CHAPTER - 1

INTRODUCTION

1.1 OVERVIEW OF OFDM

The Orthogonal Frequency Division Multiplexing (OFDM) [1] was first introduced by R. W. Chang. But it took till 1990s to reach a sufficient maturity level for utilization in standard communication industries. Recently, it has been selected as standard modulation technique in 4G systems and became a part of the Wireless Local Area Network (IEEE 802.11), Worldwide Interoperability for Microwave Access (IEEE 802.16), 3GPP Long Term Evolution (LTE) and LTE-advanced standards.

In order to achieve high data rate using conventional single carrier modulation based techniques, higher bandwidth is required and hence symbol duration decreases. Also, because of dispersive nature of the wireless channel the delay spread becomes significant as compared to symbol duration. Due to spread in symbol duration over-lapping of pulses happen at the receiver side which causes inter symbol interference (ISI). Also, high bandwidth requirement causes frequency selective fading effect at the wireless channel and we need to have complex equalizers at the single carrier receiver to minimize the affect of ISI. The requirement of complex equalizer at the receivers further increases the cost and hardware complexity of the receiver. The concept of single carrier modulation can be further extended to multiple subcarriers technique using Frequency division multiplexing (FDM). Where, total data rate to be sent on the channel is divided between the various subcarriers. This way, FDM divide a single carrier broadband channel into multiple narrowband sub-channels. Since each FDM subcarrier has a narrow band data rate, the symbol duration becomes longer. Also, each sub-channel will become a flat faded channel which makes receiver less complex and costly. The FDM systems usually require a frequency guard band between different modulated subcarriers to prevent the spectrum of one subcarrier from interfering with other adjacent subcarrier. Use of these guard bands will reduce total effective bandwidth of a multiple carrier system as compared to a single carrier system. Also, at the receiver side the signal is required to pass through bank of band-pass filters to separate out individual frequency channels. Figure1.1 shows basic FDM technique.
Fig. 1.1 Basic frequency division multiplexing

To achieve higher level of spectral efficiency, orthogonal subcarriers can be used in place of FDM system, where adjacent subcarrier spectrum can overlap with each other without interference. This increases the effective spectral efficiency of the system. Also, at the receiver side, despite their overlapping spectrums it is still possible to recover the individual subcarrier’s information as long as orthogonality among the subcarriers is maintained. Therefore, Orthogonal Frequency Division Multiplexing (OFDM) [1-30] is improved form of FDM, in which subcarrier are orthogonal to each other as shown in Figure 1.2.

Fig. 1.2 Orthogonal frequency division multiplexing.

The peak of one subcarrier coincides with the nulls of the other subcarriers. Due to the orthogonality, there is no interference from other subcarriers at the peak of a desired subcarrier even though the subcarrier spectrums are overlapped [5-9]. Therefore, by using OFDM system, a large amount of bandwidth can be saved as compare to conventional FDM systems.
1.2 OFDM TRANSMITTER AND RECEIVER

The Figure 1.3 shows the basic block diagram of an OFDM system. The OFDM transmitter comprises of symbol mapper, serial–to-parallel (S/P) convertor, Inverse Fast Fourier Transform (IFFT), parallel-to-serial (P/S) convertor, cyclic prefix and up frequency convertor.

Fig. 1.3 Basic block diagram of OFDM system

The input data bits are mapped to complex symbols by $M$-point constellation using suitable mapping schemes such quadrature phase shift keying (QPSK), M-quadrature amplitude modulation (QAM) e.g., 8-QAM, 16QAM or 64QAM to map 2, 3, 4 or 6 data bits per symbol, respectively. Figure 1.4, show an example of 16QAM modulated symbol mapper. The input symbol stream from symbol mapper is divided into $N$-number of parallel symbol streams by a serial to parallel (S/P) convertor shown in figure 1.5. Where, $a_0$, $a_1$, $a_2$, ….. $a_{N-1}$ are different symbols. These parallel symbols are then modulated on $N$ orthogonal subcarriers $f_0$, $f_1$, $f_2$, …..$f_{N-1}$ by Inverse Discrete Fourier Transform (IDFT) technique as shown in figure 1.6. The symbols $a_0$, 


