CHAPTER 1

INTRODUCTION

High data-rate is desirable in many recent wireless multimedia applications [1]. Traditional single carrier modulation techniques can achieve only limited data rates due to the restrictions imposed by the multipath effect of wireless channel and the receiver complexity. In single carriers systems, as the data-rate in communication system increases, the symbol duration gets reduced. Therefore, the communication systems using single carrier modulation suffer from severe inter-symbol interference (ISI) caused by dispersive-channel impulse response, and thereby need a complex equalization scheme. Orthogonal Frequency Division Multiplexing (OFDM) is a potential candidate to fulfil the requirements of current and next generation wireless communication systems.

1.1 BACKGROUND TO OFDM

OFDM is a special form of multicarrier modulation scheme, which divides the entire frequency selective fading channel into many orthogonal narrowband flat-fading sub channels, in which high-bit-rate data stream is transmitted in parallel over a number of lower data rate subcarriers thereby substantially reducing the ISI due to larger symbol duration [2].

The fundamental principle of OFDM originates from the paper by Chang [3], and over the years a number of researchers have worked on this technique [4]-[9]. Despite its conceptual elegance, its use was initially limited to military systems, such as KINEPLEX, KATHRYN and ANDEFT [2] due to its implementation difficulties. Weinstein and Ebert’s proposal to use the Discrete Fourier Transform (DFT) to perform the subcarrier modulation with a single oscillator [5] was a pioneering effort. Ebert, Salz and Schwartz demonstrated the efficacy of Cooley-Tukey fast Fourier transform (FFT) algorithm to further reduce the computational complexity of DFT [10], thereby making it possible to utilize the OFDM technique in commercial communication systems. Its use in commercial systems started with a number of wire-line standards, which included High bit rate Digital Subscriber Lines (HDSL) [11], Asynchronous Digital Subscriber Lines (ADSL) [12], and Very high speed Digital Subscriber Lines (VDSL) [12], to support a throughput upto 100Mbps. Thereafter, it has been utilized by wireless standards like DAB [13] and WLAN [14], [15], DVB [16] and WMAN. In WMAN applications, OFDM is considered for the World wide Interoperability for Microwave Access
(WiMAX) implementation via IEEE 802.16d, a, e [17], [18] standards. OFDM is also being considered for 3GPP Long term Evolution (LTE) and 3GPP LTE-Advanced. Undoubtedly, OFDM can be a potential air interface candidate for future generation high speed wireless communications systems [19]-[22].

OFDM systems use cyclic prefix insertion to eliminate the effect of ISI and require a simple one-tap equalizer at the receiving end. OFDM brings in unparalleled bandwidth savings, leading to higher spectral efficiency. These properties make OFDM system extremely attractive for high speed wireless applications [2]. In OFDM systems different modulation schemes can be used on individual sub-carriers which are adapted to the transmission conditions on each sub-carrier.

Despite the widespread acceptance of OFDM, it has its drawbacks:

- OFDM signals with their high peak-to-average power ratios (PAPRs) require highly linear amplifiers. Otherwise, performance degradation occurs and out-of-band power requirement will be enhanced.
- OFDM systems are more sensitive to Doppler spread than single-carrier modulated systems.
- Phase noise caused by the imperfections of the transmitter and receiver oscillators degrades the system performance.
- Accurate frequency and time synchronization is required.
- Loss in spectral efficiency due to cyclic-prefix (CP) operation takes place in OFDM systems.

1.2 MOTIVATION

Increasing the spectral efficiency of wireless communication systems is one of the greatest challenges faced by wireless communication engineers. The available bandwidth is scarce and costly, whereas, there is a huge demand for data rate created by increasing number of subscribers and increase in multimedia applications, which require large bandwidth. OFDM, with its spectrally efficient versions like MIMO-OFDM and multiple access versions like OFDMA are under active consideration to fulfil the requirements of present and next generation wireless systems.
As discussed in section 1.1, large envelope fluctuation in OFDM signal is one of the major drawbacks of OFDM technique. Such fluctuations create difficulties, because practical communication systems are peak-power limited. Envelope peaks require the system to accommodate an instantaneous signal power that is much larger than the signal average power, necessitating either low operating power efficiencies or power amplifier (PA) saturation.

