

In DSL can be transmitted data up to 52 Mbps using Discreet Multitone (OFDM) on the same copper wire pair, which is used to transmit no more than 64 kbps using conventional PCM. In ADSL, DMT uses 249 channels in the frequency range of 26 kHz to 1.1 MHz in downstream and 25 channels between 26 kHz to 133.8 kHz in upstream. The carriers are spaced at 4.3125 kHz. A comparative analysis of various DSL standards is provided in table 2.3.

Modem	Data Rate	Modulation	Bandwidth Efficiency
HDSL	2048kbps	2BIQ	2bits/s/Hz
ADSL	Downstream 1.554-8.45 Mbps Upstream 16-2.3 Mbps	CAP/DMT	8bits/s/Hz
VDSL	Downstream 13-52 Mbps Upstream 1.5-2.3 Mbps	CAP/DMT	<4 bits/s/Hz

Table 2.3 Comparison of Various DSL Standards

2.5.3 Digital Audio Broadcasting (DAB)

DAB is a European standard for digital broadcasting that is intended to replace the current analog technologies such as AM and FM with a good sound quality and better spectrum efficiency even in multipath fading channel. DAB uses DQPSK modulation for subcarriers and has got four transmission nodes shown in table 2.4.

Parameters	Mode-I	Mode-II	Mode-III	Mode-IV
No.of subcarriers	1536	384	192	768
Subcarrier spacing	1kHz	4kHz	8kHz	2kHz
Symbol Time	1.246ms	311.5 μs	155.8 μs	623 μs
Guard Time	246 μs	61.5 μs	30.8 μs	123 μs
Carrier Frequency	<375MHz	<1.5GHz	<3GHz	<1.5GHz

Table 2.4 Parameters for Some DAB Transmission Modes

2.5.4 Digital Video Broadcasting (DVB-T)

DVB is also an ETSI standard for broadcasting digital television over satellites, cables and thorough terrestrial transmission. DVB-T receiver installed in a moving vehicle provides clear pictures and good music quality (as compared to analogue TV technology) and since the technology is digital, multiplex transmission of maps and other navigation information is possible as a supplementary data service.

Parameters	2k mode	8k mode
No. of subcarriers	1705	6817
Modulation Type	QPSK,16PSK, 16QAM, 64 QAM	QPSK,16PSK, 16QAM, 64 QAM
Sub-carrier Spacing	4464Hz	1116Hz
Symbol Time (Ts)	224 μs	896 μs
Allowed Guard Interval	1/4, 1/8, 1/16, 1/32	1/4, 1/8, 1/16, 1/32

Table 2.5 Parameters for DVB-T Transmission Modes

2.6 Major Limitations of OFDM

One major limitations of OFDM is the high peak-to-average power ratio of the transmit signal which occurs due to the summation of many subcarrier modulated signals. A high PAPR requires a wide dynamic range for the power amplifier at the transmitter, or more commonly the power amplifier needs to be backed off to accommodate high peaks. This results in significant reduction of the transmission power which leads to very low power efficiency. It is therefore preferable to reduce the PAPR of the signal. Several methods have been proposed by researchers to reduce PAPR, such as Clipping, Clipping and Filtering, Selected Mapping, and Partial Transmit Sequence [20].Clipping is the simplest technique for reducing the PAPR, however it causes both in-band and out-of-band distortion [21]. Filtering can be employed to alleviate out-of-band distortion but results peak re-growth. Repeated clipping and filtering can lead to degradation in BER. Windowing is another approach that offers reduced out-of-band radiation but window has to be as narrow as possible in the frequency domain and the impulse response in the time domain should not last too long, otherwise more signal samples are affected. Tone reservation is also an effective technique for reducing the PAPR of OFDM signals but causes a reduction in data through-put as data carriers are used to generate an effective cancellation signal in the time domain to reduce high peaks. SLM and PTS schemes can handle any number of subcarriers. But the drawback associated with the schemes is the overhead of side information that needs to be transmitted to the receiver's end [22] [23] [24] [25].

The other major limitation of OFDM is its sensitivity against carrier frequency offset which causes attenuation and rotation of subcarriers, and inter-carrier interference (ICI) [28]. Because of the orthogonality of the sub-carriers, we are able to extract the symbols at the receiver as they do not interfere with each other. Orthogonality is preserved as long as sub-carriers are harmonics to each other. If at the receiver's end there is a change in frequency of the sub-carriers due to any reason, then the orthogonality among them are lost and ICI occurs. As a result the signal degrades heavily. This change in frequency is called frequency offset. There are two main reasons for frequencies offset which are frequency mismatch between transmitter & receiver and

Doppler Effect. The undesired ICI degrades the performance which is discussed in [28]. Several methods have been presented to reduce ICI, including self-cancellation schemes [29], frequency domain equalization, and time domain windowing at the receiver. Among them frequency domain equalization and time domain windowing methods are not so efficient because they do not address to the major cause of ICI which is due to the frequency mismatch between the transmitter and receiver, and Doppler shift. The drawback of the ICI self-cancellation method is that the same data is modulated into two or more carriers, thus reducing the spectral efficiency.

2.7 The Simulation model of OFDM System

The simulation model OFDM system is presented in fig 2.6. This model consists of a transmitter, a channel and a receiver. A brief description of the model is provided below.

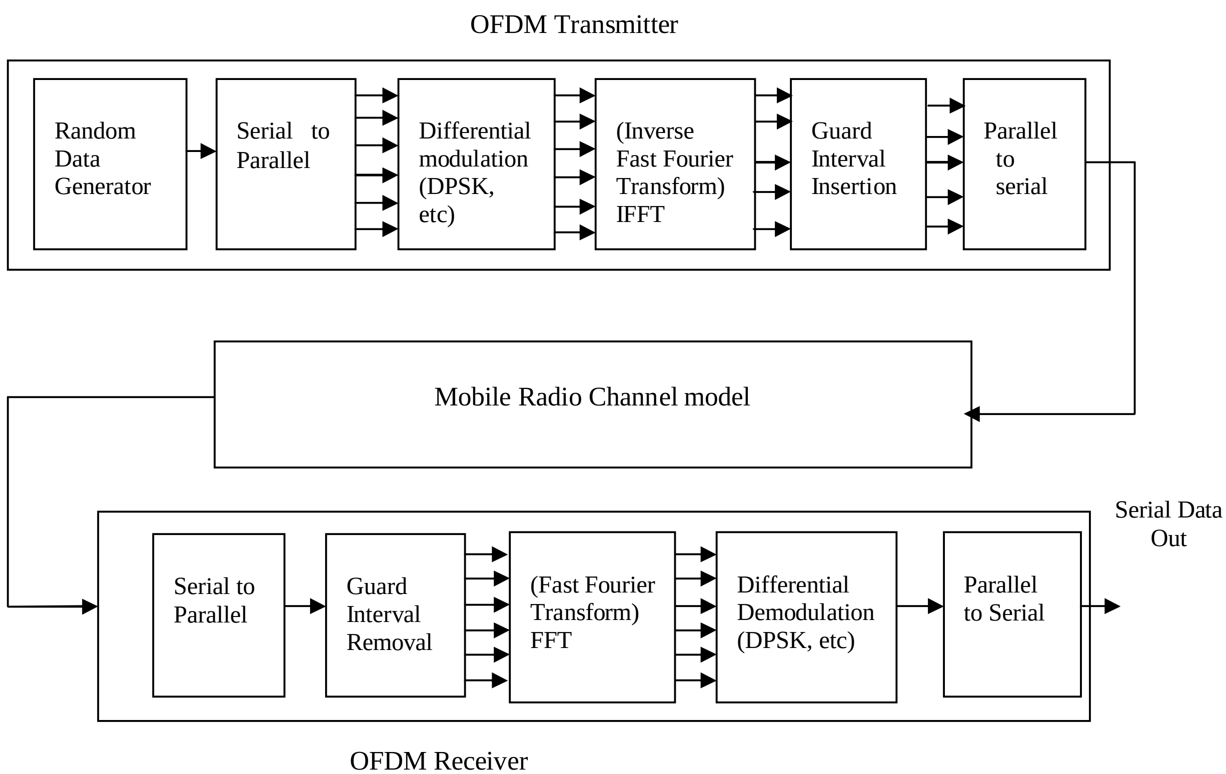

Fig 2.7 OFDM model used for simulation

Random Data Generator

Random data generator is used to generate a serial random binary data. This binary data stream models the raw information that going to be transmitted. The serial binary data is then fed into OFDM transmitter

Serial to Parallel Conversion

The input serial data stream is formatted into the word size required for transmission, and shifted into a parallel format. The data then transmitted in parallel by assigning each data word to one carrier in the transmission.

Modulation of Data

The data to be transmitted on each carrier is then differential encoded with previous symbols, then mapped into a Phase shift Keying (PSK) format. Since differential encoding requires an initial phase reference an extra symbol is added at the start for this purpose. The data on each symbol is then mapped to a phase angle based on the modulation method.

Inverse Fast Fourier Transform

After the required spectrum is worked out, an Inverse Fourier Transform is used to find the corresponding time waveform. The guard period is then added to the start of each symbol.

Guard Period

The type of guard period used in this simulation is a cyclic extension of the symbol. The length of guard period is then added to the start of each symbol.

Parallel to Serial Conversion

After guard period has been added, the symbol is then converted back to a serial time waveform. This signal is the baseband signal for the OFDM.

Channel

A channel model is then applied to the transmitted signal. Hence both AWGN and Rayleigh fading model are included for investigation. The AWGN is applied to the OFDM signal by adding noise factor $10^{(-SNR/10)}$ to the transmitted signal. In Rayleigh fading model the power of a signal will very randomly according to a Rayleigh distribution. Multipath delay spread then added by simulating the delay spread using an FIR filter. The length of FIR filter represents the maximum delay spread while the coefficient amplitude represents the reflected signal magnitude. The power clipping is applied to the OFDM signal by cutting the signal that higher than a certain determined power value.

Receiver

The receiver basically does the reverse operation to the transmitter. The guard period is removed. The FFT of each symbol is then taken to find the original transmitted spectrum. The phase angle of each transmission carrier is then evaluated and converted back to the data word by demodulating the received phase. The data words are then combined back to the same word size as the original data.

2.8 Simulation Results and Analysis

OFDM system model in fig 2.7 has been simulated using Matlab-Toolbox package. The simulation parameters for the OFDM system is given in table 2.6. BER performance of the system is compared for various SNRs of different carrier modulation schemes (i.e., BPSK, QPSK, 16PSK).

Parameter	Value
Carrier modulation used	BPSK, QPSK, 16PSK
Number of carrier	200
IFFT size	512
Guard period type	Cyclic extension of the symbol
Guard Time Length	102
Carrier Frequency	1GHz
Bandwidth	5MHz
Space frequency between two carrier	25KHz

Table 2.6 The Simulation Parameters for OFDM Transceiver

The effect of Additive White Gaussian Noise (AWGN) channel in OFDM system is shown in fig 2.8 below. It is observed from fig 2.8 that to achieve the BER level of 10^{-3}, the OFDM system using BPSK modulation needs at least SNR of around 6dB, the OFDM system using QPSK modulation needs SNR of about 10 dB and the OFDM system using 16PSK modulation needs at least SNR of about 21dB. Though the system capacity improves using QPSK schemes, performance is better in BPSK.

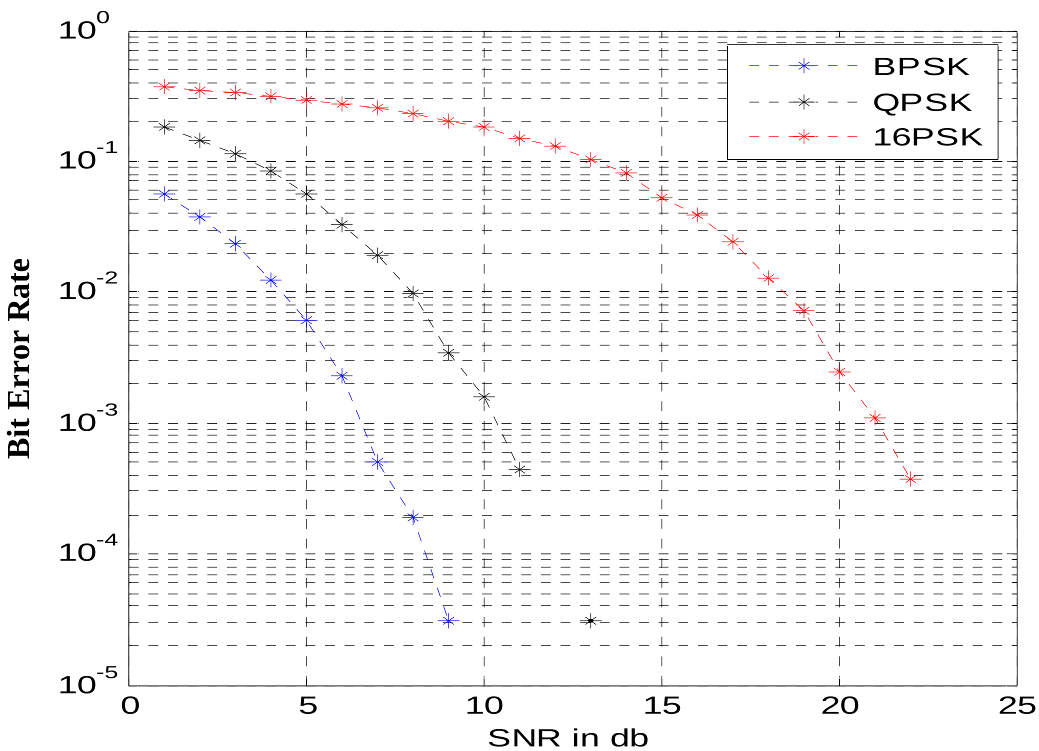

Fig 2.8 BER versus SNR for OFDM in AWGN channel using BPSK, QPSK and 16PSK modulation

The performance of OFDM transceiver in a multipath fading is studied next. It can be concluded from the fig 2.9 that OFDM using BPSK modulation gives better performance than the high data capacity QPSK and 16PSK modulations in terms of BER.

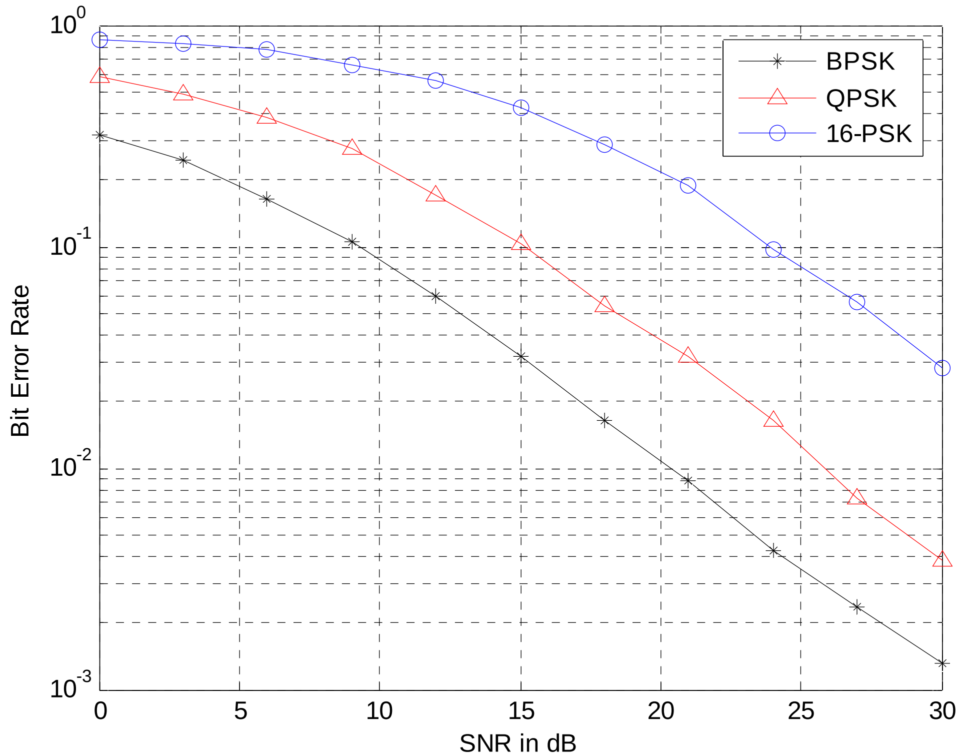

Fig 2.9 BER versus SNR for OFDM in Rayleigh channel using BPSK, QPSK and 16PSK modulation

2.8.1 Effect of Peak Power Clipping on BER Performance

The effect of power clipping to the performance of OFDM system for three modulation techniques is shown in fig.2.10. It is observed form fig.2.10 that for a BER level of 10^{-3}or below, the OFDM signal using BPSK modulation can be clipped up to about 15dB, the OFDM signal using QPSK modulation can be clipped up to about 10dB and the OFDM signal using 16PSK modulation can be clipped up to about 5dB. It is concluded from the analysis that the OFDM signal is resistant enough to clipping distortion caused by nonlinearity in power amplifier used in transmitting the signal.

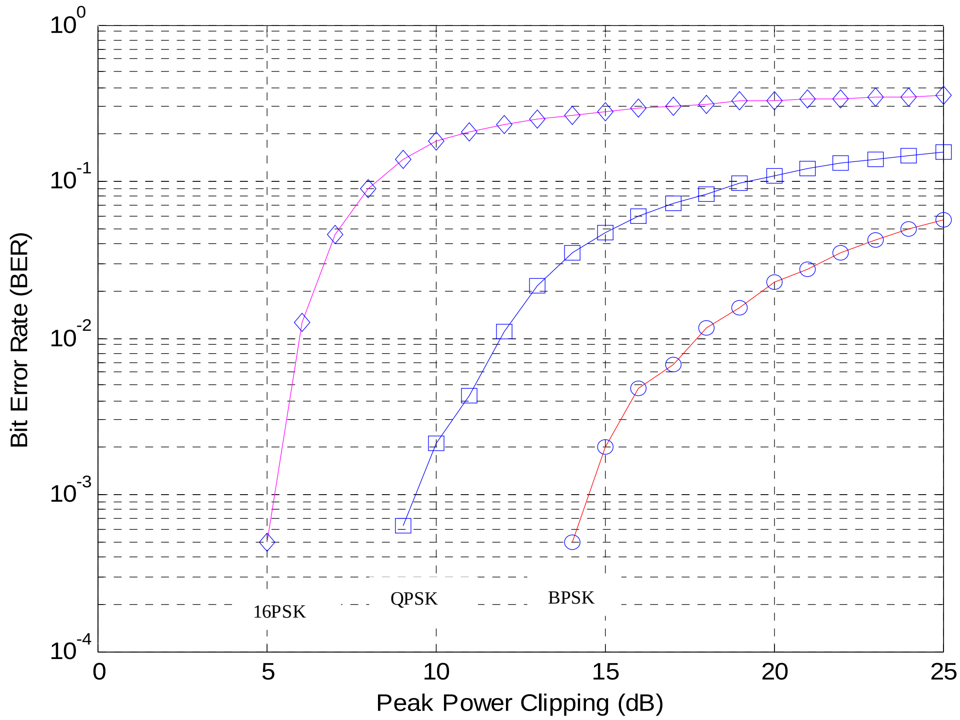

Fig 2.10 Effect of Peak Power Clipping of OFDM on BER Performance

2.8.2 Effect of Delay Spread on BER Performance

Delay spread is the time interval between the arrival of the fast and last multipath signal seen by the receiver. Due to delayed multipath, signal overlapping with the following symbols ISI occurs. This can cause significant errors in high bit rate symbols.