a_1, a_2, \ldots, a_{N-1} are modulated on orthogonal subcarriers f_0, f_1, f_2, \ldots, f_{N-1} respectively. The modulated symbols can be represented as \( a_k \exp\{j2\pi f_k t\} \), where, \( k = 0, 1, 2, 3, \ldots, N-1 \).

Fig. 1.4 Symbol mapper

The orthogonality among subcarriers can be viewed in time domain as shown Figure 1.7. The mathematical representation of orthogonality among two functions is shown by equation (1.1) below. Let's assume a set of functions i.e. \( g_1(t), g_2(t), \ldots, g_n(t) \ldots \) defined over the interval \( t_1 \leq t < t_2 \). Any two functions in the given set are called orthogonal if they satisfy the following condition in the interval \( t_1 \) to \( t_2 \):

\[
\int_{t_1}^{t_2} g_m(t) g_n^*(t) dt = \begin{cases} 
0 & \text{if } m \neq n \\
1 & \text{if } m = n
\end{cases}
\] (1.1)
In case of OFDM systems, subcarrier frequencies are chosen in such a way that all of them are mutually orthogonal. The time and frequency domain representations of orthogonal subcarrier signals are shown in figure 1.6. In practice, OFDM systems implement orthogonal subcarrier modulation concept using a combination of Inverse Fast Fourier transform (IFFT) at transmitter and Fast Fourier Transform (FFT) at the receiver. The IFFT and FFT are mathematically equivalent versions of the Inverse Discrete Fourier Transform (IDFT) and Discrete Fourier Transform (DFT), respectively, but more efficient to implement. The IFFT takes in $N$ input symbols at a time and modulates them on $N$ orthogonal subcarriers. The symbols after being modulated by orthogonal subcarriers are then applied at the input of a parallel to serial converter.
Fig. 1.6 Inverse Fast Fourier Transform signal waveforms to show the orthogonality among subcarriers in time-domain and frequency domain

The output of P/S converter is the summation of all $N$ sinusoids from IFFT output as shown in figure 1.7. Thus, the IFFT block provides a simple way to modulate data onto $N$ orthogonal subcarriers and P/S converter block make up a single OFDM symbol from $N$ output samples of IFFT. The length of the OFDM symbol is $NT$ where $T$ is the IFFT input symbol period.

Since Data from source to destination reaches via many different paths, therefore data from one path might get superimposed with that of other path at the receiver and inter symbol interference (ISI) may take place. To mitigate inter symbol interference (ISI) problem, a guard time interval is inserted between two OFDM symbols. The duration of guard time interval must be greater than maximum delay spread. In case, guard time interval consist no information signal (empty guard time interval), the problem of inter-carrier interference (ICI) would arise because of orthogonality loss among the subcarriers. To overcome this problem OFDM symbols are
cyclically extended in guard time interval as shown in figure 1.8. The cyclic prefix transforms linear convolution of a frequency selective multipath channel into circular convolution and ensures the orthogonality among the OFDM subcarriers.

![Parallel to serial converter diagram](image)

**Fig. 1.7** Parallel to serial converter

As shown in figure 1.8, in case OFDM symbol duration is $T_{OS}$, then in cyclic prefix process we copy a time portion of OFDM symbol (equivalent to $T_g$) from the back and append it at the front of the same OFDM symbol to fill time guard period ($T_g$) interval. This way a part of OFDM symbol is available at both side of the symbol.

At receiver side, firstly frequency down conversion take places, then after passing the signal through low pass filter, cyclic prefix remover removes the cyclic prefix. Then, S/P
conversion convert a serial stream of OFDM symbols to $N$ parallel streams which are applied at the FFT inputs.