In addition to this, OFDM system requires tight frequency synchronization, in comparison to single carrier systems, due to narrowband subcarriers. Therefore, it is sensitive to a small frequency offset between the transmitted and the received signal. The frequency offset may arise due to Doppler effect or due to mismatch between transmitter and the receiver local oscillator frequencies. The carrier frequency offset (CFO) disturbs the orthogonality between the subcarriers, and therefore, the signal on any particular subcarrier will not remain independent of the remaining subcarriers. This phenomenon is known as inter-carrier interference (ICI), which is a big challenge for error-free demodulation and detection of OFDM symbols.

The current implementations of OFDM do not fully exploit its capabilities. There are still several avenues which can be explored to reduce the peak-to-power ratio (PAPR) and intercarrier interference (ICI) of OFDM signal. Therefore, the necessity to reduce the PAPR of standard OFDM signal is a prime motivating factor for this work.

Clipping and filtering [23]-[26] is the simplest solution to reduce the PAPR but it achieves the PAPR reduction capability at the cost of BER performance degradation. Existing companding transforms [27]-[33] achieve acceptable PAPR reduction capability but they introduce high non-linear distortion, due to which their BER performances degrade. Moreover, both the schemes result in out-of-band radiation and in-band distortion. Improving BER performance using companding based PAPR reduction schemes is a prime motivating factor for our work.

The distortion-less schemes proposed in literature [34]-[39] provide PAPR reduction capability at the cost of increased computational complexity. In most of these techniques like Selected Mapping (SLM) [34] and Partial Transmit Sequence (PTS)[35], side information (SI) is required at the receiver to recover the original data signal, which not only causes data-rate loss but also results in severe BER performance degradation, if SI gets corrupted during transmission. In order to avoid spectral deficiency of these schemes, various SI embedding
schemes have been proposed, but in most of them the SI detection capability depends on the available signal-to-noise ratio. Elimination of SI requirement at the receiving end motivates a major part of this work.

ICI cancellation schemes [40]-[46] effectively mitigate the effect of ICI but PAPR performance of existing ICI cancellation schemes [40], [41], [44] is either same or worse than that of standard OFDM signal. Therefore, there is a necessity to reduce the PAPR of OFDM signal obtained from ICI cancellation schemes. Hence the need for a joint ICI cancellation and PAPR reduction scheme is another motivating factor for this work.

1.3 PROBLEM DEFINITION

High PAPR and intercarrier interference (ICI) are the two major issues in the implementation of an OFDM system. The thesis aims at exploring and arriving at efficient, low complexity schemes for PAPR reduction in OFDM based systems (with and without ICI cancellation) of practical use. The first problem addressed in this thesis is the high PAPR of an OFDM signal. We begin by exploring the existing PAPR reduction techniques and to find out their advantages and major limitations for implementing a practical OFDM system. Investigation of efficient PAPR reduction schemes for an OFDM system is thus considered as one of the problem areas explored in this thesis.

Being a multicarrier modulation scheme, OFDM brings all major benefits of a multicarrier scheme but unlike single carrier modulation schemes, it suffers from the problem of ICI. In this thesis, we explore the existing ICI cancellation schemes and perform a comparison of CIR and BER performances. As discussed above, the PAPR is an important parameter that must be taken into consideration while designing an ICI cancellation scheme for the OFDM system of practical use. Therefore, investigation of PAPR performance of OFDM systems utilizing ICI cancellation schemes is also considered as another area to be explored in this thesis. Final aim of this thesis is to suggest a joint scheme for simultaneous PAPR reduction and ICI cancellation in OFDM systems.

1.4 GOAL AND SCOPE OF THE THESIS

The goals met by the thesis are listed as follows:
Investigation of companding transforms for PAPR reduction scheme and development of a generalized companding transform with good PAPR and BER performances.

Study of PTS based PAPR reduction schemes and development of an efficient PTS based PAPR reduction scheme that does not require side information (SI).