Effect of delay spread on the performance of OFDM system for three modulation techniques BPSK, QPSK, and 16PSK is shown in the fig 2.11. It observed that BER will start to increase when the length of delay spread reaches the length of effective guard period and will increase rapidly when the length of delay spread is longer than the length of guard period. The effect of ISI due to multipath fading can be eliminated as long as the length of effective guard period use 128 samples which is longer than the length of delay spread.

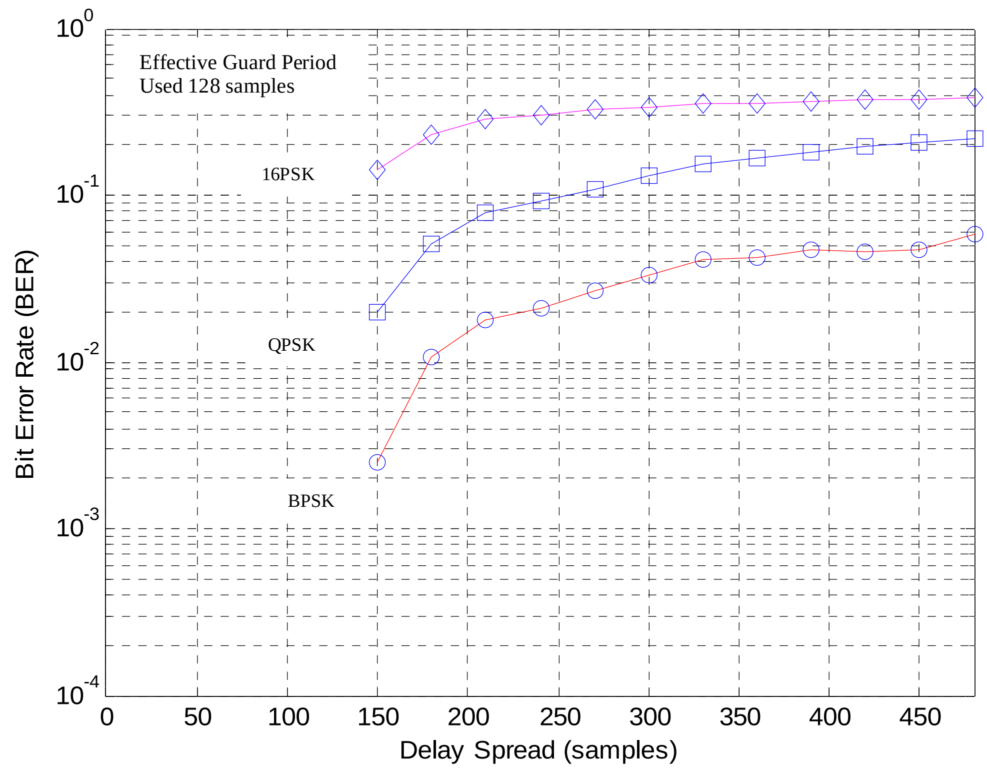

Fig 2.11 Delay Spread Tolerance of OFDM on BER Performance

2.9 Conclusion

In this chapter, the background and the basic concepts of OFDM technique are discussed. It is concluded that OFDM technique has the potential of enhancing the data rate in a band-limited channel. Instead of transmitting data on a single carrier requiring more bandwidth, in OFDM, the high data rate signal is split into many low data rate streams, which are then transmitted on multiple closely spaced orthogonal carriers. A brief description of the OFDM system is given in this chapter. Advantages and prominent applications of OFDM are briefed. The simulation model of OFDM system implemented using Matlab Toolbox package is presented. BER performance analysis for both AWGN and fading channel model are demonstrated. The three sub-carrier modulation schemes (BPSK, QPSK, 16PSK) are compared on the basis of their performance. 16PSK increases the system capacity but the BER degrades as compared to BPSK and QPSK. It shows that a trade-off between system capacity and system robustness is necessary. Delay spread and peak power clipping are introduced to mobile radio channel and the BER performance of the system is investigated. For the delay spread that is longer than the effective guard period, the BER rises rapidly due to the inter-symbol interference and OFDM signal is resistant to clipping distortions caused by the power amplifier used in transmitting the signal. Techniques to overcome the two major drawbacks like high PAPR and ICI are considered as the key research issues from application point of view. Overviews of various schemes suggested by researchers in this regard are investigated in the next chapter.

Chapter 3

OVERVIEW OF PAPR AND ICI REDUCTION TECHNIQUES

OVERVIEW OF PAPR AND ICI REDUCTION TECHNIQUES

3.1 Introduction

Orthogonal Frequency Division Multiplexing is a form of multi carrier modulation technique with high spectral efficiency, robustness to channel fading, immunity to impulse interference, uniform average spectral density capacity of handling very strong echoes and non-linear distortion. Despite of its many advantages, OFDM suffers from two main drawbacks, i.e., high peak to average power ratio (PAPR) and inter-carrier interference (ICI). So researchers have developed many schemes to overcome those over the years.

Section 3.2 introduces the peak to average power ratio in OFDM system. In section 3.3, a few important PAPR reduction techniques are analyzed and the simulation results are presented to prove their effectiveness. Section 3.4 explains the various parameters inducing ICI in OFDM system. Various ICI cancellation schemes in section 3.5 and ICI self cancellation scheme is investigated. The conclusion is presented in section 3.6.

3.2 Peak to Average Power Ratio (PAPR) in OFDM Systems

An OFDM signal consists of a number of independently modulated sub-carriers, which can give a large PAPR when added up coherently. When N signals are added with the same phase, they produce a peak power that is N times the average power of the signal. So OFDM signal has a very large PAPR, which is very sensitive to non-linearity of the high power amplifier.

In OFDM, a block of N symbols $\{X_k,\ k = 0,1,....,N-1\}$, is formed with each symbol modulating one of a set of subcarriers, $\{f_k,\ k = 0,1,.....,N-1\}$. The N subcarriers are chosen to be orthogonal, that is, $f_k = k\Delta f$, where $\Delta f = 1/NT$ and T is the original time period. The resulting signal is given as

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

PAPR is defined as

$$PAPR = \frac{\max |x(t)|^2}{E\left[|x(t)|^2\right]} \tag{3.2}$$

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

3.2.1 Distribution of PAPR

When the number of sub-carriers in an OFDM system is high, conventional OFDM signals can be regarded as Gaussian noise like signals; their variable amplitude is approximately Rayleigh-distributed, and the power distribution has a cumulative distribution function given by

$$F(z) = 1 - e^{-z} \tag{3.3}$$

Assuming the samples of OFDM symbol are mutually uncorrelated, the probability that PAPR is below some threshold level which can be expressed as

$$P(PAPR \le z) = F(z)^N = (1 - \exp(-z))^N \tag{3.4}$$

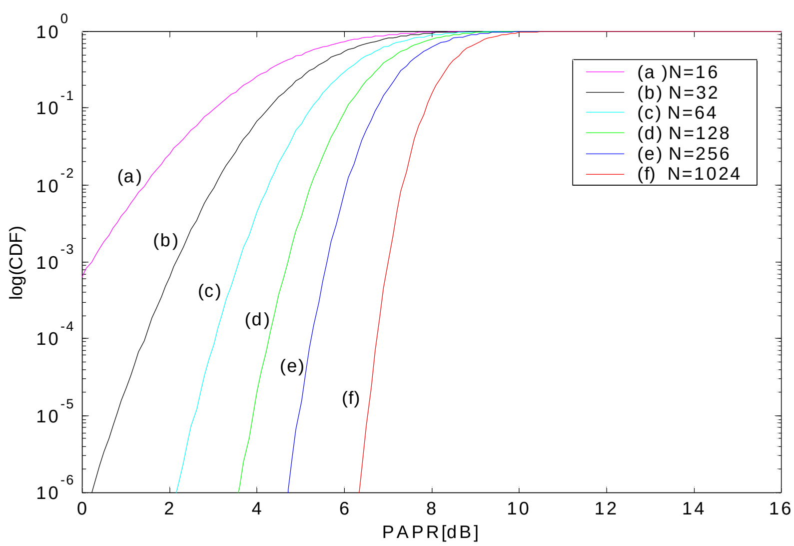

Fig 3.1 Cumulative Distribution Function of PAPR

Fig.3.1 shows the Cumulative Distribution Function (CDF) with varying the sub-carrier N = 16, 32, 64, 128, 256, 1024. It shows that PAPR increases with the number of subcarriers. Complementary CDF is the complement of CDF (CCDF=1-CDF).

Commonly CCDF of PAPR is plotted as a performance parameter instead of CDF because it emphasizes the peak amplitude excursions, while CDF emphasizes minimum values.

3.2.2 Effect of High PAPR

High PAPR corresponds to a wide power range which requires more complicated analog-to-digital (A/D) and digital-to-analog (D/A) converters in order to accommodate the large range of the signal power values. Therefore, high PAPR increases both the complexity and cost of implementation.

The power amplifiers at the transmitter need to have a large linear range of operation. When considering a system with a transmitting power amplifier, the nonlinear distortions and peak amplitude limitation introduced by the high power amplifier (HPA) will produce inter-modulation between the different carriers and introduce additional interference into the system. This additional interference leads to an increase in the bit error rate (BER) of the system. One way to avoid such non-linear distortion and keep low BER low is to force the amplifier to work in its linear region. Unfortunately such solution is not power efficient and thus is not suitable for wireless communication. Hence a high PAPR in the system design should be restricted.

3.3 PAPR Reduction Techniques

Researchers have suggested several techniques to reduce PAPR over the years [21] [22] [23] [24] [25]. This research work presents the simulation study and analysis three PAPR reduction techniques in this section.

a) Clipping and Filtering Technique
b) Selected Mapping Technique
c) Partial Transmit Sequence Technique

3.3.1 Clipping and Filtering Technique

Clipping is a way of reducing PAPR by simply limiting the maximum amplitude of the OFDM signal, such that all signal values are limited to the threshold. Clipping the OFDM signal before amplification is a simple method to limit PAPR. However clipping may cause large out of band (OOB) and in band interference as it is a nonlinear process which results in the system performance degradation.

A block diagram of the OFDM transmitter is in Fig.3.2. The QPSK block maps the input data bits into complex symbols. Then, the OFDM modulation is realized using an inverse fast Fourier transforms (IFFT). With the complex QPSK symbol denoted as $X_k = (0 \le k \le N-1)$, the complex baseband OFDM samples are

$$x_n = \sum_{k=0}^{N-1} X_k e^{j2\pi nk/N}, \qquad 0 \le n \le N-1 \tag{3.5}$$

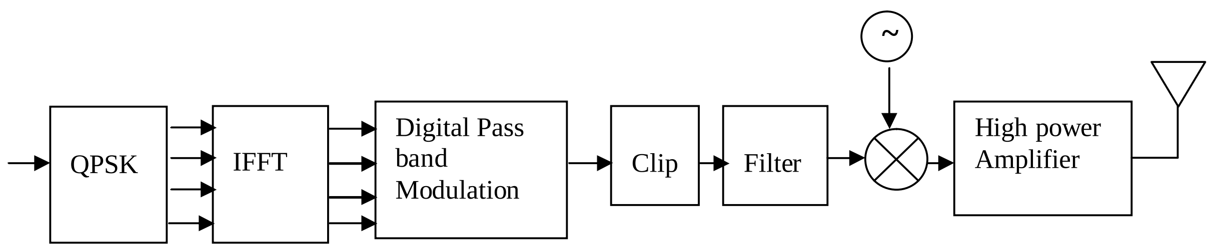

Fig. 3.2 OFDM Transmitter Block Diagram.

If these digital signals are clipped directly, the resulting clipping noise will all fall in-band and cannot be reduced by filtering. To address this aliasing problem, each OFDM block is oversampled by padding the original input with zeros and taking a longer IFFT.

The input to the IFFT block is

$$X_k' = \begin{cases} X_{k+N/2}, & 0 \le k \le N/2-1 \\ 0, & N/2 \le k \le rN - N/2 - 1 \\ X_{k-(rN-N/2)}, & rN - N/2 \le k \le rN-1 \end{cases} \tag{3.6}$$

and the oversampled OFDM signal after IFFT is

$$x_n = \sum_{k=0}^{rN-1} X'_k \, e^{j2\pi nk/rN}, \quad 0 \le n \le rN-1 \tag{3.7}$$

Clipping the complex OFDM baseband signal by limiting its magnitude and maintaining its phase would require extra hardware, such as a divider, and hence might not be suitable for practical implementation. Therefore, the real band pass signal is clipped instead of the complex baseband signal.

To generate the band pass signal the band pass carrier frequency f_c is chosen to be 1/4 of the sampling frequency $\boldsymbol{f}_s$. The real band pass samples can be written as

$$\begin{aligned} y_n &= x_n \cos(2\pi \frac{f_c}{f_s} n) - x_n \sin(2\pi \frac{f_c}{f_s} n) \\ &= x_n \cos(\frac{n\pi}{2}) - x_n \sin(\frac{n\pi}{2}) \end{aligned} \tag{3.8}$$

This band pass modulation can be easily reached by alternately taking the real and imaginary part of x_n

$$y_n = \begin{cases} \mathrm{Re}\{x_n\}, & n = 4l \\ -\mathrm{Im}\{x_n\}, & n = 4l+1 \\ -\mathrm{Re}\{x_n\}, & n = 4l+2 \\ \mathrm{Im}\{x_n\}, & n = 4l+3 \end{cases} \qquad l = 1,2,3,\ldots\ldots \tag{3.9}$$

The clipping operation on the real band pass signal is given by

$$z_n = \begin{cases} -A, & if\ y_n < -A \\ y_n, & if -A \le y_n \le A \\ A, & if\ y_n > A \end{cases} \tag{3.10}$$

where z_n is the clipped signal and A is the clipping level. A normalized clipping level, called the clipping ratio (CR), is calculated as

$$CR = A/\sigma \tag{3.11}$$

where σ is the rms power of the OFDM signal, and for OFDM signal with N sub-channels, $\sigma = \sqrt{N}$ for a baseband signal and $\sigma = \sqrt{N/2}$ for a band pass signals.

A CR of 0.8 means the clipping level is about 2 dB lower than the rms level and a CR of 1.4 means the clipping level is about 3 dB higher than the rms level. Filtering after clipping is required to reduce the out-of band clipping noise. An equiripple band pass FIR filter with 103 coefficients is used in the simulation.

3.3.1.1 Simulation Study

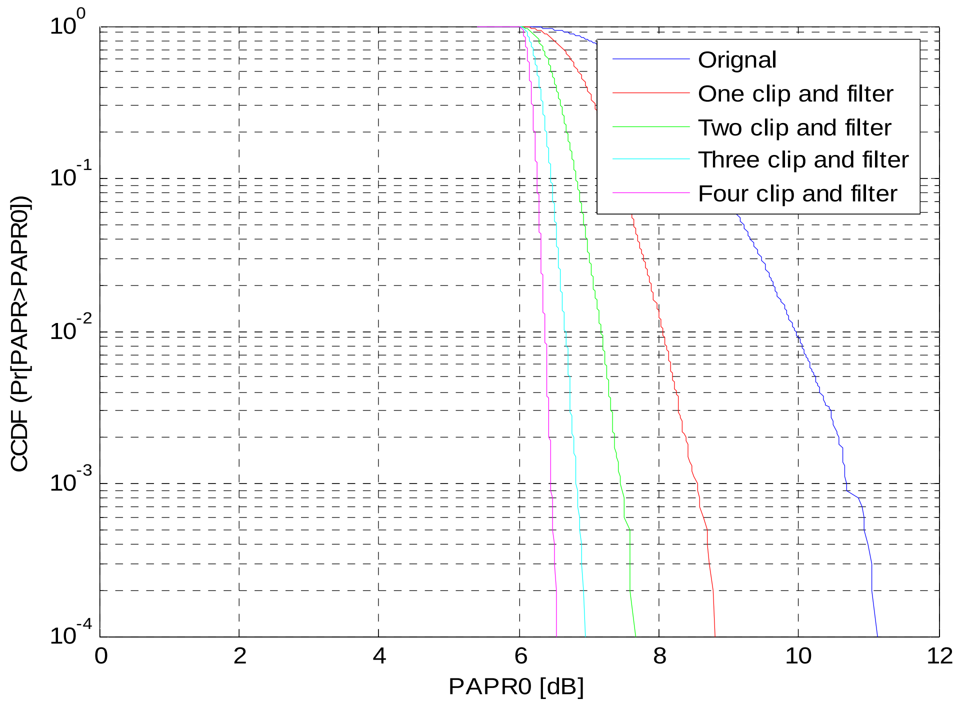

Fig 3.3 Cumulative Distributions for Signal after PAPR Reduction

The fig 3.3 shows the complementary cumulative distribution function of the oversampled signal after one to four stages of clipping and filtering. In this case N=128, the modulation used is QPSK and CR is chosen to be 6dB. It is seen from the graph that repeated clipping and filtering significantly reduces the PAPR and the performance in the table 3.1 indicates the reduction in PAPR value.

	CCDF (Pr[PAPR>PAPR0])	PAPR0(dB)
Original	10^{-3}	10.5
After one clip and filter	10^{-3}	9
After two clip and filter	10^{-3}	8.5
After three clip and filter	10^{-3}	7
After four clip and filter	10^{-3}	7.5

Table 3.1 PAPR Reduction Using Clipping & Filtering

Clipping causes in-band noise, which is approximately white, and this causes degradation in the BER performance. This degradation is investigated by plotting the BER versus SNR for various clipping ratio as shown in Fig. 3.4**.** BER performance of the system improves with increase in CR from 0.6 to 0.9.