![Diagram of OFDM system](image)

**Fig. 1.8** Guard time interval and cyclic prefix

FFT outputs are then put in a serial complex symbols stream by P/S converter. Then, the amplitude and phase of the symbols are converted back to digital data bits by the symbol de-mapper.

### 1.3 Issues with OFDM Systems

OFDM systems have got a tremendous attraction from wireless research community because of its multipath fading immunity and high spectral efficiency. But, OFDM has two major issues. The first major issue of OFDM system is its sensitivity to frequency offset [23-39] and other is high peak to average power ratio (PAPR) [43-63] of transmitted signal. The OFDM system’s frequency offset arises due to frequency mismatch between transmitter side and receiver side
oscillators. Because of the frequency offset orthogonality among subcarriers is disturbed and hence inter-carrier interference (ICI) [27-30], arises. Due to ICI the performance of OFDM system is degraded greatly, as shown in figure 1.9.

![Fig. 1.9 Plot of SNR Vs Normalised frequency Offset (ε)](image)

As shown in figure 1.10, the input high speed data stream is encoded by using the digital modulation techniques i.e. QPSK or QAM. If output symbols are represented as $X_k$ then the output of IFFT at transmitter could be expressed as [26]:

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{2\pi jnk/N} \quad (1.2)$$

Where, $n = 0, 1, 2------N-1$. The frequency offset arises due to the frequency mismatch at the transmitter and receiver oscillators. At the receiver side, the received signal after passing through the channel can be shown as [26]:

$$\frac{B_c}{N_0} = 0 \text{ dB} \quad \frac{B_c}{N_0} = 5 \text{ dB} \quad \frac{B_c}{N_0} = 10 \text{ dB} \quad \frac{B_c}{N_0} = 15 \text{ dB}$$
\[ y_n = \exp \left( \frac{j2\pi \varepsilon n}{N} \right) \left[ x_n * h \right] + w_n \]  

(1.3)

Where, \( h_n \) is channel impulse response, \( w_n \) is additive white Gaussian noise (AWGN). The effect of normalized frequency offset is constant over a period IFFT as discussed in [26-

![Block diagram of an OFDM system with mathematical representation of signals at different points](image)

**Fig. 1.10** Block diagram of an OFDM system with mathematical representation of signals at different points

27]. The frequency offset causes two effects on OFDM signal: 1) It reduces signal amplitude in the output of the filters matched to each carrier and 2) it introduces inter carrier interference (ICI) [26]. Due to the effect of ICI, the performance of OFDM based communication systems is degraded significantly. After some mathematical modification the Equation (1.3), could be expressed as:
\[ y_n = \frac{1}{N} \left[ \sum_{k=0}^{N-1} S_k H_k e^{2\pi j n(k + \varepsilon)/N} \right] + w_n \]  

(1.4)

Where, \( H_k \) is the channel transfer function at the frequency of \( k^{th} \) subcarrier and \( \varepsilon \) is the normalized frequency offset and \( w_n \) is additive white Gaussian noise (AWGN) with uniform spectral density. Also, the thermal and electrical noise present during amplification primarily has white Gaussian noise properties. The output of DFT demodulator could be expressed as:

\[ R_k = \sum_{n=0}^{N-1} \left\{ \frac{1}{N} \left[ \sum_{k=0}^{N-1} H_k S_k e^{2\pi j n(k + \varepsilon)/N} \right] + w_n \right\} e^{-2\pi j k n/N} \]  

(1.5)

and

\[ \begin{align*}
R_k &= \left( S_k H_k \right) \left\{ \frac{\sin \pi \varepsilon}{N(\pi \varepsilon / N)} \right\} e^{j\pi (N-1)/N} + I_k + w_k 
\end{align*} \]  

(1.6)