Mathematical analysis of the error performance of SI free PTS based methods for PAPR reduction in OFDM systems.

Exploring the available phase sequence set generation schemes for SLM-OFDM system and proposing a new phase sequence set generation scheme.

To propose a new mapping scheme for both PTS and SLM based OFDM systems which completely eliminates the requirement of SI.

Analyzing PAPR, BER and CIR performance of existing ICI self-cancellation schemes and suggesting a scheme with good PAPR, BER and CIR performances.

To propose a joint ICI cancellation and PAPR reduction scheme for OFDM systems.

1.5 ORGANIZATION OF THE THESIS

This thesis is organised into nine chapters. The chapter wise flow is summarized below:

Chapter 2: Orthogonal Frequency Division Multiplexing

This chapter presents the technical background and introduction to OFDM needed to explain the work in the following chapters. It details the fundamental description of standard OFDM systems and explains its important concepts such as orthogonality of subcarriers and the use of cyclic prefix among others.

Chapter 3: Peak-to-Average Power Ratio (PAPR) and Inter Carrier Interference

This chapter consist of two parts, the first part deals with PAPR, while the other part presents ICI. The first part starts with the definition of PAPR of OFDM signal and then PAPR analysis of baseband and bandpass OFDM signal is presented. Various standard existing PAPR reduction techniques like clipping, companding, SLM, PTS, ACE etc. are also presented in full detail. In the second part of this chapter, we introduce the intercarrier interference caused by frequency mismatch between transmitted and receiver oscillator or motion induced Doppler shift followed by ICI cancellation schemes to mitigate the effect of ICI. Some popular ICI cancellation schemes include ICI cancellation using correlative
coding, ICI self-cancellation, new ICI self-cancellation, ICI conjugate cancellation and general phase rotated conjugate cancellation.

Chapter 4: PAPR Reduction using Quadrilateral Companding Transform

In this chapter, a quadrilateral companding transform is proposed to reduce the PAPR of the OFDM signal. The mathematical expression of companding function is derived by transforming the distribution of original OFDM signal to a quadrilateral distribution. The mathematical expression of de-companding function is also derived which is used at the receiver to retrieve the original OFDM signal. The proposed scheme is the most generalized companding transform because the existing exponential companding transform, trapezoidal companding and trapezium distribution based companding methods are special cases of the suggested quadrilateral companding transform. The PAPR and BER performance of the proposed scheme is compared with other existing companding transforms.

Chapter 5: Concentric Circle Constellation Mapping for PTS based PAPR Reduction Schemes without SI

This chapter starts with exploring SI embedding and SI free schemes for PTS based PAPR reduction scheme and then presents a novel quaternary to concentric circle constellation mapping for PTS (CCM-PTS) based PAPR reduction scheme to completely eliminate the requirement of side information. To decode the CCM, a new decoding scheme called as circular boundary decoding is also proposed besides conventional minimum distance decoding. A complete SER analysis of CCM using both the decoding schemes and a multipoint square mapping using minimum distance decoding is also presented. Finally, a CCM based PTS scheme is proposed for PAPR reduction of OFDM signal. Computational complexity analysis of CCM-PTS and MPSM-PTS is also carried out in this chapter. Finally, a comparison of PAPR and SER performances is presented to show the superior performance of the proposed scheme.

Chapter 6: M-ary Chaotic Sequence based SLM-OFDM System for PAPR Reduction

We begin this chapter by exploring the existing phase sequence sets for SLM based PAPR reduction schemes and then suggest a new phase sequence set generation scheme, based on $M$-ary chaotic sequence for achieving better PAPR reduction capability in SLM-OFDM system. In this scheme, first phase sequence is generated using an $M$-ary chaotic sequence and then its elements are used as indices to select the phase factors from a predetermined
phase set containing $M$ different phase factors. The remaining phase sequences of phase sequence set are generated by cyclic shifting of the first phase sequence. Further, to eliminate the requirement of SI at the receiver, concentric circle constellation mapping has been proposed. SER performance analysis of existing Riemann matrix based phase sequence is carried out in this chapter to show the superior performance of the proposed scheme. PAPR reduction capability of the proposed scheme is also compared with existing phase sequences.