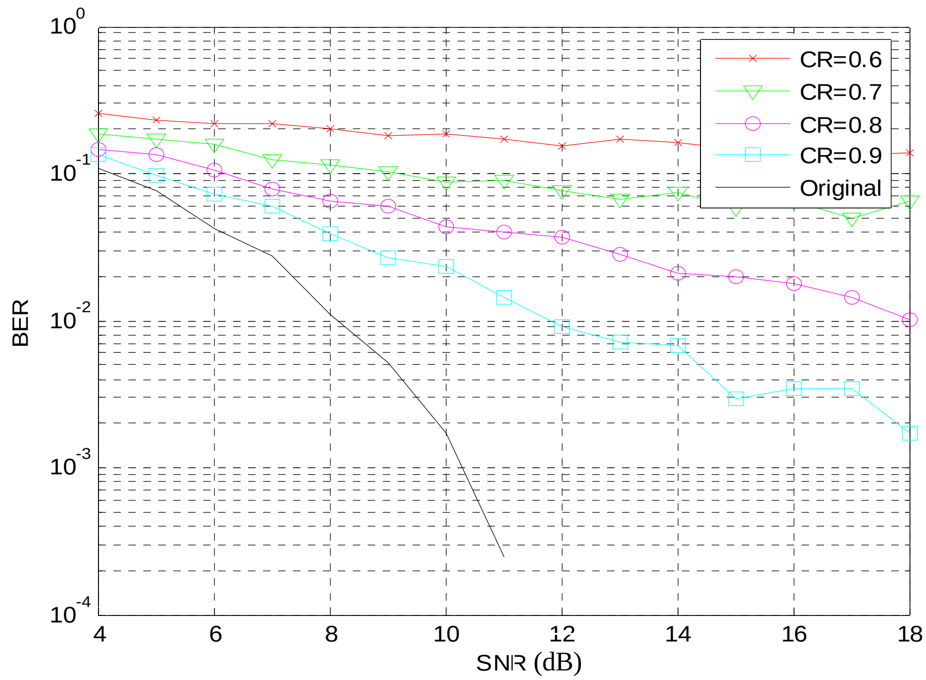

Fig 3.4 BER Performance Varying Clipping Ratio (CR= 0.6, 0.7, 0.8, 0.9) for N=64

3.3.2 Selected Mapping (SLM) Technique

Selected mapping (SLM) is an effective PAPR reduction technique [20]. Block diagram of the SLM OFDM transmitter system is depicted in the fig 3.5. Input data is partitioned into a U statistically independent alternative transmit sequences $a_{\mu}{}^{(u)}$ represent the same information. Then, that sequence $\tilde{a}_{\mu} = a_{\mu}{}^{(\tilde{u}_{\mu})}$ with the lowest PAPR, denoted as $\tilde{X}_{\mu}$, is selected for transmission. The probability that $\tilde{X}_{\mu}$ exceeds X_0 is approximated by [23]

$$\Pr\{\tilde{X}_{\mu} > X_0\} = \left(1-(1-e^{-x_0})^{D}\right)^{U} \qquad (3.12)$$

Because of the selected assignment of binary data to the transmit signal, this principle is called as selected mapping.

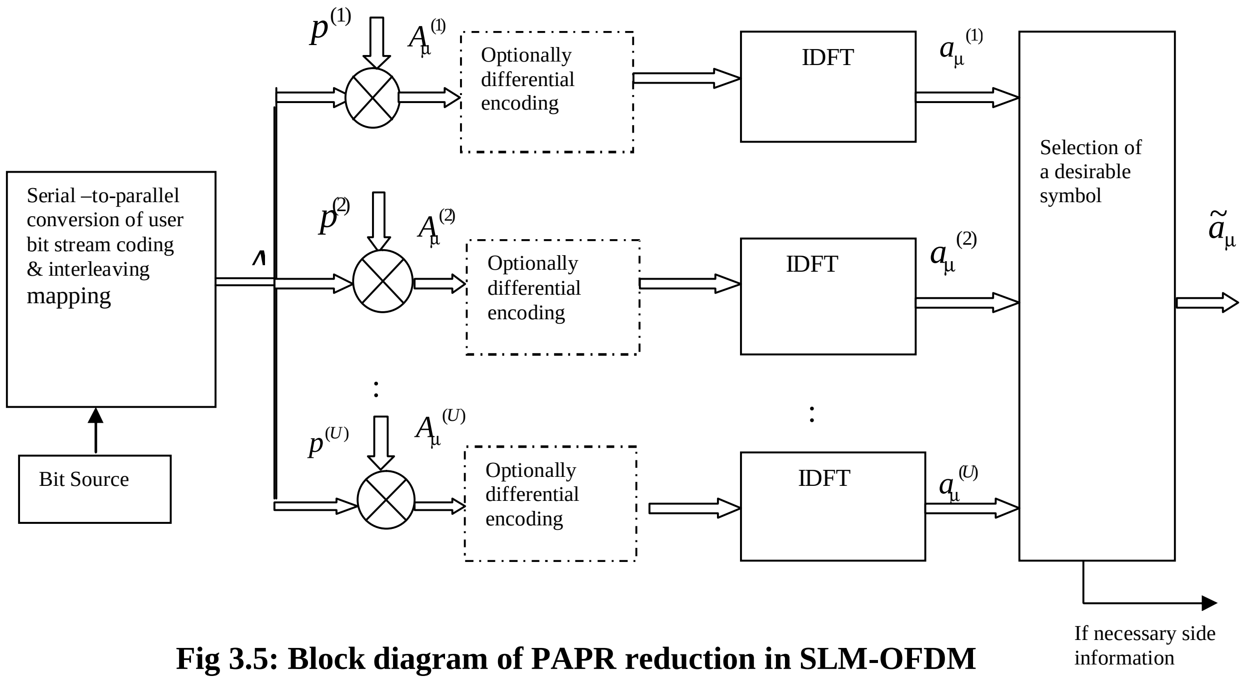

Fig 3.5: Block diagram of PAPR reduction in SLM-OFDM

A set of U markedly different, distinct, pseudo-random but fixed vectors $\mathsf{P}^{(u)} = [P_0^{(u)}, \ldots\ldots, P_{D-1}^{(u)}]$, with $P_V^{(u)} = e^{+j\phi_v^{(u)}}$, $\phi_v^{(u)} \in [0, 2\pi]$, $v = 1:D$ and $u = 1:U$ are defined. The subcarrier vectors $\mathbf{A}_\mu$ is multiplied subcarrier wise with each one of the U vectors $\mathsf{P}^{(U)}$, resulting in a set of U different subcarrier vectors $\mathsf{A}_\mu^{(u)}$ with components $A_{\mu,v}^{(u)} = A_{u,v} \cdot e^{j\phi_v^{(u)}}$, $v = 1:D,\ u = 1:U$ (3.13)

Then all U alternative subcarrier vectors are transformed into time domain to get $a_\mu^{(u)} = IDFT\{\mathsf{A}_\mu^{(u)}\}$ and finally that transmit sequence $\tilde{a}_\mu = a_\mu^{(\tilde{u}_\mu)}$ with the lowest PAPR $\tilde{X}_\mu$ is selected and transmitted.

3.3.2.1 Simulation Study

Performance of SLM scheme is evaluated on the basis of CCDF of PAPR of transmitted symbol. In simulation study, the number of carriers D=512, and the modulation in each carrier is chosen to be QPSK. Phase vectors U=2, 4, 8, and 16 are selected. SLM with U=16 outperforms others as shown in fig.3.6. The performance comparison is given in table 3.2.

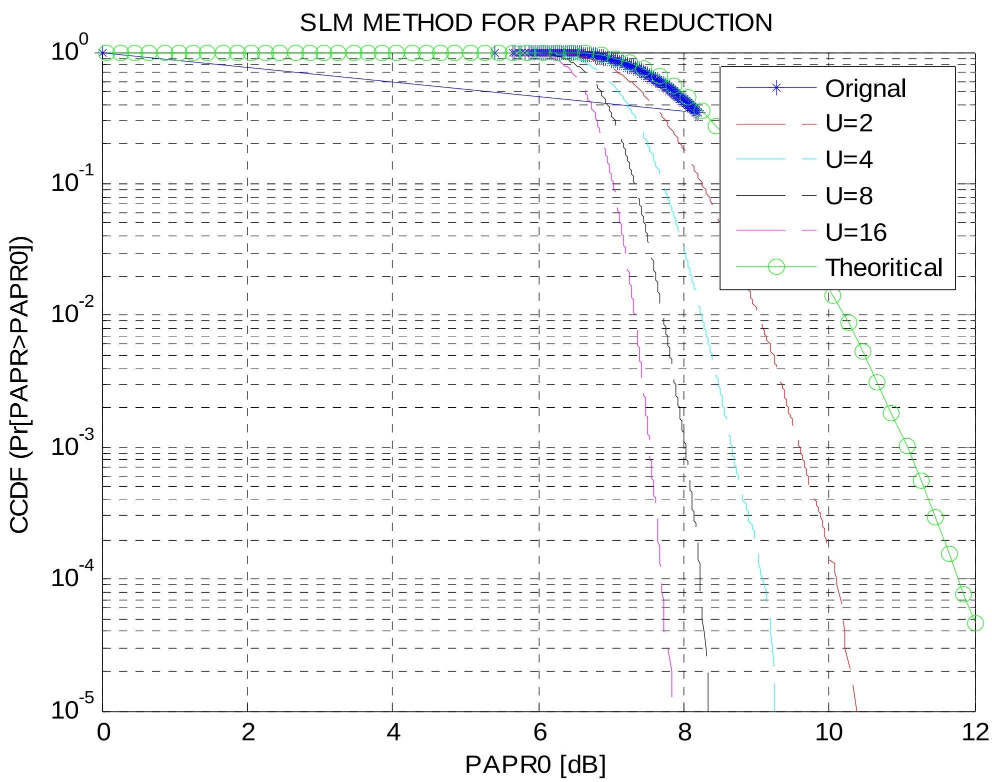

Fig 3.6 Performance Study of SLM Method for PAPR Reduction

	CCDF (Pr[PAPR>PAPR0])	PAPR0(dB)
Original	10^{-3}	8
U=2	10^{-3}	9
U=4	10^{-3}	8.5
U=8	10^{-3}	8
U=16	10^{-3}	7.5
Theoretical	10^{-3}	11

Table 3.2 A Comparison Table of Performance Using SLM-OFDM

One of the factors that determine the PAPR reduction performance of SLM techniques is the design of phase sequences. Besides the design of phase sequences, the number of phase sequences, U, is another important factor. The amount of PAPR reduction is proportional to U. Although a large number of phase sequences promises a good PAPR reduction performance, the computational complexity of SLM increases with large U which is a major drawback of the SLM technique.

3.3.3 Partial Transmit Sequences (PTS) Technique

The partial transmit sequence (PTS) is a distortion-less PAPR reduction technique [24] [25]. The main idea of PTS is to partition the subcarrier vector A_μ into V pair-wise disjoint sub-blocks $A_\mu^{(\upsilon)}$, $1 \le \upsilon \le V$ as shown in the fig 3.7. All subcarrier positions in $A_\mu^{(\upsilon)}$, which are already represented in another sub-block are set to zero, so that $A_\mu = \sum_{v=1}^{V} A_\mu^{(\upsilon)}$. Introducing complex valued rotation factors $b_\mu^{(\upsilon)} = e^{+j\varphi_\mu^{(\upsilon)}}$, $\varphi_\mu^{(\upsilon)} \in [0, 2\pi], 1 \le \upsilon \le V$, a modified subcarrier vector is obtained as given by

$$\tilde{\mathsf{A}}_\mu = \sum_{\upsilon=1}^{V} b_\mu^{(\upsilon)} . \mathsf{A}_\mu^{(\upsilon)} \tag{3.14}$$

which represents the same information as A_μ, if the set $\{b_\mu^{(\nu)}, 1 \le \nu \le V\}$(as side information) is known for each μ. Clearly, simply a joint rotation of all subcarriers in sub-block ν by the same angle $\varphi_\mu^{(\nu)} = \arg\left(b_\mu^{(\nu)}\right)$is performed.

The sub-blocks are transformed by separate and parallel D-point IDFTs, yielding

$$\tilde{a}_\mu = \sum_{\upsilon=1}^{V} b_\mu^{(\upsilon)} . IDFT\left\{A_\mu^{(\upsilon)}\right\} = \sum_{\upsilon=1}^{V} b_\mu^{(\upsilon)} . a_\mu^{(\upsilon)} \tag{3.15}$$

where the V so-called partial transmit sequences $a_\mu^{(\upsilon)} = IDFT\left\{A_\mu^{(\upsilon)}\right\}$.

A peak value optimization is performed by suitably choosing the free parameters $b_\mu^{(\upsilon)}$ such that the PAPR is minimized for $\tilde{b}_\mu^{(\upsilon)}$.

The optimum transmit sequence is

$$\tilde{a}_{\mu} = \sum_{\upsilon=1}^{V} \tilde{b}_{\mu}^{(\upsilon)} . a_{\mu}^{(\upsilon)} \tag{3.16}$$

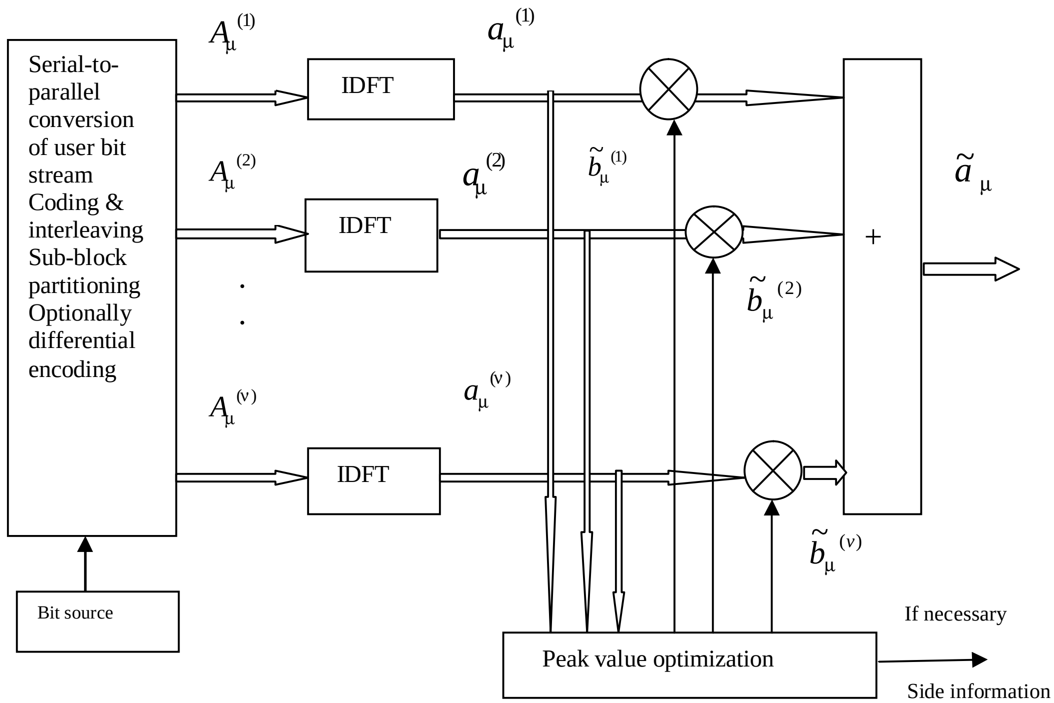

Fig 3.7: Block Diagram of PAPR Reduction in PTS-OFDM

3.3.3.1 Simulation Study

The performance of PTS-OFDM is presented in fig.3.8 and results are compared with SLM-OFDM. Simulation are performed using D=512 carriers modulated with QPSK.

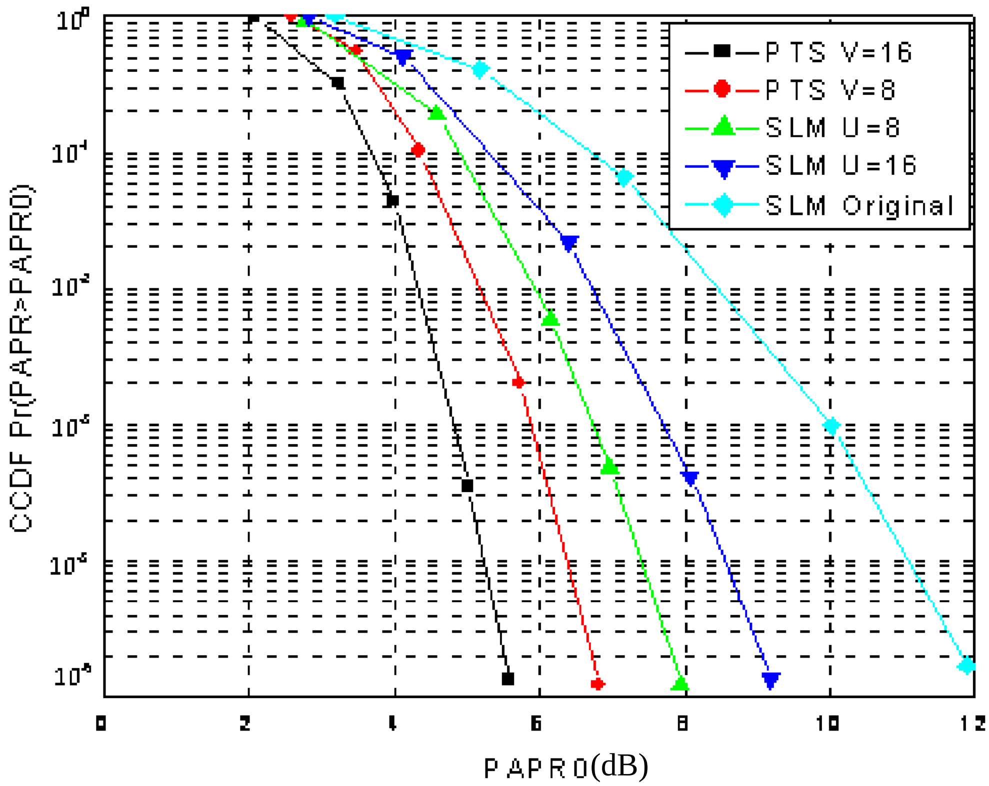

Fig 3.8 Comparison between both SLM and PTS Technique with Varying Parameter (V=16, 8 and U=16, 8)

PTS-OFDM with V=16 gives a PAPR threshold gain of around 3dB at the CCDF level 10^{-4} compared to SLM method with U=16 as shown in fig 3.8. For a SLM scheme with U phase sequences, $\log_2 U$ bits are required to transmit the side information, there by resulting loss in data rate.

The three PAPR reduction techniques discussed in this section are compared now on the basis of distortion, power increase, data rate loss and complexity as given in table 3.3. It is concluded here that PTS-OFDM is superior compared to others.