The first term of Equation (1.6) is the transmitted signal modified by the channel transfer function because of amplitude reduction and phase shift due to the frequency offset. The second component is the ICI, which appears because of the frequency mismatch of the transmitter and receiver oscillators. Where, the ICI could be expressed as:

\[ I_k = \sum_{l=0}^{N-1} \left[ \sum_{n=0}^{N-1} S_l H_l e^{2\pi j n(l + \varepsilon - k)/N} \right] \bigg|_{l \neq k} \]  

(1.7)

After some mathematical simplification the equation (1.8) can be expressed as [26]:

\[ I_k = \sum_{l=0}^{N-1} \left[ \frac{S_l H_l}{N} \frac{\sin \pi (l + \varepsilon - k)}{\sin \pi \left( \frac{l + \varepsilon - k}{N} \right)} \right] e^{j\pi (N-1)\left( \frac{l + \varepsilon - k}{N} \right)} \]  

(1.8)

Where, sequence \( Q(l-k) \) is defined as the ICI coefficient between subcarriers \( l \) and \( k \), and can be expressed as:
In Equation (1.9), the first term in the right-hand side represents the desired signal. With frequency error \( i.e. \epsilon = 0 \) the maximum value of ICI coefficient between subcarriers \( l \) and \( k \), \( Q(0) = 1 \). The second term is ICI component and third term is AWGN.

The second major problem in an OFDM system is high Peak-to-Average Power Ratio (PAPR) [43-63] of transmitted OFDM signals. The OFDM system has high PAPR as compared to single carrier system because many subcarrier components are added in time domain after IFFT operation. The high PAPR value reduces OFDM system’s efficiency because high power amplifier (HPA) used in the up conversion of the transmitted signal starts operating in saturation region. Figure 1.11 shows the input power verses output power characteristics of HPA. It is clear from the figure that the maximum power is limited to \( (P_{\text{out}}) \text{ max} \) for the corresponding input \( (P_{\text{in}}) \text{ max} \). The large input to HPA takes it into non-linear region. The nonlinear operation of HPA causes in-band distortion and out-of-band radiation. The in-band distortions result in phase rotation, attenuation on the received signal and out-band radiations affects signals in adjacent bands.

![Input/Output characteristic of HPA](image)

**Fig. 1.11** Input verses out power characteristics of high power amplifier

The variation in OFDM signal envelope can be defined as crest factor (CF) as:
values.m.r

\[ CF = \frac{\text{peak value}}{\text{r.m.s value}} \]  

(1.10)

and PAPR can be defined as:

\[ \text{PAPR} = \frac{\text{peak power}}{\text{average power}} \]  

(1.11)

Where, \( \text{Crest factor} = \sqrt{\text{PAPR}} \).

In an OFDM system, all the subcarriers are added in IFFT operation which may lead the OFDM signal with large peaks and dynamic range in time domain. For an OFDM signal \( s(t) \) the PAPR can be expressed as:

\[ \text{PAPR} \{ s(t) \} = \frac{\max\{ |s(t)|^2 \}}{E\{ |s(t)|^2 \}} \]  

(1.12)

Where, \( \max\{ |s(t)|^2 \} \) is the peak signal power and \( E\{ |s(t)|^2 \} \) is the average signal power.

1.4 PROBLEM DEFINITION AND RESEARCH CONTRIBUTION

As discussed in the last section, the significant disadvantages of the OFDM systems are: Its sensitivity to the ICI caused by carrier frequency mismatch between the transmitter and receiver oscillators and/or the Doppler shift and its relatively high PAPR. Therefore, we always try to enhance the performance of an OFDM system by reducing average ICI power and PAPR. In the literature, there are several techniques to reduce ICI and PAPR.

The methods to reduce ICI, include self-cancellation schemes [24, 30], frequency domain equalization [32], windowing at the receiver [28, 41, 44, 70], and the use of frequency domain pulse shaping [27, 64-66] at transmitter side. To reduce PAPR of transmitted OFDM signals different standard techniques are clipping [72-73], coding schemes [74], phase optimization[11], nonlinear companding transforms [75], Tone Reservation (TR) [76] and Tone Injection (TI) [77], Partial Transmission Sequence (PTS) [45], Selective Mapping (SLM)[43,45] and techniques such as pre-scrambles [78].

