INTER CARRIER INTERFERENCE CANCELLATION IN OFDM SYSTEMS

A THESIS SUBMITTED IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Telematics and Signal Processing

BY

RAVITEJ AMASA

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Department of Electronics and Communication Engineering

National Institute of Technology, Rourkela-769008

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ORISSA-2009

CERTIFICATE

This is to certify that the progress report of the thesis work entitled **"Inter Carrier Interference cancellation in OFDM Systems."** submitted by **Amasa Ravitej** Department of **Electronics and Communication Engineering**, with specialization in **'Telematics and Signal Processing'** at **National Institute of Technology, Rourkela** (Deemed University) is an authentic work carried out by him under my supervision and guidance.

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

Mrs. Poonam Singh

Date: 28-05-09 **Department of ECE**

Place: Rourkela **National Institute of Technology**

Rourkela-769008

ACKNOWLEDGEMENT

Words are inadequate to express the overwhelming sense of gratitude and humble regards to my guide supervisor **Mrs. Poonam Singh**, Department of Electronics and Communication Engineering for her constant motivation, support, expert guidance, constant supervision and constructive suggestion for the submission of my progress report of thesis work **“Inter Carrier Interference cancellation in OFDM Systems”**.

I express my gratitude to **S.K.Patra**, Professor and Head of the Department, Electronics and Communication Engineering for his invaluable suggestions and constant encouragement all through the thesis work.

I also thank all the teaching and non-teaching staff for their nice cooperation to the students.

This report would have been impossible if not for the perpetual moral support from my family members, and my friends. I would like to thank them all.

RAVITEJ AMASA

CONTENTS

ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) is an emerging multi-carrier modulation scheme, which has been adopted for several wireless standards such as IEEE 802.11a and HiperLAN2. A well-known problem of OFDM is its sensitivity to frequency offset between the transmitted and received carrier frequencies. This frequency offset introduces inter-carrier interference (ICI) in the OFDM symbol. This project investigates two methods for combating the effects of ICI: ICI self-cancellation (SC), and extended Kalman filter (EKF) method. These two methods are compared in terms of bit error rate performance, bandwidth efficiency, and computational complexity. Through simulations, it is shown that the two techniques are effective in mitigating the effects of ICI. For high values of the frequency offset and for higher order modulation schemes, EKF method performs better than the SC method.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION:

The demand for high data rate services has been increasing very rapidly and there is no slowdown in sight. Almost every existing physical medium capable of supporting broadband data transmission to our homes, offices and schools has been or will be used in the future. This includes both wired (Digital Subscriber Lines, Cable Modems, Power Lines) and wireless media. Often, these services require very reliable data transmission over very harsh environments. Most of these transmission systems experience many degradations, such as large attenuation, noise, multipath, interference, time variation, non-linearity's, and must meet many constraints, such as finite transmit power and most importantly finite cost. One physical-layer technique that has recently gained much popularity due to its robustness in dealing with these impairments is multi-carrier modulation. High capacity and variable bit rate information transmission with high bandwidth efficiency are just some of the requirements that the modern transceivers have to meet in order for a variety of new high quality services to be delivered to the customers. Because in the wireless environment signals are usually impaired by fading and multipath delay spread phenomenon, traditional single carrier mobile communication systems do not perform well.

In such channels, extreme fading of the signal amplitude occurs and Inter Symbol Interference (ISI) due to the frequency selectivity of the channel appears at the receiver side. This leads to a high probability of errors and the system's overall performance becomes very poor. Techniques like channel coding and adaptive equalization have been widely used as a solution to these problems. However, due to the inherent delay in the coding and equalization process and high cost of the hardware, it is quite difficult to use these techniques in systems operating at high bit rates, for example, up to several Mbps. An alternative solution is to use a multi carrier system. Orthogonal Frequency Division Multiplexing (OFDM) is an example of it and it is used in several applications such as asymmetric digital subscriber lines (ADSL), a system that makes high bit-rates possible over twisted-pair copper wires. It has recently been standardized and recommended for digital audio broadcasting (DAB) in Europe and it is already used for terrestrial digital video broadcasting (DVB-T). The IEEE 802.11a standard for wireless local area networks (WLAN) is also based on OFDM.