	Distortion Less	Power Increase	Data Rate Loss	Requires Processing at Transmitter (Tx) and Receiver (Rx)
Clipping and Filtering	No	No	No	Tx: Amplitude Clipping, Filtering Rx: None
Selected Mapping	Yes	No	Yes	Tx: U IDFTs Rx: Side information Extraction
Partial Transmit Sequence	Yes	No	Yes	Tx: M IDFTs W^{M-1} complex vector sums. Rx: Side information Extraction

Table.3.3 A Comparison of Three PAPR Reduction Techniques

3.4 Inter Carrier Interference in OFDM System

Orthogonal Frequency Division Multiplexing (OFDM) is a promising technique for the broadband wireless communication systems. However, a critical problem in OFDM system is its vulnerability to frequency offset errors between the transmitted and received signals, which may be caused by Doppler shift in the channel or by the difference between the transmitter and receiver local oscillator frequencies [18]. In such situations, the orthogonality of the carriers is no longer maintained, which result in Inter-carrier Interference (ICI). ICI problem would become more complicated when the multipath fading is present. If ICI is not properly compensated it results in power leakage among the sub-carriers, thus degrading the system performance.

3.5 ICI Reduction Techniques

Some of ICI reduction techniques are listed below.

a) Frequency domain equalization

b) Time domain windowing

c) ICI self cancellation

3.5.1 Frequency Domain Equalization

The fading distortion in the channel causes ICI in the OFDM demodulator. The pattern of ICI varies from frame to frame for the demodulated data but remains invariant for all symbols within a demodulated data frame. Compensation for fading distortion in the time domain introduces the problem of noise enhancement. So frequency domain equalization process is approached for reduction of ICI by using suitable equalization techniques. We can estimate the ICI for each frame by inserting frequency domain pilot symbols in each frame as shown in fig 3.9.

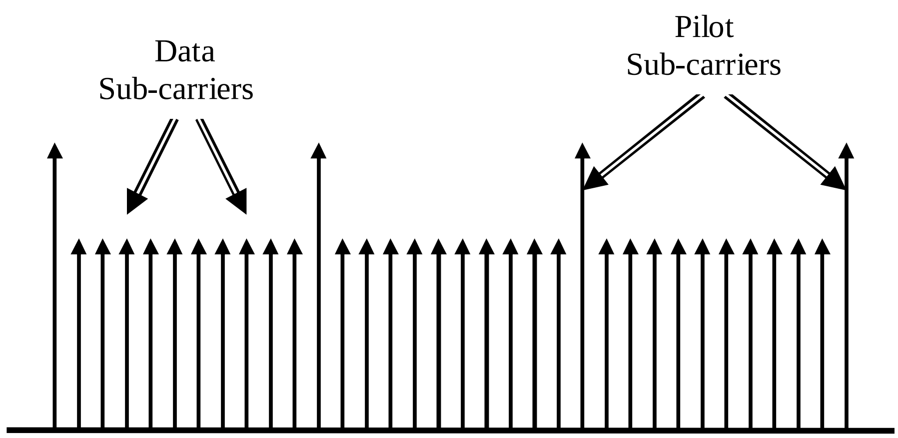

Fig. 3.9- Pilot Subcarrier Arrangement

The equalizer co-efficient for eliminating ICI in the frequency domain can be derived from the pattern of the pilot symbol and hence a suitable equalizer can be constructed.

This technique can only reduce the ICI caused by fading distortion which is not the major source of ICI. The major source of ICI is due to the frequency mismatch between the transmitter and receiver. The above method cannot address to it. Again it is only suitable for flat fading channels, but in mobile communication the channels are frequency selective fading in nature because of multipath components. Here also the channel needs to be estimated for every frame. Estimation of channel is complex, expensive & time consuming. Hence this method is not an effective one.

3.5.2 Time Domain Windowing

OFDM signal has widely spread power spectrum. So if this signal is transmitted in a band limited channel, certain portion of the signal spectrum will be cut off, which will lead to inter carrier interference. To diminish the interference the spectrum of the signal wave form need to be more concentrated. This is achieved by windowing the signal. Basically windowing is the process of multiplying a suitable function to the transmitted signal wave form. The same window is used in the receiver side to get back the original signal. The IC1 will be eliminated if the product of the window functions satisfies the Nyquist vestigial symmetry criterion.

This method only reduces the ICI caused by band limited channel which is not the major source of ICI. The major source of ICI is due to the frequency mismatch between the transmitter and receiver, and the Doppler shift. Futher windowing is done frame by frame & hence it reduces the spectral efficiency to a large extent. Hence this method is not an effective one.

3.5.3 ICI Self- Cancellation

The self-cancellation schemes works in two very simple steps. At the transmitter side, one data symbol is modulated onto a group of adjacent subcarriers with a group of weighting coefficients. The weighting coefficients are designed so that the ICI caused by the channel frequency errors can be minimized. At the receiver side, by linearly combining the received signals on these subcarriers with proposed coefficients, the residual ICI contained in the received signals can then be further reduced.

This method is suitable for multipath fading channels as here no channel estimation is required because in multipath case channel estimation fails as the channel changes randomly.

3.5.3.1 ICI Cancelling Modulation and Demodulation

In an OFDM communication system, assuming the channel frequency offset normalized by the subcarrier separation is ε, the received signal on subcarrier k can be written as

$$r(k) = X(k)S(0) + \sum_{l=0, l\neq k}^{N-1} X(l)S(l-k) + n_k, \qquad k = 0,1,\ldots\ldots,N-1 \tag{3.16}$$

where N is the total number of the subcarriers $X(k)$ denotes the transmitted symbol for the k^{th} subcarrier and n_k is additive noise . The first term in the right-hand side of (3.16) represents the desired signal. The second term is the ICI components. The sequence *S (l-k)* is defined as the ICI coefficient between l^{th} and k^{th} subcarriers, which can be expressed as

$$S(l-k) = \frac{\sin(\pi(l+\varepsilon-k))}{N\sin\left(\frac{\pi}{N}(l+\varepsilon-k)\right)}.\exp\left(j\pi\left(1-\frac{1}{N}\right)(l+\varepsilon-k)\right) \tag{3.17}$$

It is seen that the difference of ICI coefficient between two consecutive sub-carrier {(S(*l*-*k*) and S(*l*+1-*k*)} is very small. Therefore, if a data pair (a, -a) is modulated onto two adjacent subcarriers (*l* , *l*+1), where *a* is a complex data, then the ICI signals generated by the subcarrier *l* will be cancelled out significantly by the ICI generated by subcarrier *l*+1 .

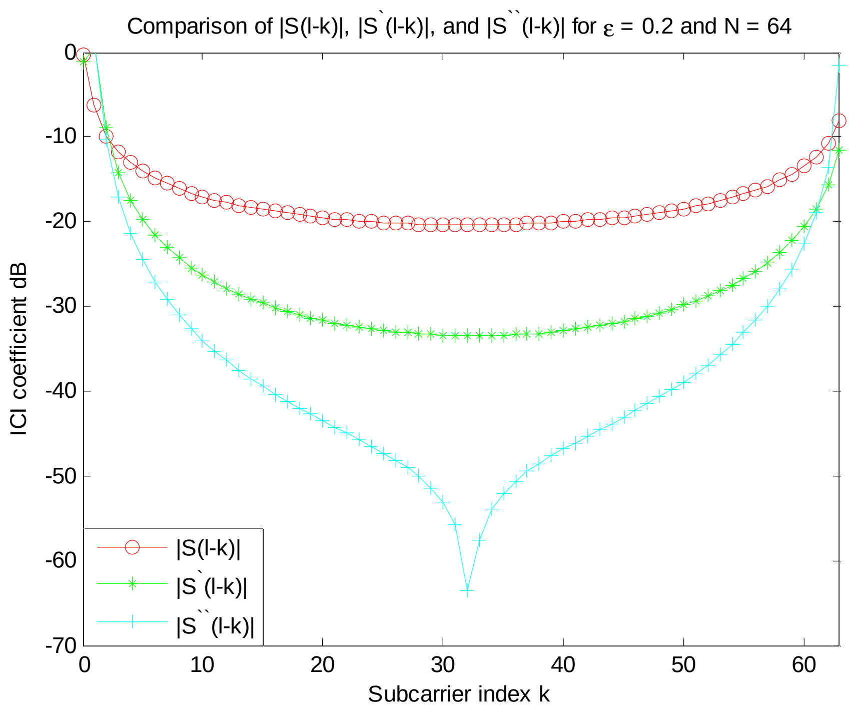

Fig 3.10 - Comparison between $|S(l-k)|$, $|S'(l-k)|$ and $|S''(l-k)|$

Assuming the transmitted symbols are such that

X(1) = -X(0), X(3) = -X(2),…….., X(N-1) = -X(N-2), then the received signal on subcarrier k becomes

$$r'(k) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[S(l-k) - S(l+1-k)] + n_k \tag{3.18}$$

Similarly the received signal on subcarrier $k+1$ becomes

$$r'(k+1) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[S(l-k-1) - S(l-k)] + n_{k+1} \tag{3.19}$$

In such a case, the ICI coefficient is denoted as

$$S'(l-k) = S(l-k) - S(l+1-k) \tag{3.20}$$

To further reduce ICI, ICI cancelling demodulation is done. The demodulation is suggested to work in such a way that each signal at the $k+1^{th}$ subcarrier (now k denotes even number) is multiplied by "-1" and then summed with the one at the k^{th} subcarrier. Then the resultant data sequence is used for making symbol decision. It can be represented as

$$\begin{aligned} r''(k) &= Y'(k) - Y'(k+1) \\ &= \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[-S(l-k-1) + 2S(l-k) - S(l-k+1)] + n_k - n_{k+1} \end{aligned} \tag{3.21}$$

The corresponding ICI coefficient then becomes

$$S''(l-k) = -S(l-k-1) + 2S(l-k) - S(l-k+1) \tag{3.22}$$

when compared to the two previous ICI coefficients |S(l-k)| for the standard OFDM system and |S'(l-k)| for the ICI canceling modulation, |S''(l-k)| has the smallest ICI coefficients, for the majority of l-k values, followed by |S'(l-k)| and |S(l-k)|. It is observed in Fig 3.10 for N = 64 and ε = 0.2. It is shown that the difference between the ICI co-efficient of two consecutive sub-carriers is very small. This makes the basis of ICI self cancellation. Here one data symbol is not modulated in to one sub-carrier, rather at least in to two consecutive sub-carriers. If the data symbol 'a' is modulated in to the 1st sub-carrier then '-a' is modulated in to the 2nd sub-carrier. Hence the ICI generated between the two sub-carriers almost mutually cancels each other. The combined modulation and demodulation method is called the ICI self-cancellation scheme. The reduction of the ICI signal levels in the ICI self-cancellation scheme [26] leads to a higher carrier to interference ratio (CIR). CIR is calculated as

$$CIR = \frac{\left| -S(-1) + 2S(0) - S(1) \right|^2}{\sum_{l=2,4,6.,\ldots}^{N-1} \left| -S(l-1) + 2S(l) - S(l+1) \right|^2} \tag{3.23}$$

The CIR expression for subcarrier $0 < k < N-1$ of a standard OFDM system is derived as

$$CIR = \frac{S(k)^2}{\sum_{l=0,l\neq k}^{N-1} S(l-k)^2} = \frac{\left| S(0)^2 \right|}{\sum_{l=1}^{N-1} S(l)^2} \tag{3.24}$$

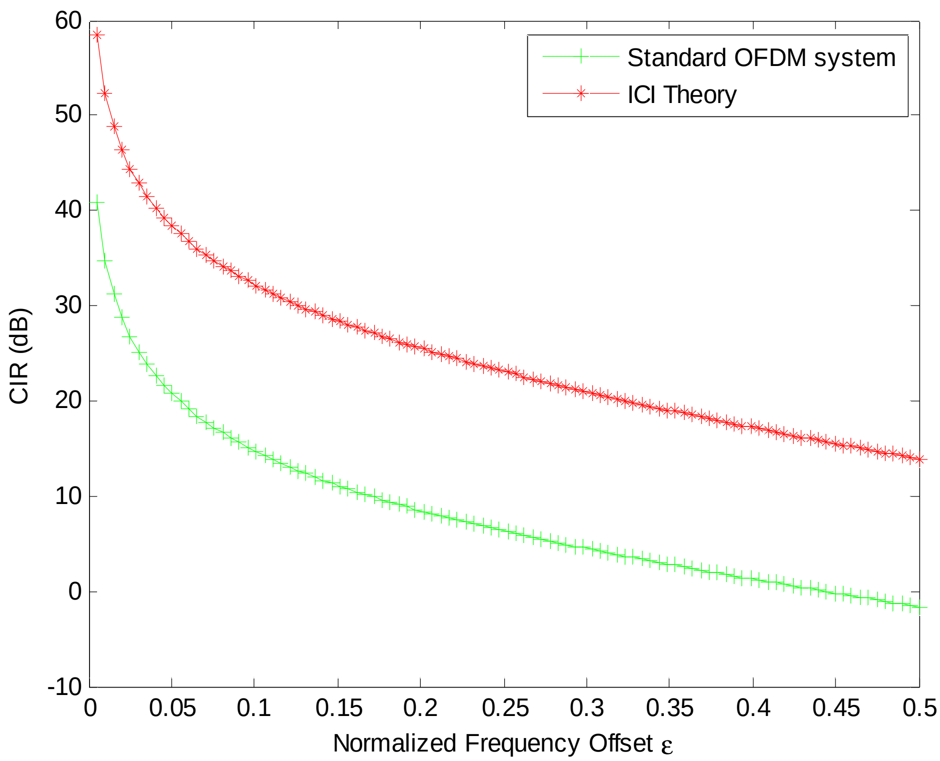

Fig 3.11 CIR Improvement Using ICI Self-Cancellation Schemes

Fig 3.11 shows the comparison of the theoretical CIR curve of the ICI self-cancellation scheme, calculated by (3.23), and the CIR of a standard OFDM system calculated by (3.24). The ICI self-cancellation scheme provides more than 15dB CIR improvement for $0 < \varepsilon \leq 0.5$. The CIR improvement is around 17dB for small to medium normalized frequency offset in the range $0 < \varepsilon \leq 0.2$

3.5.3.3 Performance Analysis

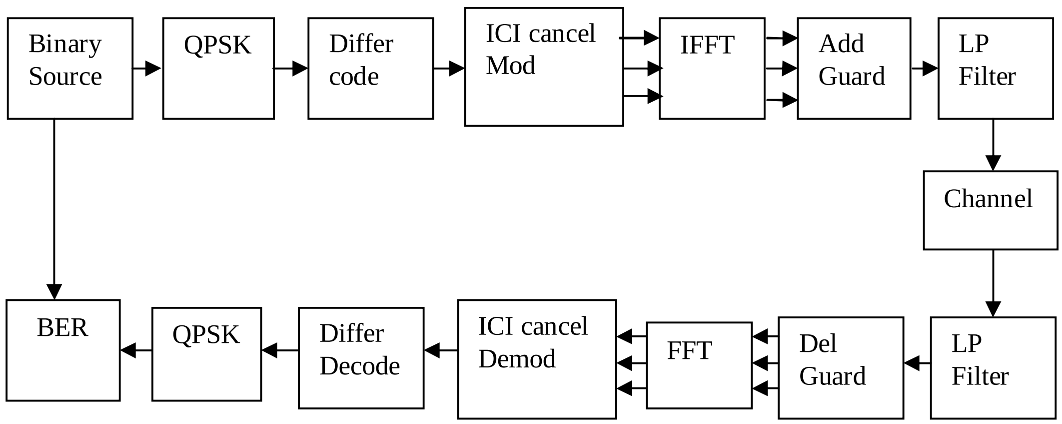

Fig 3.12 Simulation Block diagram of the Self-cancellation Schemes

The simulation block diagram of the ICI self-cancellation scheme is shown in fig. 3.12. The simulation parameters used for the model are as given below.

Parameter	**Specifications**
IFFT Size	64
Number of Carriers in one OFDM symbol	52
Channel	AWGN
Frequency Offset	0, 0.15, 0.3
Guard Interval	12
Modulation	QPSK

Table 3.4 Simulation Parameters

Fig. 3.13 shows the BER performance comparisons between standard OFDM and OFDM with ICI self cancelation technique for frequency offset values from 0 to 0.3 and it is observerd that BER degrades.

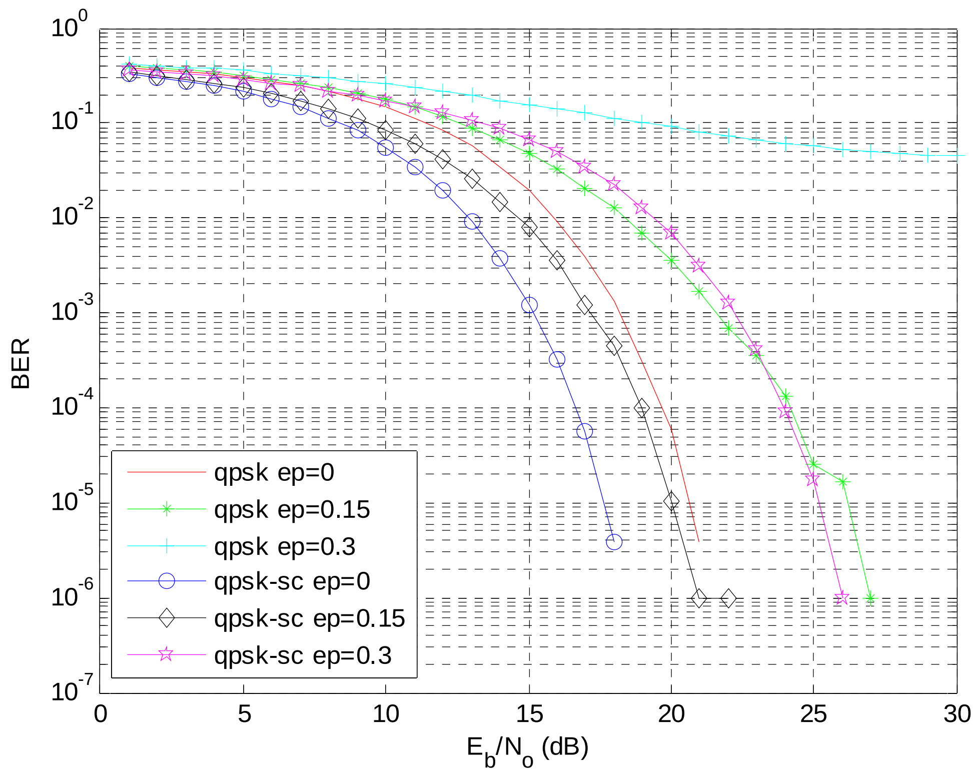

Fig 3.13 BER Performance of a QPSK OFDM system with & without Self Cancellation

3.6 Conclusion

In this chapter, the two drawbacks of OFDM system, peak-to-average power ratio (PAPR) and inter-carrier interference (ICI) are addressed. Some of previously reported PAPR reduction schemes like Clipping and Filtering, Selected Mapping, Partial Transmit Sequence (PTS) and ICI reduction schemes like ICI Self-Cancellation are investigated in detail. Their performances are compared through simulation work. Clipping and filtering the OFDM signal before amplification is a simple method to limit PAPR. However clipping and filtering may cause large out-of band and in band interference, which results in the system performance degradation. It also faces the peak regrowth problem, so the final signal exceeds the clipping level at some points. Selected mapping scheme can handle any number of subcarriers and drawback associated with the scheme is the overhead of side information that needs to be transmitted to the receiver. PTS scheme can be interpreted as a structurally modified case of SLM scheme and it is found that the PTS scheme performs better than SLM scheme. ICI self-cancellation scheme provides CIR improvement which has been analyzed theoretically and by simulations. OFDM system using ICI-self cancellation performs much better than the standard OFDM system. All these previously reported techniques discussed are suitable for either PAPR or ICI reduction not for eliminating both. So designing an efficient scheme without increasing system complexity to overcome both the limitations of OFDM has been the major focus of this research work.