Therefore, we have several different techniques to reduce ICI and reduce PAPR which are independent from each other. In this thesis work, author has proposed novel transmitter side
frequency domain pulse shaping techniques which can reduce both ICI and PAPR at the same time, as shown in figure 1.12.

Fig. 1.12 System model of an OFDM system with pulse shaping

In this research work, four novel pulse shaping function have been proposed that are called New Windowing Function (NWF), Modified Raised Cosine Power (MRCP) pulse, Improved Phased Modified Sinc (IPMS) pulse and Modified Better Than Raised Cosine Power (MBTRCP) pulse respectively. For the performance comparison we have chosen recently proposed transmitter side frequency domain pulse shapes which are called sinc pulse (SP) [67], Improved Sinc pulse (ISP) [68] and phase modified sinc pulse (SM) [69] respectively. Although, SP, ISP and SM pulse shapes were proposed to reduce ICI only, but in our analysis we have considered ICI, signal to interference ratio (SIR), bit error rate (BER) and PAPR performance comparisons. The results shows that newly proposed pulse shapes outperform as compared to SP, ISP and SM pulse shapes in term of ICI, SIR, BER and PAPR.
1.5 ORGANIZATION OF THESIS

Chapter 1 deals with the basic block diagram of IFFT based OFDM systems with detailed explanation of each block. Concept of single carrier and multi-subcarrier transmission with their relative comparison is also discussed. Thereafter main advantages and disadvantages of OFDM system are explained. The inter carrier interference (ICI) and peak to average power ratio (PAPR) problems and their relative causes are stated. Different types of techniques which are available in the literature to reduce the main issues have been discussed. Out of which we have concentrated on transmitter side pulse shaping techniques.

In Chapter 2, A new transmitter side pulse shaping function called NWF is proposed to reduce Inter-carrier interference (ICI) for \(N\)-subcarrier BPSK orthogonal frequency division multiplexing (OFDM) systems. The results are examined in terms of ICI, SIR, BER and PAPR. The analytical results show that the proposed NWF method outperforms all the recently proposed windowing functions in the literature in terms of average signal power to average ICI power ratio (SIR), bit error rate (BER) and peak to average power ratio (PAPR).

Chapter 3, Studies the performance of novel MRCP pulse shaping. The MRCP pulse shape enhances the performance of OFDM systems with respect to ICI and PAPR. We investigated the ICI, SINR, CCDF Vs. PAPR, and BER performances of the proposed MRCP pulse shape for 64-subcarrier OFDM systems. Results show that there is significant reduction in ICI and PAPR values in case of MRCP pulse shape as compared to SM pulse, SP pulse and ISP pulse.

Chapter 4, In this work, a novel IPMS pulse shape has been proposed to reduce ICI in OFDM systems. Further, the effect of proposed pulse shape on PAPR performance of the proposed pulse shape on different OFDM systems is investigated. Results show that there is significant reduction in ICI and PAPR values in case of IPMS pulse shape as compare to other recently proposed pulse shapes.

In Chapter 5, a novel MBTRCP transmitter side pulse shape for \(N\)-subcarriers orthogonal frequency division multiplexing (OFDM) systems that reduces the impact of frequency offset and
peak to average power ratio (PAPR) is proposed. It has been observed that the ICI, SINR, BER and CCDF of the PAPR verses threshold PAPR (PAPR₀) performances of the OFDM system with proposed transmitter side pulse shape is far better than all recently proposed transmitter side pulse shaping function e.g. sinc pulse (SP), improved sinc pulse (ISP) and phase modified sinc (SM) pulse.

Chapter 6 discusses conclusion and future scope of this thesis work.