**Chapter 7: $M\cdot2M$ Mapping Scheme for PAPR Reduction in SLM and PTS Based OFDM Systems without SI**

In this chapter, a novel $M\cdot2M$ mapping scheme for PTS and SLM based OFDM systems is presented. In conventional PTS and SLM based OFDM systems, SI is required to recover the original data signal at the receiver whereas $M\cdot2M$ mapping scheme completely eliminates the requirement of SI. The $M\cdot2M$ mapping based PTS or SLM system utilizes the two phase factors $(1, j)$ instead of the two conventional phase factors $(1,-1)$. The detailed reasoning for this choice is also presented in this chapter. The $M\cdot2M$ mapping scheme is a generalized mapping scheme which is extended to various data type like binary, quaternary, octal or hexadecimal etc. But the choice of $(1, j)$ as phase factors requires a new mechanism to generate a phase sequence set for SLM-OFDM system. In order to fulfil this requirement, we have proposed two new phase sequence set generation schemes based on binary chaotic sequence and Walsh Hadamard sequence to achieve good PAPR reduction capability.

**Chapter 8: Joint PAPR Reduction and ICI Cancellation in OFDM Systems**

In this chapter, mathematical analysis of PAPR for an OFDM signal obtained from ICI cancellation schemes has been presented. The analysis emphasizes the need of PAPR reduction in ICI cancellation schemes. Further, an $M\cdot2M$ mapping based PTS scheme for PAPR reduction is proposed to reduce the PAPR of OFDM signal resulting from ICI cancellation schemes. A comparison of standard ICI cancellation schemes has been performed by taking PAPR, CIR and BER as the performance metrics. Based on the comparison, new ICI cancellation scheme with $M\cdot2M$ mapping based PTS scheme for PAPR reduction has been suggested for achieving a good PAPR, CIR and BER performances.

**Chapter 9: Conclusions and Future Work**

This is the concluding chapter of the thesis, which summarizes the conclusion of each of the contributing chapters and list possible directions for future work.
1.6 CONTRIBUTIONS OF THIS THESIS

- The OFDM based multiple access schemes have been adopted for downlink communication in 3GPP LTE standards, but not chosen in uplink communication due to high PAPR. In uplink communication, when a mobile terminal has to transmit an OFDM signal, it requires an expensive and bulky high power amplifier, which is difficult to accommodate, due to its cost and size limitation. The mobile terminal is also having a limited computational power and battery life. Therefore, the proposed quadrilateral companding transform can be utilized in uplink communication because the proposed quadrilateral companding scheme provides very good PAPR reduction capability with low computational complexity. The quadrilateral companding transform requires only one additional block at transmitter and receiver to perform companding and decompanding operations respectively.

- Day by day operational speed of the wireless communications system is increasing with the rapid advances in VLSI technology. Next-generation high data rate wireless communication systems based on OFDM are under consideration. To provide higher data speeds, RF transceivers in next-generation communications are expected to offer higher RF performance in both transmitting and receiving circuitry, to meet the quality of service requirements. Hence computational complexity is not a limiting factor for highly efficient wireless communication systems. Therefore, the proposed concentric circle constellation and $M-2M$ mapping for SLM and PTS based PAPR reduction schemes are found to be useful because no additional hardware is required to implement the OFDM system.

- The number of subcarriers in OFDM based next generation communications systems are increasing day-by-day to cater to the need of high data rate, thereby reducing the subcarrier spacing between two adjacent subcarriers, which makes an OFDM based communication system highly sensitive to a small carrier frequency offset (CFO). In order to mitigate the effect of CFO, an ICI cancellation scheme with good CIR, BER and PAPR performances is required. The PAPR performance of existing ICI cancellation schemes is either same or worse than standard OFDM signal with ICI cancellation. The proposed joint ICI cancellation and PAPR reduction schemes serve the purpose of simultaneous ICI and PAPR reduction.