Chapter 4

AN EFFICIENT TECHNIQUE FOR PAPR AND ICI POWER REDUCTION USING PULSE SHAPING

AN EFFICIENT TECHNIQUE FOR PAPR AND ICI POWER REDUCTION USING PULSE SHAPING

4.1 Introduction

The Orthogonal Frequency Division Multiplexing (OFDM) is a promising wideband communication technique for achieving high data rate in wired and wireless environments. There are numerous benefits associated with OFDM systems. One of them is its high spectral efficiency due to the minimum spectral spacing between the subcarriers, attributed to their orthogonality [4]. Also adaptive modulation schemes can be used on individual subcarriers, according to the transmission conditions on each subcarrier. Futher this multicarrier transmission system can be implemented in the digital domain by using computationally efficient IFFT. Despite its multidimensional benefits of OFDM systems suffer however from a number of drawbacks. The high Peak-to-Average Power Ratio (PAPR) is the most severe one [20] [21]. This is caused by constructive interference between many sub-carriers, which may occur at few time instants within the symbol duration. One of the obvious difficulties related to high PAPR is the necessity of having very wide linear dynamic range for the power amplifiers at the transmitter RF stage. Minimizing the PAPR allows a higher average power to be transmitted to for a fixed peak power, improving the overall signal to noise ratio at the receiver. It is therefore important to minimize the PAPR. Many techniques have been suggested in the literature to tackle this problem [22]-[25]. The reduction in PAPR achieved by these techniques is relative and is obtained at the expense of either an additional complexity to the OFDM transmitter and receiver. Other possible alternative solution is to try to exploit other parameters of the OFDM signal. Employing the subcarrier waveforms of the OFDM signal appears as an attractive solution for reducing PAPR of OFDM signals.

Another accurate frequency and time synchronization are essential for OFDM system. The sensitivity against carrier frequency offset causes attenuation and rotation of subcarriers. Hence orthogonality among the carriers is lost and it results inter-carrier-interference (ICI). The undesired ICI degrades the performance of the system. Various researchers have proposed numerous ICI mitigation techniques to solve this problem [33]

[34]. The pulse shaping technique in OFDM system proposed in this research work for PAPR reduction is also employed for reduction of inter-carrier-interference power through the reduction of side lobes in each carrier. Efficient Pulse shaping technique using new pulse shapes for improving the performance of OFDM system is the major focus of this research work.

4.2 Pulse Shaping Approach in OFDM System

In OFDM system pulse shaping is the usage of time waveforms of the different sub-carriers to create the appropriate correlation that reduces the PAPR of the multi-carrier signal. It has been using this technique it is possible to design a set of time waveforms of OFDM systems that decreases the peak power of the transmitted signal and improve its power spectrum simultaneously. The pulse shaping method avoids the use of an extra Inverse Fast Fourier Transformations (IFFTs). It works with arbitrary number of sub carriers for any type of base band modulation used. The implementation complexity of the suggested technique is by far much low compared to previously established methods. This proposed method has the potential of reducing the PAPR of the OFDM signal without affecting the bandwidth efficiency of the system. Another drawback of OFDM system is its sensitivity to frequency offset between the transmitted and received signal, which may be caused by Doppler shift in channel, or by difference between the transmitter and receiver local oscillator frequencies.

In OFDM spectrum each carrier consists of a main lobe followed by a number of side lobes with reducing amplitude. As long as orthogonality is maintained, there is no interference among the carriers because at the peak of the every carrier, there exists a spectral null. At that point the component of all other carriers is zero. Hence the individual carrier is easily separated. But due to the carrier frequency offset orthogonality is lost, now spectral null does not coincide to the peak of the individual carriers. So some power of the side lobes exists at the centre of the individual carriers which is called ICI power. The ICI power will go on increasing as the frequency offset increases which, degrades the performance. ICI mitigation techniques are essential in improving the performance of an OFDM system is an environment which induces frequency offset error in the transmitted signal. This thesis work emphasizes on pulse shaping of transmitted signal to reduce the side lobes such that the ICI power decreases significantly and the system performance improves.

4.2.1 Simulation Model

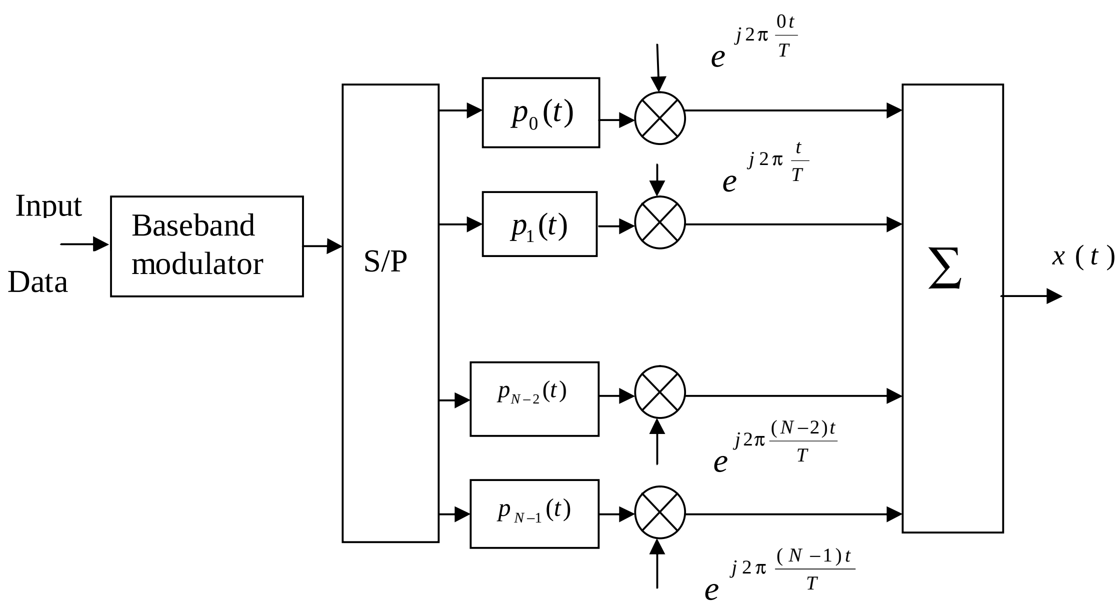

Fig.4.1 OFDM Transmitter Model Using Pulse Shaping

The fig 4.1 illustrates the transmitter block diagram of a N sub-carrier OFDM system using pulse shaping. Here the incoming data is first modulated in baseband using a bandwidth efficient modulation (QPSK modulation). The baseband modulated stream, with data rate *1/T*$_s$ is then split into N parallel streams. Each stream is shaped by a time waveform (pulse shaping waveform) and transmitted over a given subcarrier. Thus the OFDM transmitted signal can be expressed as

$$x(t) = \sum_{k=0}^{N-1} X_n(k)\, p_k(t) e^{j2\pi k\frac{t}{T}}, \qquad nT \le t \le (n+1)T \tag{4.1}$$

where $X_n(k)$ the modulated data symbol of sub-carrier is k, T is the duration of the OFDM block. The waveform $p_k(t)$ is a pulse shape, of duration T, used at subcarrier

k and having a bandwidth less or equal to the bandwidth of the OFDM signal $x(t)$.The OFDM band-pass signal is related to its equivalent low-pass by the following expression:

$$s(t) = \Re\{x(t)\ e^{j2\pi f_c t}\} \qquad (4.2)$$

where f_c is the carrier frequency. The total bandwidth of the OFDM band-pass signal can be approximated as follows:

$$B_s \approx \frac{1}{T_s} + \frac{\beta}{T_s}$$

where $0 \le \beta < 1$ is a coefficient related to the number of subcarrier and the transmit filter. And T_s is the symbol duration of the baseband modulated signal.

4.2.2 Peak-to-Average Power Ratio of OFDM Signals

The peak-to-average power ratio of the OFDM transmitted signal of eq. (4.1) can be defined as follows:

$$PAPR = \frac{\max|x(t)|^2}{E\{|x(t)|^2\}} \qquad (4.3)$$

Assuming uncorrelated symbols within each OFDM block, the maximum PAPR is obtained as

$$PAPR_{\max} = \frac{1}{N} \max_{0 \le t \le T} \left(\sum_{m=0}^{N-1} |p_k(t)| \right)^2 \qquad (4.4)$$

which is a function of the number of subcarriers N and the pulse shape used at each subcarrier. With large number of subcarriers, the maximum of the PAPR occurs with very low probability. A better measure of the PAPR of communication signals is to use the complementary cumulative distribution function (CCDF) defined as

$$P_{PAPR} = \Pr(PAPR \ge PAPR_0)$$

where $PAPR_0$ is the PAPR threshold.

4.2.3 Effect of Pulse Shaping on PAPR Reduction

A possible solution to reduce the PAPR of OFDM signals is to create some correlation between the different OFDM samples of the same block. By making the cross-correlation close one, a multicarrier signal with very low PAPR is obtained. The cross-correlation function of the OFDM signal is obtained as:

$$R_s(t_1,t_2)=\sum_{n=0}^{N-1}\sum_{k=0}^{N-1}\overline{s_{n,l}s_{k,l}^{*}}\,p_n(t_1)\,p_k^{*}(t_2)e^{j2\pi(nt_1-kt_2)/T} \tag{4.5}$$

The cross correlation function is a function of the signal modulated symbol and the subcarrier waveforms. Hence, increasing the correlation between the OFDM signal samples of the same block can be increased through these two parameters. As a result, the PAPR of OFDM signal can be reduced. The use of time waveforms of the different subcarriers is suggested as a way of reducing the PAPR of the OFDM signal without affecting the bandwidth efficiency of the system. A set of time waveforms that reduces the PAPR of OFDM signals was proposed in [39]. However, the reduction obtained was not considerable. The reason for the limited improvement in PAPR is due to the fact that the set proposed in [40] is formed of narrowband pulses. Better reduction in PAPR of OFDM signals may be achieved by using broadband pulse shapes.

A time waveform $p(t)$ with constant energy equals to T and having the following properties is considered here.

$$\begin{cases} p(t)=0, & \left|t-T/2\right|>T/2 \\ P(f)\approx 0, & \left|f-1/(2T_s)\right|>\dfrac{1}{2T_s}+\dfrac{\beta}{2T_s} \end{cases} \tag{4.6}$$

As the waveform $p(t)$ is time limited, it can be approximated by the Fourier series representation within the interval of definition T, i.e.,

$$p(t)\approx\sum_{l=-L}^{N+L-1}C(l)e^{j2\pi\frac{l}{T}t}, \qquad 0\le t<T \tag{4.7}$$

where $C(l)=\frac{1}{T}\int_0^T p(t)e^{-j2\pi\frac{l}{T}t}dt=\frac{1}{T}p\left(\frac{k}{T}\right)$ (4.8)

where $L=\lfloor N\beta/2\rfloor$ and $C(l)$ is the Fourier series coefficient of $p(t)$

Using the waveform $p(t)$, the pulse shape of subcarrier k is defined as follows

$$p_k(t)=\sum_{l=-L}^{N+L-1}C(l)e^{-j2\pi\frac{kl}{N}}e^{j2\pi\frac{l-k}{T}t}, \qquad 0\le t<T \tag{4.9}$$

$$p_k(t)e^{j2\pi\frac{k}{T}t}=p_i(t-\tau_{k-i})e^{j2\pi\frac{i}{T}(t-\tau_{k-i})} \tag{4.10}$$

Where, $\tau_{k-i}=[(k-i)\,\mathrm{mod}N]T_s$.

It indicates that the subcarrier waveforms of the OFDM modulation, as defined above, are cyclic shifts of each other within the time interval $0\le t<T$. With this property the peak amplitudes of the N subcarrier waveforms will not occur at the same time, and thus the peak power to average power ratio (PAPR) of the OFDM signal will be reduced. Hence the selection of pulse shaping function as discussed in the subsequent section is done maintaining the orthogonality property between the different subcarriers as given below.

$$\int_0^T p_k(t)p_l^*(t)e^{j2\pi\frac{k-l}{T}t}dt=\begin{cases}T, & l=k\\ 0, & l\neq k\end{cases}. \tag{4.11}$$

4.3 Modified Pulse Shaping Functions

Two new pulse shaping functions, denoted as Improved Sinc power pulse (ISP) suggested in [34]. And Modified Raised Cosine (MRC) suggested in [40] is employed to reduce PAPR and ICI power functions of N-subcarrier OFDM system. Researchers have worked to improve the conventional pulse shaping filters (rectangular (REC), raised cosine (RC), and Sinc power pulse (SP)) [33] over the years. The Improve Sinc Power (ISP) Pulse [34] is implemented considering a design parameter ‘a’ which adjusts the amplitude of the conventional sinc pulse and has a fast decaying rate decreasing the lobes of sinc function.

Similarly certain modifications are incorporated in the raised cosine function to develop MRC pulse shape by introducing a new design parameter called the shaping parameter d [40] which shapes the impulse response and minimizes the PAPR of the transmitted signal.

4.3.1 Spectrum Analysis of Modified Pulse Shaping Functions

4.3.1.1 Improved Sinc Power pulse (ISP)

The improved sinc power pulse (ISP) is inspired from the conventional SP pulse shape. The conventional sinc pulse is defined below.

$$P_{SP}(f) = \sin c^{m}(fT)$$

The Fourier transform of the continuous time Improved Sinc power pulse (ISP) is described by modifying SP as follows.

$$P_{ISP}(f) = \exp\left\{-a(fT)^{2}\right\}\sin c^{m}(fT)$$

Where '*a*' is a design parameter to adjust the amplitude and *m* is the degree of the sinc function. Fig 4.2 shows the spectral comparisons of different pulse shapes.

The purpose of pulse shaping is to reduce the main lobe as well as side lobe, as the side lobes contain the ICI power and the main lobe contains peak power. It is observed that the magnitude spectral of side lobe is maxi-mum for rectangular pulse and minimum for ISP pulse shapes. It is also noticed from fig 4.2 that the amplitude of ISP pulse shape is the lowest at all frequencies when compared with the previously reported pulse shapes and it has a fast decaying rate decreasing the lobes of sinc function. These properties help in providing better performance due to both PAPR & ICI reduction.

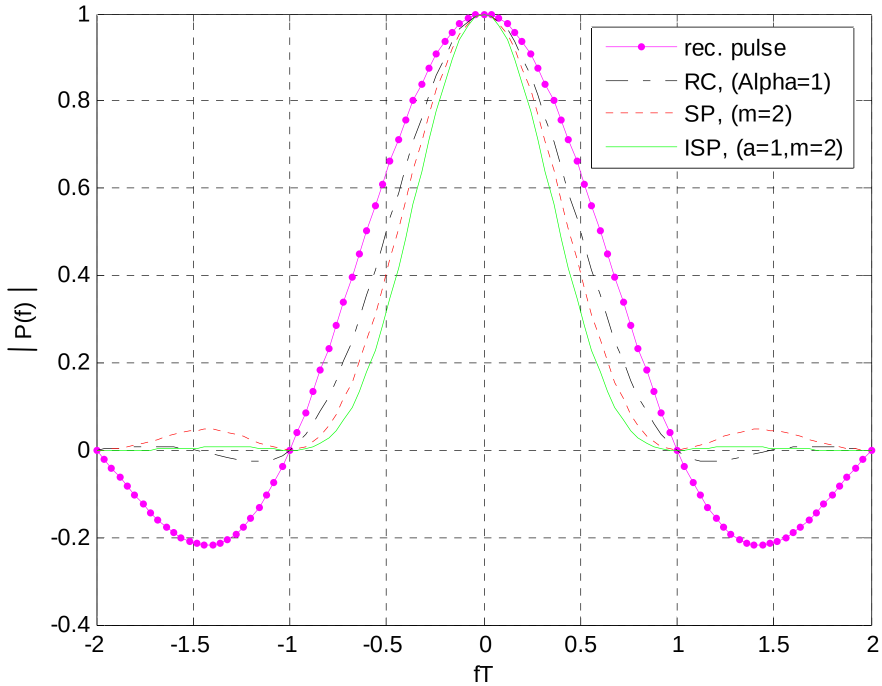

Fig. 4.2 Spectral Comparison of REC, RC, SP and ISP Pulse

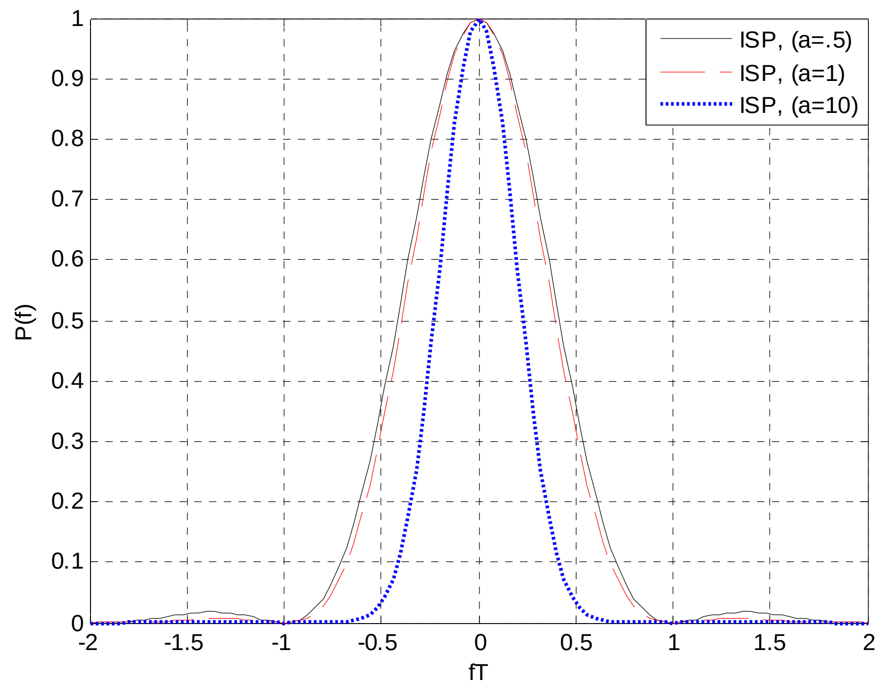

Fig. 4.3 ISP Pulse Shapes for m=2 & Varying the design parameter

Futher the effect of design parameter '*a*' on magnitude and frequency spread is studied for a fixed value of sinc function degree of $m = 2$. As shown in fig 4.3, increasing a from 0.5 to 10, the amplitude in the frequency space decreases. For very large values of a (a =10), ISP pulse shape converges to a narrow pulse shape.

4.3.1.2 Modified Raised Cosine Pulse (MRC)

The Fourier transform of the continuous-time conventional raised cosine pulse is defined by [40].

$$P(f)=\begin{cases} T & 0\le|f|\le\dfrac{1-\alpha}{2T} \\ \dfrac{T}{2}\left\{1+\cos\left[\dfrac{\pi T}{\alpha}\left(|f|-\dfrac{1-\alpha}{2T}\right)\right]\right\} & \dfrac{1-\alpha}{2T}\le|f|\le\dfrac{1+\alpha}{2T} \\ 0 & |f|>\dfrac{1+\alpha}{2T} \end{cases} \qquad (4.12)$$

where α is the roll-off factor that determines the filter bandwidth $B=(1+\alpha)/2T$. Researchers have studied to improve the conventional raised cosine filter by incorporating new parameters. The conventional raised cosine solution, given in Eq 4.12, is obtained by fitting a (raised) half-cycle of cosine, in the transition region, $\dfrac{1-\alpha}{2T}\le|f|\le\dfrac{1+\alpha}{2T}$. Here modification is based on simply allowing any multiple or fraction of cosine cycles to be fitted in the transition region; this is done by introducing a multiplicative factor d that scales the period (in frequency domain) of the raised cosine function. It is found that d is inversely related to the length of cosine cycles fitted in the transition region, measured relative to one half cycles. The fig 4.4 shows the range of spectral shaping possible by varying d. There can be two types of modified solutions, known as "convex" and "concave". The names denote the curvature of the response in the first half portion of the transition region.

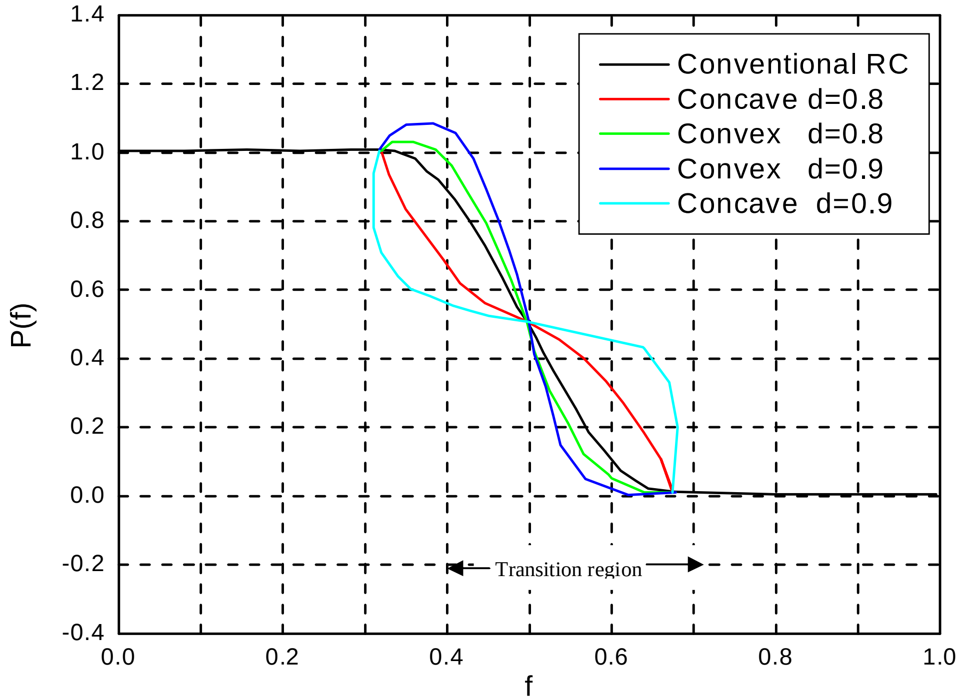

Fig 4.4 Modified Raised Cosine Spectra (in frequency domain) for α =0.35

Using the modified method, the frequency responses of the convex and concave filters in the transition region are obtained to be, respectively.

$$P_{CV}(f) = \frac{T}{2}\left\{1 + q\cos\left[\frac{\pi T}{\alpha.d}\right]\left(|f| - \frac{(1-\alpha.d)}{2T}\right)\right\} \tag{4.13}$$

$$P_{CC}(f) = \frac{T}{2}\left\{1 + \frac{2}{\alpha}(1-2T|f|) - q\cos\left[\frac{\pi T}{\alpha.d}\left(|f| - \frac{(1-\alpha.d)}{2T}\right)\right]\right\} \tag{4.14}$$

where $q = \cos^{-1}\left(\frac{\pi}{2}\frac{(d-1)}{d}\right)$ represents an amplitude normalization factor needed to make the frequency responses to be continuous across the borders between different regions. The subscripts *CV* and *CC* denote the convex and concave solutions, respectively.

The corresponding impulse responses for the convex and concave filters are obtained, by taking the inverse Fourier Transform of $P_{CV}(f)$ and $P_{CC}(f)$, respectively, to be

$$P_{CV}(t) = P_1(t) + P_2(t) \tag{4.15}$$

$$P_{CC}(t) = P_1(t) - P_2(t) + P_3(t) \tag{4.16}$$

where $P_1(t) = \sin c(t)\cos(\pi\alpha t)$

$$P_2(t) = q.\frac{\alpha}{2}\left(\sin c(\alpha t - \frac{1}{2d})\sin \pi t - \sin c(\alpha t + \frac{1}{2d})\sin \pi t\right) \tag{4.17}$$

$$P_3(t) = 2.\sin c(t)\left(\sin c(\alpha t) - \cos(\pi\alpha t)\right) \tag{4.18}$$

Fig 4.5 and 4.6 show the effects of the shaping parameter d on impulse responses of convex and concave filters, for d = 0.8,1 and 1.5 with a constant roll-off factor α = 0.35. It is observed that d affects the side lobe responses in a significant way. PAPR analysis using ISP and Modified RC pulse shapes is described in the next section.

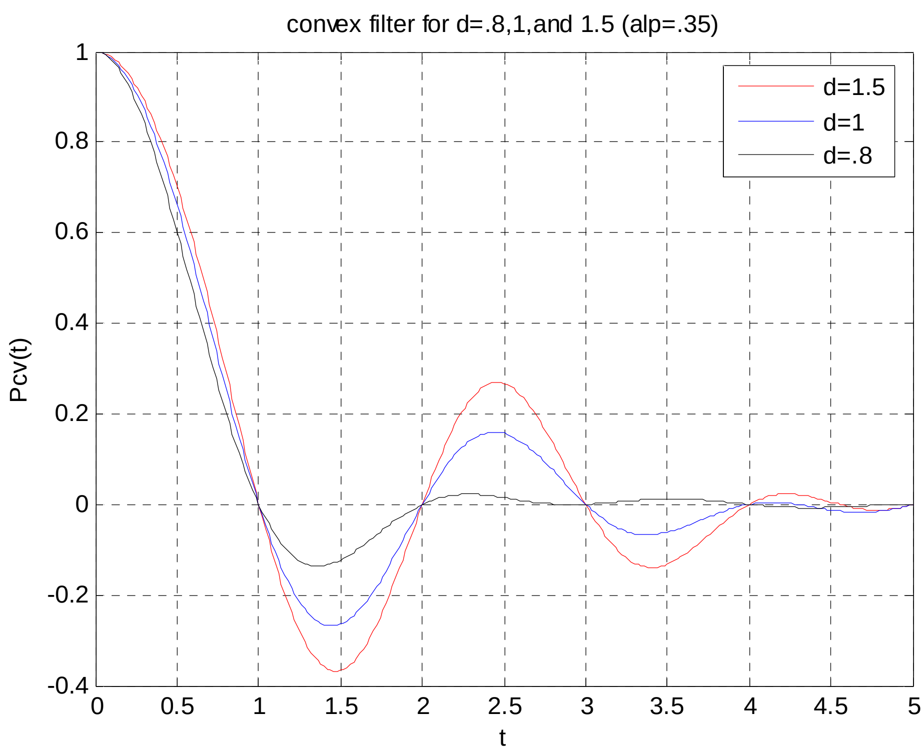

Fig 4.5 Convex Filter for d=.8, 1, and 1.5 for (Alpha=.35)

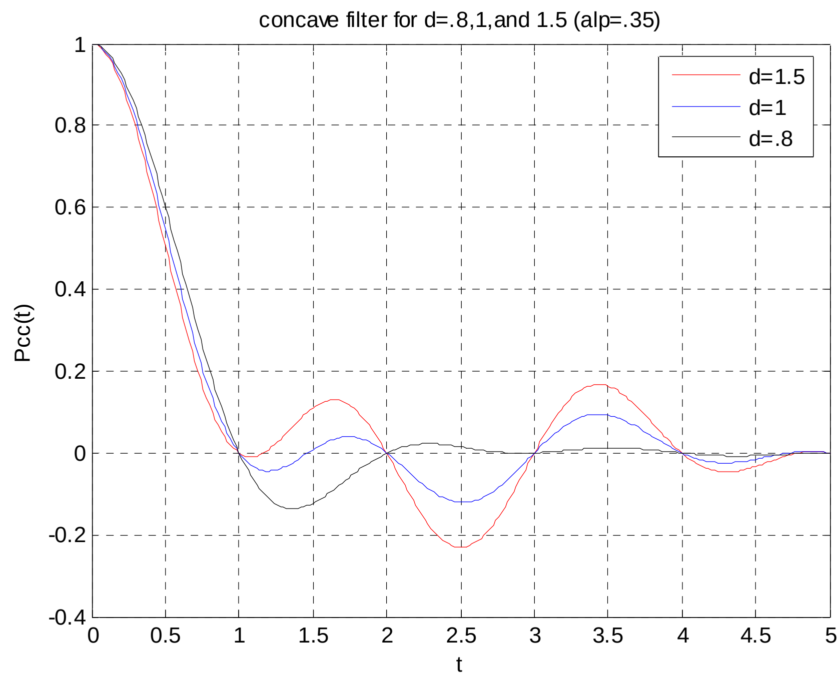

Fig 4.6 Concave Filter for d=.8, 1, and 1.5for (Alpha=.35)

4.4 PAPR Analysis Using Pulse Shaping

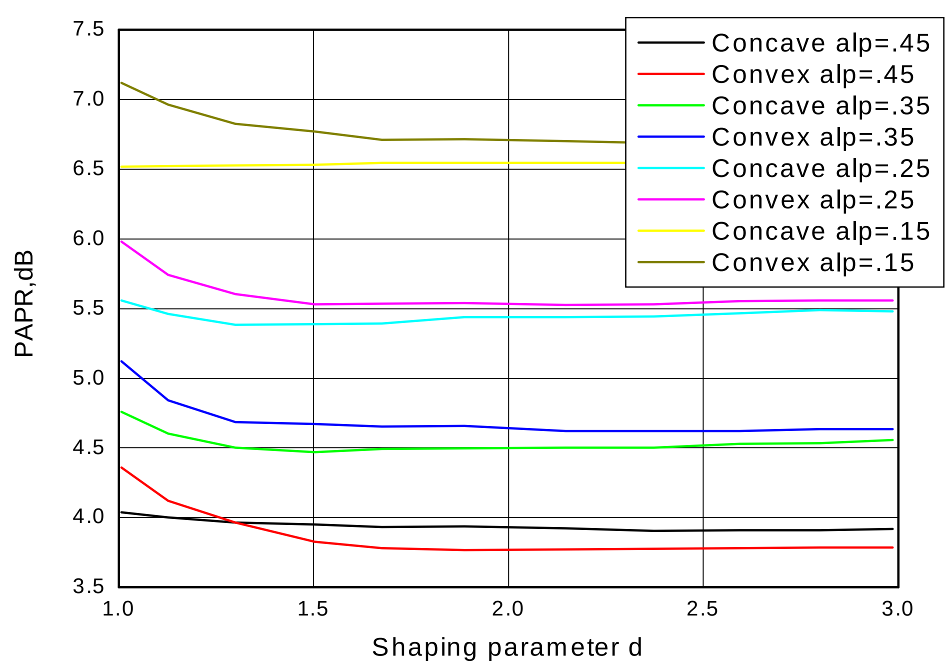

Fig 4.7 PAPR vs. d for Concave and Convex filters

Fig 4.7 shows that PAPR variation as a function of shaping parameter d for both convex and concave filters for indicated values of roll-off factor α. This figure illustrates that the concave filter yields minimum PAPRs, although at different values of d, for α =.15, .25 and .35, where as the convex filter yields the minimum for α =0.45. It can be seen that PAPR reduction of more than .5dB is possible with an appropriate choice of d using the modified filters over the conventional raised cosine filter. For example, for α =.35, PAPR is about 4.5dB for the concave filter at $d \approx 1.5$, as compared to about 5.1dB for the conventional raised cosine filter.

The fig 4.8 shows the minimum PAPR possible as a function of roll off factor α with the modified filters, along with those of the conventional raised cosine. It can be that the modified filters can give a PAPR reduction of about .5 to 1 dB at α =0.9.

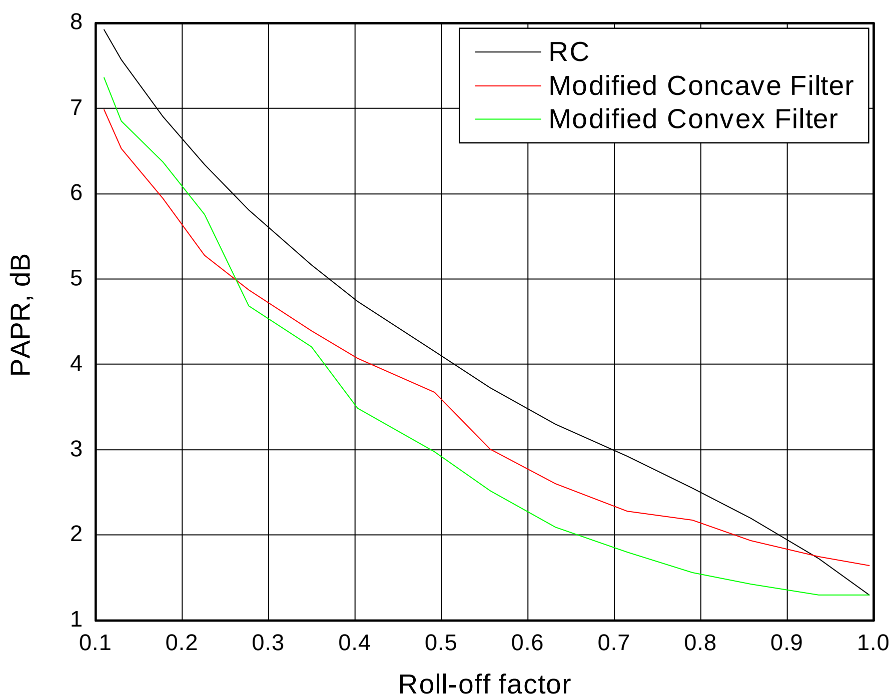

Fig 4.8 Minimum PAPR vs. Roll-off Factor

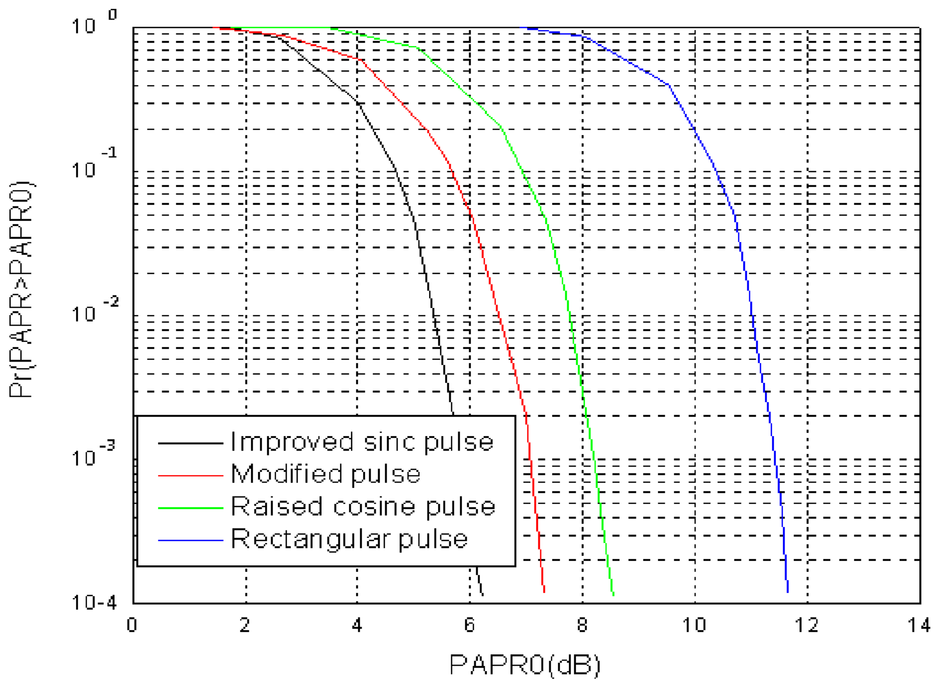

Fig.4.9 CCDF of the PAPR Using Different Pulse Shape

Parameter	**Specifications**
FFT Size	64
Number of Carriers	64
Symbol rate	250000
Signal Constellation	QPSK
OFDM symbols for one loop	12
Number of simulation loops	100

Table 4.1- Simulation Parameters of OFDM Transmitter Model

The fig 4.9 illustrates the complementary cumulative distribution function (CCDF) of the PAPR for a 64 subcarrier OFDM signals using different pulse shapes. The simulation parameters are provided in the table 4.1. It is observed that the pulse shaping technique is beneficial providing considerable gain in PAPR reduction compared to that of conventional OFDM. This is because the improved sinc pulse has the smallest side-lobe and peak amplitudes of subcarrier waveforms do not occur at the same time instant. It is found that ISP pulse shape outperforms to all other pulse shaping functions in terms of PAPR reduction. A performance comparison table 4.2 given below shows a PAPR reduction of 5dB at a CCDF level of 10^{-2} using ISP pulse.

	CCDF (Pr[PAPR>PAPR0])	PAPR0(dB)
Rectangular pulse	10^{-2}	11
Raised Cosine Pulse	10^{-2}	8
Modified Raised Cosine Pulse	10^{-2}	7
Improve Sinc Power Pulse	10^{-2}	6

Table 4.2- A Comparison table of Different Pulse shaping Functions

Fig.4.10 illustrates the complementary cumulative distribution (CCDF) function of the PAPR of the OFDM signal. It is observed that using improved sinc power pulse reduces the PAPR reduction is better compared to the existing partial transmit sequence technique discussed in chapter 3. At a CCDF level of 10^{-3}, PAPR threshold gain of around 3dB compared to that of the original OFDM signal is obtained using ISP pulse. Thus through simulation study it is verified that the proposed pulse shaping schemes helps to reduced high PAPR of OFDM system significantly.

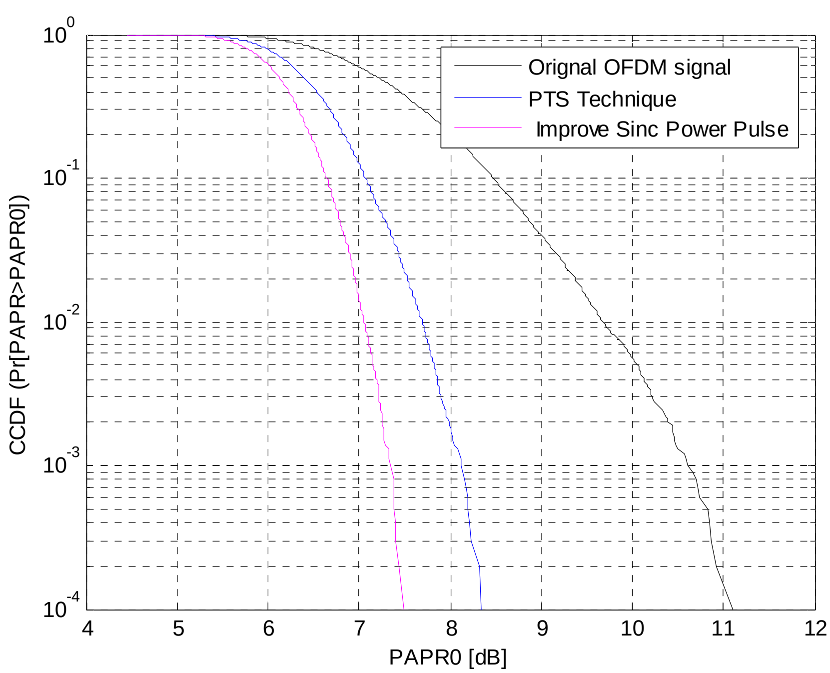

Fig. 4.10 CCDF Comparison between PTS and Pulse Shaping Technique

4.5 ICI Cancellation Using Pulse Shaping Functions

In OFDM communication systems, as long as orthogonality is maintained, there is no interference among the carriers because at the peak of every carrier, there exists a spectral null. Thus at that point the component of all other carriers is zero. But frequency offset in mobile radio channels distort the orthogonality between subcarriers and hence spectral null does not coincide to the peak of individual carriers. So some power of the carriers' side lobes exists at the center of the individual carriers, which is called ICI power. The power goes on increasing as the frequency offset increases and this degrades BER performance. Pulse shaping technique for ICI power reduction is investigated in this section. The purpose of pulse shaping is to reduce the side lobes. Both the improved pulse shapes used for PAPR reduction scheme have been considered for ICI power reduction. Also for the simulation study, the OFDM system model employs QPSK modulation over the AWGN channel. The simulation results are obtained for a 64-subcarrier OFDM system. Performance parameters like average ICI power, average signal power to interference ratio (SIR) and bit-error-rate (BER) rate are evaluated and compared to prove the efficacy of the new pulse shapes.

4.5.1 System Description and Analysis

The transmitter block creates the signal $x(t)$ which is transmitted through the channel with pulse shaping as shown in fig 4.1. The complex envelope of N subcarrier OFDM block with pulse shaping is expressed as [32].

$$x(t) = \exp\{\ j2\pi f_c t\}\sum_{k=0}^{N-1} s_k\, p_k(t)\exp\{\ j2\pi f_k t\}, \qquad (4.19)$$

where f_c is the carrier frequency of OFDM system, N is the number of subcarriers, f_k is the k^{th} subcarrier frequency, where k = 0, 1,……………. , $N-1$, s_k is the data symbol transmitted on the k^{th} subcarrier and $p_k(t)$ is the pulse shaping function. The transmitted symbol s_k is assumed to have zero mean and normalized average symbol energy. And all data symbols are uncorrelated, i.e.,

$$E[s_k s_l^*] = \begin{cases} 1, & k = l \\ 0, & k \neq l \end{cases} \qquad (4.20)$$

where s_l^* is the complex conjugate of s_l .

To ensure the subcarrier orthogonality, which is very important for OFDM systems the equation below has to be satisfied

$$f_k - f_l = \frac{k-l}{T}, \quad k, l = 0, 1, \ldots, N-1, \qquad (4.21)$$

$$\int_{-\infty}^{+\infty} p_k(t) e^{j2\pi(f_k - f_l)t} dt = \begin{cases} 1, & k = l \\ 0, & k \neq l \end{cases} \qquad (4.22)$$

where *1/T* is the minimum subcarrier frequency spacing required to satisfy orthogonality between subcarriers. Equation (4.22) indicates the important condition that the Fourier transform of the pulse $p_k(t)$ should have spectral nulls at the frequencies $\pm 1/T, \pm 2/T$,......to ensure subcarrier orthogonality.

In the receiver block, the received signal can be expressed as the following:

$$r(t) = x(t) \otimes h(t) + n(t) \qquad (4.23)$$

where ⊗ denotes convolution and *h(t)* is the channel impulse response. In (4.23), *n(t)* is the additive complex Gaussian noise process with zero mean and variance $N_0/2$ per dimension. For this work we assume that the channel is ideal, i.e., $h(t) = \delta(t)$ in order to investigate the effect of the frequency offset only on the ICI performance. At the receiver, the received signal after multiplication by $\exp\{ j(2\pi(-f_c + \Delta f)t + \theta)\}$ becomes

$$r'(t) = \exp\{j(2\pi\Delta f t + \theta)\} \sum_{k=0}^{N-1} s_k p_k(t) \exp\{j2\pi f_k t\} + n(t) \exp\{j(2\pi(-f_c + \Delta f)t + \theta)\} \quad (4.24)$$

where θ is the phase error and Δf $(\Delta f \geq 0)$ is the carrier frequency offset between transmitter and receiver oscillators. For the transmitted symbol s_k, the decision variable is given as

$$\hat{s}_l = \int_{-\infty}^{\infty} r'(t) \exp\{-j2\pi f_m t\} dt \qquad (4.25)$$

Putting the value of $r'(t)$ in equation 4.25 and rearranging it, the decision variable $\hat{s}_l$ can be expressed as

$$\hat{s}_l = \int_{-\infty}^{+\infty} \left\{ \exp\{ j(2\pi\Delta ft + \theta)\} \sum_{k=0}^{N-1} s_k\, p_k(t) \exp\{ j2\pi f_k t\} \right\} \exp\{ -j2\pi f_l t\}\, dt$$

$$+ \int_{-\infty}^{+\infty} n(t) \exp\{ j(2\pi(-f_c + \Delta f)t + \theta)\} \exp\{ -j2\pi f_l t\}\, dt$$

$$= \int_{-\infty}^{+\infty} \left\{ \exp\{ j\theta\} \sum_{k=0}^{N-1} s_k\, p_k(t) \exp\{ j2\pi\Delta ft\} \exp\{ -j2\pi(f_l - f_k)t\}\, dt + n_l \right.$$

$$= \int_{-\infty}^{+\infty} s_l \exp\{ j\theta\}\, p_k(t) \exp\{ j2\pi\Delta ft\}\, dt$$

$$+ \int_{-\infty}^{+\infty} \exp\{ j\theta\} \sum_{\substack{k=0 \\ k\neq m}}^{N-1} s_k\, p_k(t) \exp\{ j2\pi\Delta ft\} \exp\left\{ -j2\pi\left(\frac{l-k}{T}\right)t\right\} dt + n_l,$$

$$\textit{where} \quad f_l = {}^{l}\!/_{T}$$

$$= \int_{-\infty}^{+\infty} s_l \exp\{ j\theta\}\, p_k(t) \exp\{ j2\pi\Delta ft\}\, dt$$

$$+ \int_{-\infty}^{+\infty} \exp\{ j\theta\} \sum_{\substack{k=0 \\ k\neq m}}^{N-1} s_k\, p_k(t) \exp\left\{ -j2\pi\left(\frac{l-k}{T} - \Delta f\right)t\right\} dt + n_l$$

$$= s_l\, p(-\Delta f) \exp\{ j\theta\} + \exp\{ j\theta\} \sum_{\substack{k=0 \\ k\neq m}}^{N-1} s_k\, p\left(\frac{l-k}{T} - \Delta f\right) + n_l \qquad (4.26)$$

$$\text{Where} \quad p(-\Delta f) = \int_{-\infty}^{+\infty} p_k(t) \exp\{ j2\pi\Delta ft\}\, dt \qquad (4.27)$$

Now taking exp{jθ} as common, finally we get

$$\hat{s}_l = \left(s_l P(-\Delta f) + \sum_{\substack{k=0 \\ k\neq l}}^{N-1} s_k P\left(\frac{l-k}{T} - \Delta f\right)\right) \exp(j\theta) + n_{l,} \qquad (4.28)$$

where the Fourier transform of *p(t)* and n_l , $l = 0, \ldots, N-1$ is the independent complex Gaussian noise component. In (4.26), the first term contains the desired signal component and the second term represents the ICI component. Where $P(f)$ is the Fourier transform of $p(t)$.

Hence the power of the desired signal can be calculated as

$$\sigma_l^2 = E[s_k P(-\Delta f) s_l^* P(-\Delta f)^*] = E[s_k s_l^*] |P(\Delta f)|^2 = |P(\Delta f)|^2 \tag{4.29}$$

The power of the ICI can be stated as

$$\sigma_{ICI_l}^2 = \sum_{\substack{k=0\\k\neq l}}^{N-1} \sum_{\substack{k=0\\k\neq l}}^{N-1} s_k s_l^* P\left(\frac{k-l}{T} + \Delta f\right) P\left(\frac{k-l}{T} + \Delta f\right)^* \tag{4.30}$$

The average ICI power across different sequences can be calculated as

$$\overline{\sigma_{ICI}^2} = E\left[\sigma_{ICI_l}^2\right] = \sum_{\substack{k=0\\k\neq l}}^{N-1} \left| P\left(\frac{k-l}{T} + \Delta f\right)\right|^2 \tag{4.31}$$

As shown in (4.31) the average ICI power depends on the number of the subcarriers and *P(f)* at frequencies

$$\left(\frac{k-l}{T} + \Delta f\right), \quad k \neq l,\ k = 0,1,\ldots,N-1$$

By using (4.29) and (4.31), the signal-to-interference ratio (SIR) can be defined as

$$SIR = \frac{|P(\Delta f)|^2}{\sum_{\substack{k=0\\k\neq l}}^{N-1} \left| P\left(\frac{k-l}{T} + \Delta f\right)\right|^2} \tag{4.32}$$

4.5.2 ICI Power Analysis Using Pulse Shaping

The ICI power depends not only on the desired symbol location, l, and the transmitted symbol sequence, but also on the pulse shaping function and the number of subcarriers. Similarly, if the spectrum of one pulse shaping function has smaller side-lobes than another, then it is expected this pulse shaping function will lead to less ICI.

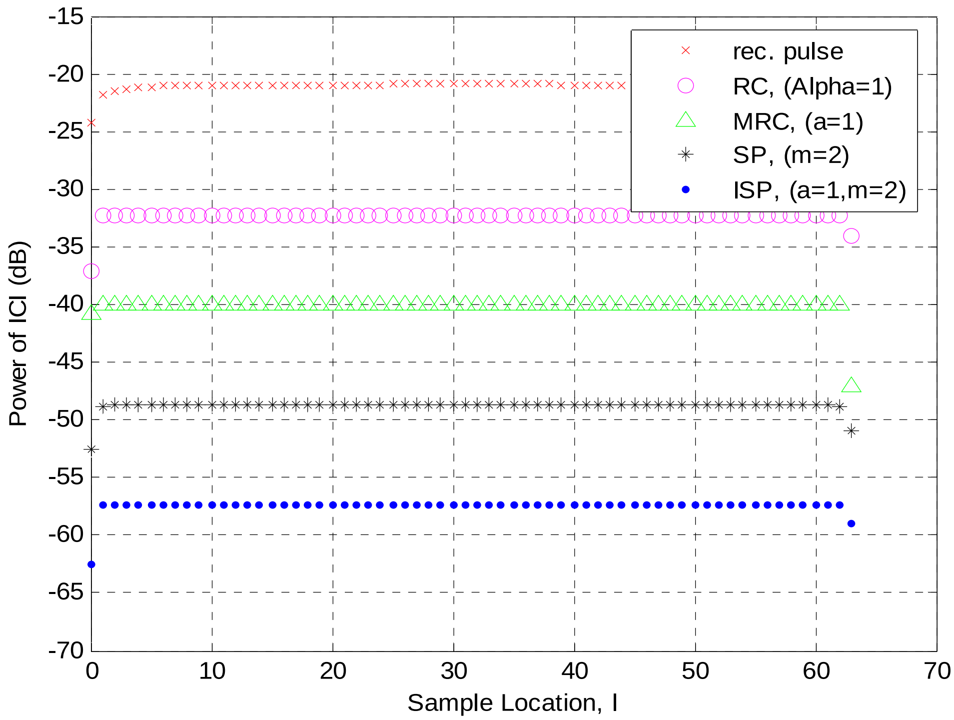

Fig. 4.11 ICI Power Performance for Different Pulse Shapes

Fig 4.11 shows the variation of the ICI power for different sample locations in a 64-subcarrier OFDM system for ΔfT = 0.05. The ICI power drops for samples located near sample locations 0 and *N-1*, because these samples have fewer interference samples. In this figure the pulse shape parameters are selected as following; $\alpha = 1$, $m = 2$, and $a = 1$. The ISP pulse shape for $a = 1$, the ICI power is −57.45 dB which is 8.79 dB better than that of SP pulse shape.

The average ICI power of a 64-subcarrier OFDM system is illustrated in Fig. 4.12, with respect to the normalized frequency offset. In this figure, the pulse shape parameters are selected as the following; $\alpha = 1$, $m = 2$, and $a = 1$. As seen in this figure, the average ICI power performance is better with ISP pulse shapes as compared to all other pulse shapes.

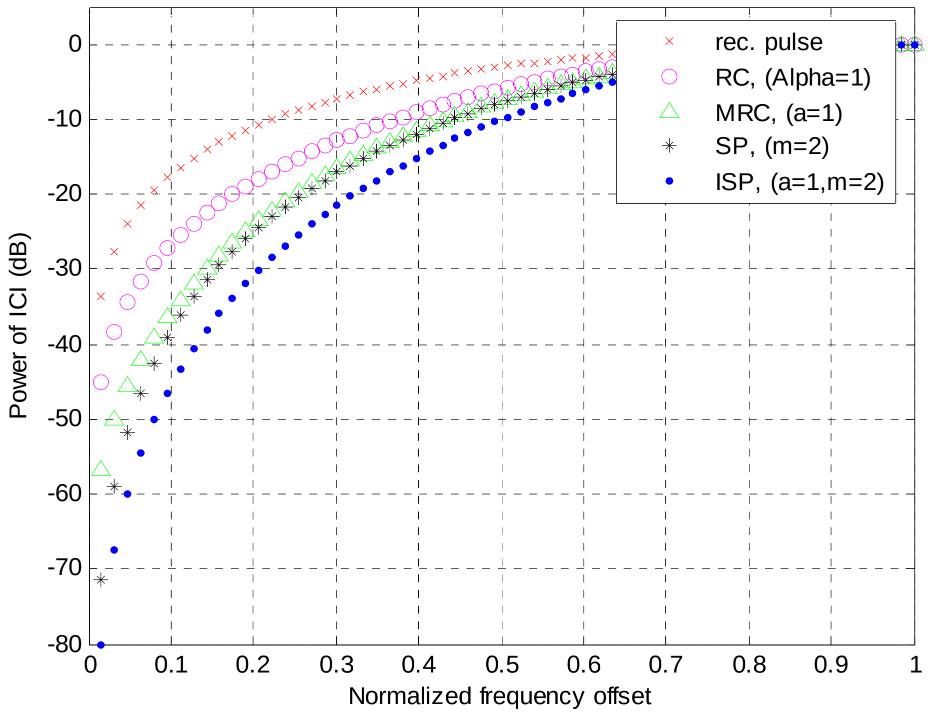

Fig.4.12 Average ICI Power Performance for Different Pulse shaping in a 64-subcarrier OFDM System

Fig.4.13 compares the SIR for different pulse shaping functions in a 64-subcarrer OFDM system plotted as functions of the normalized frequency offset; ΔfT . For RC and MRC, the roll off parameter is equal to one. The degree of sinc functions is selected as m = 2, and for ISP pulse shape a = 1. SIR performance is better using ISP pulse shape. For example, if it is desired to maintain a minimum SIR of 30dB when employing the raised-cosine pulse, the normalized frequency offset must be less than 0.1050. The tolerable normalized frequency offset may be as large as 0.1634 when MRC pulse is used and 0.210 when ISP pulse is used.

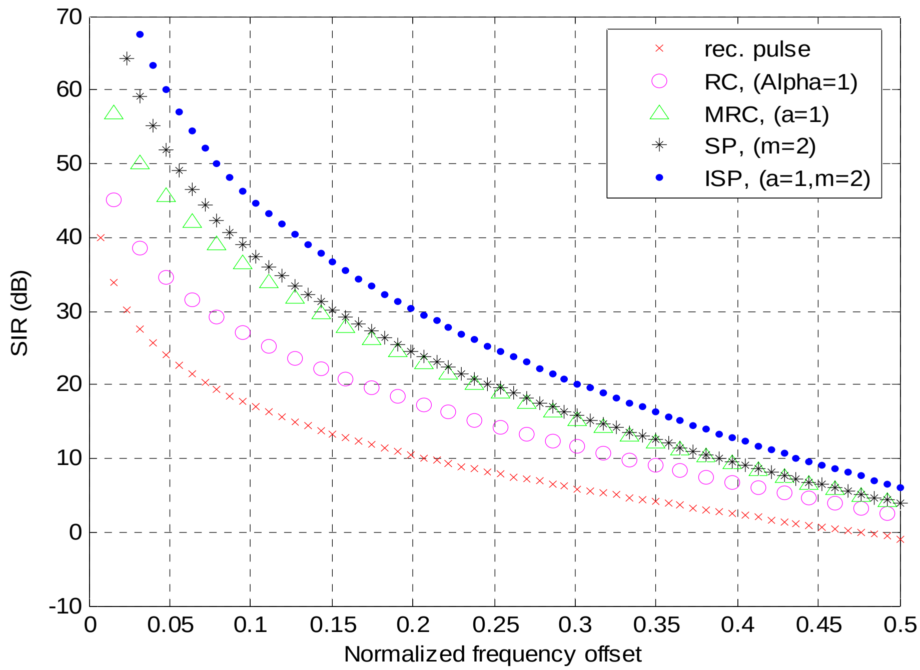

Fig 4.13 SIR Performance for Different Pulse Shapes

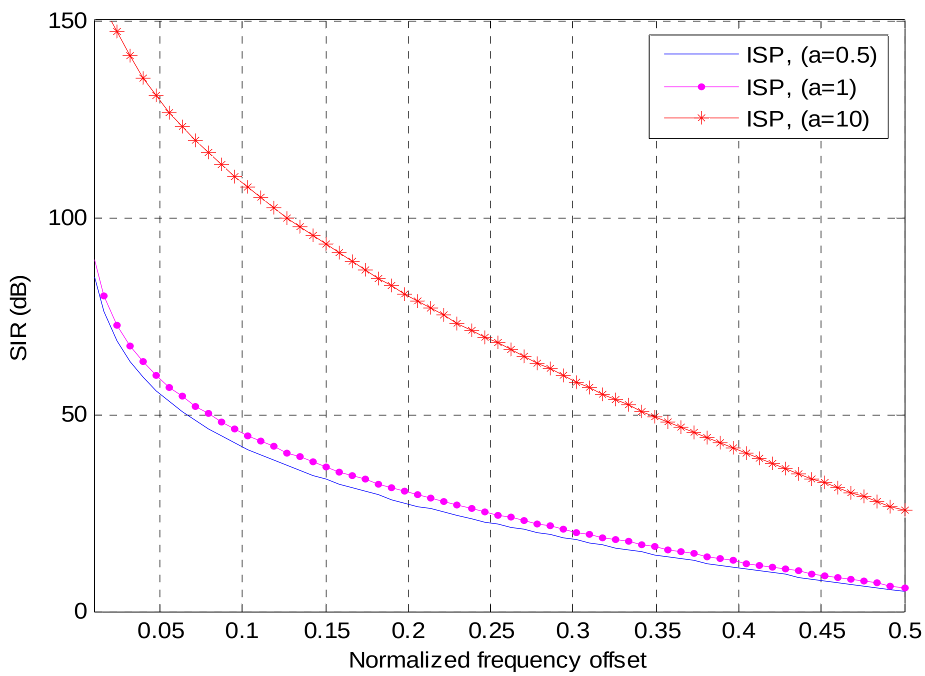

Fig 4.14 SIR Performance of ISP Pulse Shapes for m=2 & a=0.5, 1, 10

Fig. 4.14 illustrates SIR performance of ISP pulse shapes with *m* = 2, *a* = 0.5, 1, and 10 varying the normalized frequency offset from 0 to 0.5. With *a* = 10, SIR gain is maximum with this pulse shape. In other words, by increasing the value design parameter *a*, SIR gain increases. So selection of the design parameter is to be done carefully.

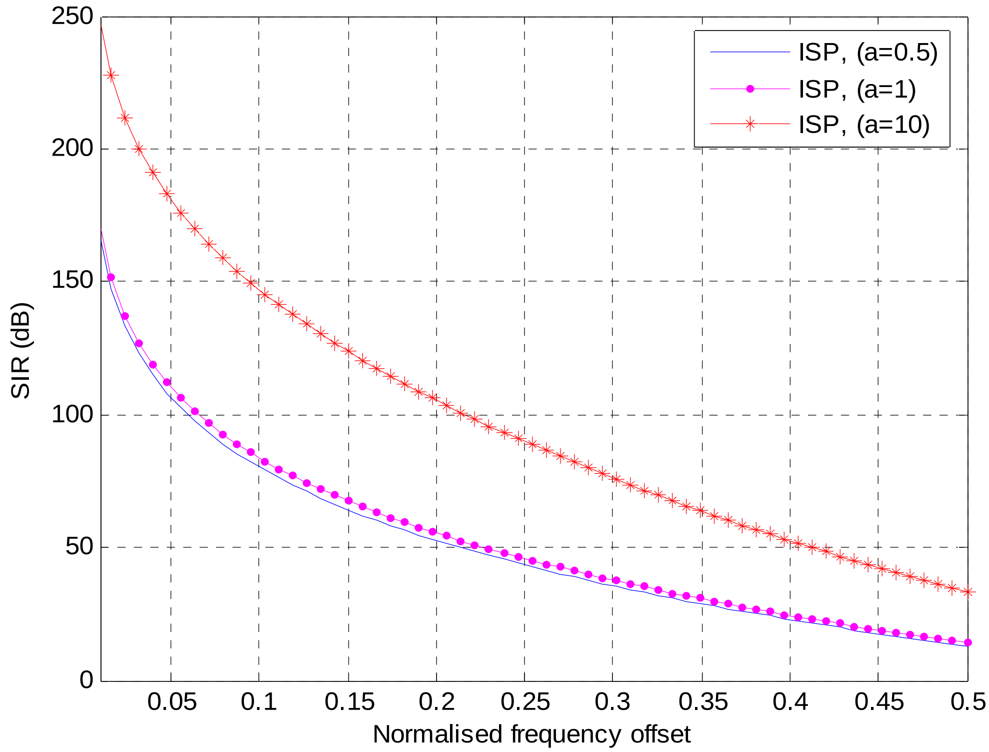

Fig 4.15 SIR Performance of ISP Pulse Shapes for m=4 & a=0.5, 1, 10

SIR performance of ISP pulse shape is demonstrated in Fig.4.15 as a function of normalized frequency offset. Increasing the degree of the ISP pulse from *m*=2 to *m*=4 SIR gain of around 10 to 20 dB is noticed for a fixed normalized frequency offset of 0.25. Thus SIR increases in proportion to the degree *m* of the pulse shaping function. For large values of *m*, the pulse shaping function will converge to a narrow pulse shape, resulting in SIR gain.

4.6 BER Performance of OFDM System with Pulse Shaping

Effect of frequency offset on BER performance of OFDM system is studied first through simulation analysis. Different normalized frequency offset values (0.1, 0.15, 0.2, and 0.25) are chosen. Fig 4.16 shows that with the increase of normalized frequency offset BER degrades noticeably. Hence reliable data decision is not possible at the end receiver for higher offset values.

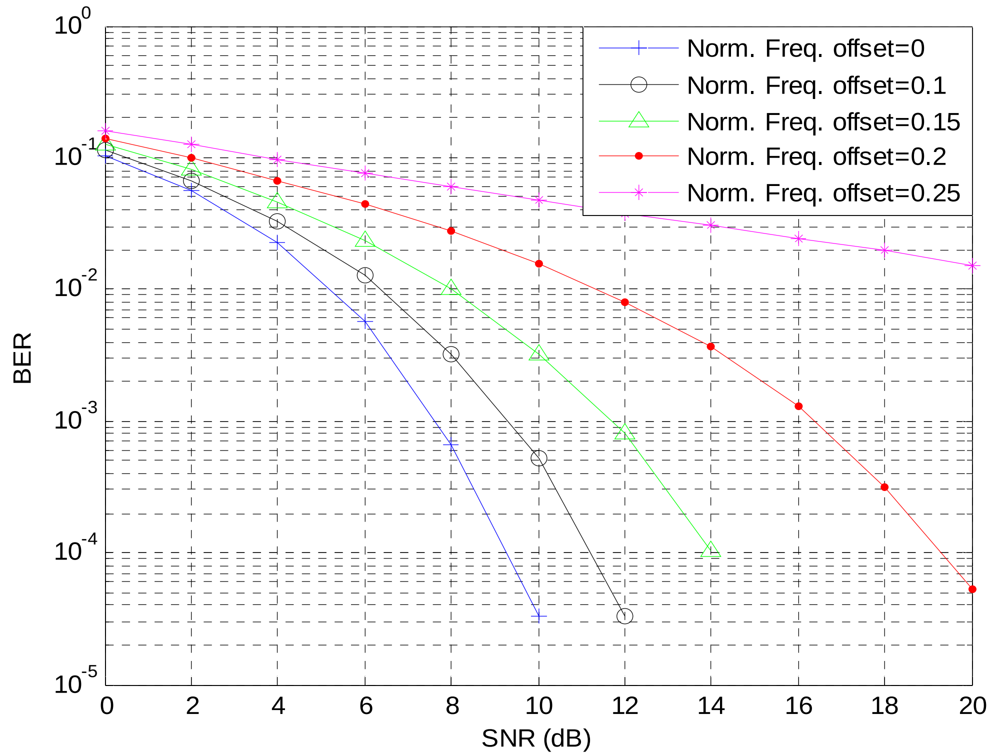

Fig.4.16 BER performance of QPSK-OFDM system varying Normalized frequency offset

Now the pulse shaping technique is applied to OFDM system with a fixed normalized frequency offset value ΔfT=0.25. Pulse shapes (MRC and ISP) with different design parameters (m=2, a=0.5, 1) are considered in this simulation.

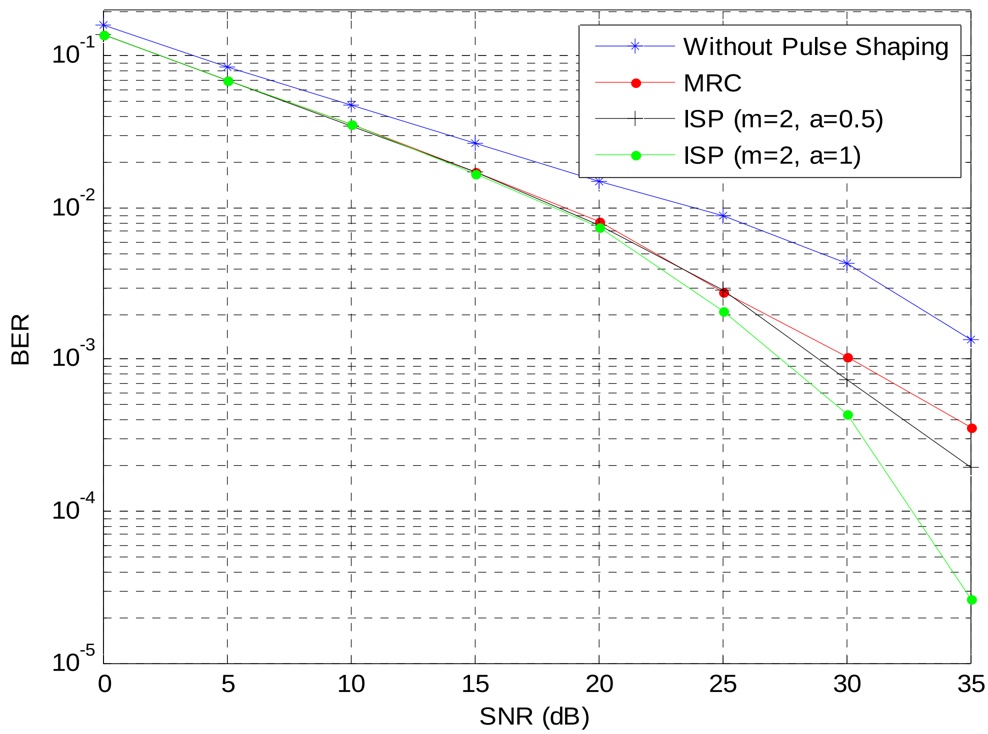

Fig 4.17 BER performance of QPSK-OFDM system for without and with Pulse Shaping ΔfT=0.25

Fig.4.17 shows that BER performance improves using pulse shaping. At a BER level of 10^{-3}, SNR gains of around 8dB and 6dB are observed for OFDM system using ISP (*m*=2, a=1) and ISP (*m*=2, a=0.5) respectively. SNR improvement is also observed using MRC pulse at a fixed BER level. Hence with the proposed pulse shaping approach, effects of both the drawbacks of OFDM system, i.e., PAPR and ICI are reduced. So performance enhancement of the OFDM system is observed.

4.7 Conclusion

An efficient technique is developed to overcome the limitations of OFDM system and improve its performance. Use of pulse shaping functions in the transmitted signal creates appropriate correlation between time waveforms of different subcarriers in the

OFDM system which decease the peak power of the transmitted signal. In OFDM spectrum each carrier consists of a main lobe followed by a number of side-lobes with reducing amplitude. Pulse shaping functions reduce the side-lobes such that ICI power is reduced significantly and the system performance is improved. Conventional pulse shapes (RC, REC etc.) are modified by including new design parameters to suit the requirements for this purpose. The Improved Sinc Power pulse has a fast decaying rate deceasing the lobes of sinc function. The design parameter shapes the impulse response in Modified Raised Cosine pulse and minimizes PAPR of the transmitted signal. It is concluded that this pulse shaping technique can contribute for reduction of both the major problems, i.e., PAPR and ICI of the transmitted signal simultaneously without affecting the bandwidth efficiency of the system. Its implementation complexity of this technique is less compared to previously reported schemes (SLM, PTS etc). OFDM system performance measures like CCDF of PAPR, ICI power, SIR and BER are analyzed through extensive simulation work to prove the efficacy of the proposed pulse shaping scheme. It was observed from performance curves that ISP pulse outperforms others.

Chapter **5**

CONCLUSION

CONCLUSION

5.1 Introduction

The thesis begins with an introduction to orthogonal frequency division multiplexing technology with its application, advantages and limitations. Also the OFDM system simulation model and the BER performance of OFDM over AWGN and Rayleigh fading channel models have been analyzed. As a whole research work undertaken in this thesis can be divided into two parts.

First part begins with the review of PAPR reduction techniques like clipping and filtering, selected mapping (SLM), partial transmit sequence (PTS). Their capabilities and drawbacks are compared on the basis of simulation results obtained. Also some of the previously reported schemes for ICI reduction are also investigated. ICI self-cancellation technique is discussed in detail and its performance evaluated though simulation in terms of CIR and BER. In the second part, an efficient PAPR and ICI reduction technique using pulse shaping approach is proposed. Design parameters of modified pulse shapes which are incorporated in the basic OFDM system are studied and optimized. CCDF of PAPR, ICI power reduction, SIR and BER performance evaluations are carried out using those modified pulse shaping functions.

Following this introduction, section 5.2 summarizes the work undertaken chapter wise. Section 5.3 provides the major contribution of the thesis work and section 5.4 presents the scope of further research work in this field.

5.2 Summary of Work

Chapter-1 reviews the developments and technological aspects of OFDM system. It also presents the motivation for this research. OFDM is recently being used for wired and wireless high data rate communication.

In chapter 2 the background and the basic concepts of OFDM technique are discussed. Implementation of OFDM in wireless LAN, Digital Subscriber Loop (xDSL), Digital Audio Broadcasting (DAB), and Digital Video Broadcasting (DVB-T) are indicated. Advantages and major limitations like PAPR & ICI are explained. The simulation model of OFDM with its design parameters is presented. BER performance analysis for both AWGN and fading channel model are provided. The effect of delay spread and peak power clipping on the performance of OFDM system is analyzed which gives encouraging results.

Chapter-3 investigates two major drawbacks, i.e., high peak to average power ratio (PAPR) and inter-carrier interference (ICI). Some of the previously reported PAPR reduction schemes like Clipping and Filtering, Selected Mapping Partial Transmit Sequence (PTS) and ICI reduction schemes like ICI Self-Cancellation are discussed through simulation study in detail. Clipping and filtering the OFDM signal before amplification is a simple method to limit PAPR. However clipping and filtering may cause large out-of band and in band interference, which results in the system performance degradation. It also faces the peak regrowth problem, so the final signal exceeds the clipping level at some points. Selected mapping scheme can handle any number of subcarriers and drawback associated with the scheme is the overhead of side information that needs to be transmitted to the receiver. PTS scheme can be interpreted as a structurally modified case of SLM scheme and it is found that the PTS scheme performs better than SLM scheme. ICI self-cancellation scheme provides CIR improvement which has been analyzed theoretically and by simulations. The major drawback of this method is the reduction in bandwidth efficiency.

In Chapter-4 an efficient PAPR and ICI reduction technique using pulse shaping approach is proposed. By using this proposed pulse shaping technique, both the problem of PAPR and ICI of the transmitted signal can be overcome. The implementation complexity of the proposed technique is by far much low compared to previous published methods. OFDM system performance like PAPR, ICI power, SIR and BER are analyzed through simulation work.

5.3 Contribution of the Thesis

In recent years OFDM has emerged as the standard of choice in a number of important high data applications. Despite its various advantages it suffers from two major drawbacks, i.e., high PAPR due to time domain OFDM signal which is a sum of several sinusoids and ICI due to frequency offset, outlined in this thesis. Various schemes have been provided by researchers to reduce the above. This thesis work overviews some of those techniques through investigation. Extensive simulation study and comparisons are don to justify their applications. But the previous literature have suggested individual schemes to reduce PAPR and ICI. Till now no scheme has been presented which can reduce both the drawbacks simultaneously. This thesis proposes an efficient technique which has the potential to compensate both PAPR and ICI problems significantly without affecting spectral efficiency of the system. Also its implementation complexity is less. It works well with arbitrary number of subcarriers for any type of baseband modulation used.

The OFDM symbols are independent identically distributed Gaussian random variables. This correlation characteristic is responsible for the high variability of the OFDM signal, which is the reason for increased PAPR. Considering this analysis, the method proposed by this research uses pulse shaping approach, i.e., the usage of time waveform of OFDM signal to create an appropriate correlation between its different subcarriers which decreases the peak power of the transmitted signal without requiring side information. This in turn reduces Peak-to-Average Power Ratio. The other drawback of OFDM system is ICI power which increases with the frequency offset and degrades the performance. Hence, ICI mitigation techniques are essential for improving the BER performance. In OFDM system each carrier consists of a main lobe followed by a number of side-lobes with reducing amplitude. Pulse shaping functions in the transmitted signal reduce the side-lobes such that ICI power decreases and the system performance improves. Modifications of the conventional pulse shapes (Rectangular Pulse, Raised Cosine, etc.) are attempted in this research by including new design parameters to reduce the main lobe as well as the side lobes of their spectral shape. As the main lobe contains peak power and as the side-lobes contain the ICI power, it is possible to decrease the high PAPR and to compensate ICI together with inclusion of pulse shaping functions in OFDM system. The design parameters shape the impulse responses of MRC and ISP pulse and hence minimize both the PAPR and ICI of the transmitted signal. The performance measures like CCDF of PAPR, ICI power; SIR and BER are analyzed through simulation to prove the efficacy of the proposed scheme. As the Improve Sinc Power pulse has a fast decaying rate deceasing the lobes of sinc function, it is observed from the performance curves that ISP pulse outperforms others.

5.4 Scope of Further Research

By concluding this thesis, the following are some pointers for scope of further research.

- Pulse shaping technique can be applied for PAPR reduction in MIMO-OFDM, which is the key technology for further 4G applications.
- Design of optimal pulse shapes with minimum interference power may be tried to provide further improvement in performance.

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Dissemination of Work

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8. Srabani Mohapatra, Susmita Das, "An efficient Technique for Reducing PAPR and ICI problems in OFDM System using pulse shaping" Communicated to *International journal of Mobile Communication (IJMC),* in Oct, 2009.

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