The purpose of this project is to investigate how OFDM performs in an Additive White Gaussian Noise (AWGN) channel only. In this channel only one path between the transmitter and the receiver exists and only a constant attenuation and noise is considered. Therefore no multipath effect is taken into account. This is a basic investigation and it is intended as a basis of understanding OFDM better in order for future studies of this technique in multipath channels.

Modulation: Mapping of information on changes in the carrier phase, frequency or amplitude or combination.

Multiplexing: Method of sharing bandwidth with other independent data channels.

OFDM is a combination of modulation and multiplexing. Multiplexing generally refers to independent signals those produced by different sources. So it is a question of how to share the spectrum with these users. In OFDM the question of multiplexing is applied to the independent signals but these independent signals are a sub-set of the one main signal. In OFDM the signal itself is first split into independent channels, modulated by data and then re multiplexed to create the OFDM carrier. OFDM is a special case of Frequency Division Multiplexing (FDM). In FDM, each of the several low rate user signals is modulated with a separate carrier and transmitted in parallel. Thus the separation of the users is in the frequency domain. In order to be able to easily demodulate each user signal, the carriers are spaced sufficiently apart from each other. Moreover, guard band has to be provided between 2 adjacent carriers so that realizable filters can be designed. Hence the spectral efficiency is very low.

OFDM is a Multi-Carrier Modulation technique in which a high rate bit-stream is split into (say) N parallel bit-streams of lower rate and each of these are modulated using one of N orthogonal sub-carriers. In a basic communication system, the data are modulated onto a single carrier frequency. The available bandwidth is then totally occupied by each symbol. This kind of system can lead to inter-symbol-interference (ISI) in case of frequency selective channel. The basic idea of OFDM is to divide the available spectrum into several orthogonal sub channels so that each narrowband sub channels experiences almost flat fading. Orthogonal frequency division multiplexing (OFDM) is becoming the chosen modulation technique for wireless communications. OFDM can provide large data rates with sufficient robustness to radio channel impairments. Many research centers in the world have specialized teams working in the optimization of OFDM systems. In an OFDM scheme, a large number of orthogonal, overlapping, narrow band sub-carriers are transmitted in parallel. These carriers divide the available transmission bandwidth.

The separation of the sub-carriers is such that there is a very compact spectral utilization. With OFDM, it is possible to have overlapping sub channels in the frequency domain, thus increasing the transmission rate. The attraction of OFDM is mainly because of its way of handling the multipath interference at the receiver. Multipath phenomenon generates two effects (a) Frequency selective fading and (b) Inter symbol interference (ISI).The "flatness" perceived by a narrowband channel overcomes the frequency selective fading. On the other hand, modulating symbols at a very low rate makes the symbols much longer than channel impulse response and hence reduces the ISI. Use of suitable error correcting codes provides more robustness against frequency selective fading. The insertion of an extra guard interval between consecutive OFDM symbols can reduce the effects of ISI even more.

The use of FFT technique to implement modulation and demodulation functions makes it computationally more efficient. OFDM systems have gained an increased interest during the last years. It is used in the European digital broadcast radio system, as well as in wired environment such as asymmetric digital subscriber lines (ADSL). This technique is used in digital subscriber lines (DSL) to provide high bit rate over a twisted-pair of wires. The major advantages of OFDM are its ability to convert a frequency selective fading channel into several nearly flat fading channels and high spectral efficiency. However, one of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes attenuation and rotation of subcarriers, and Inter carrier interference (ICI) [1, 2]. The undesired ICI degrades the performance of the system.

1.2 HISTORY OF MOBILE WIRELESS COMMUNICATIONS:

The history of mobile communication [3, 4] can be categorized into 3 periods:

- The pioneer era
- The pre-cellular era
- The cellular era

In the pioneer era, a great deal of the fundamental research and development in the field of wireless communications took place. The postulates of electromagnetic (EM) waves by James Clark Maxwell during the 1860s in England, the demonstration of the existence of these waves by Heinrich Rudolf Hertz in 1880s in Germany and the invention and first demonstration of wireless telegraphy by Guglielmo Marconi during the 1890s in Italy were representative examples from Europe. Moreover, in Japan, the Radio Telegraph Research

Division was established as a part of the Electro technical Laboratory at the Ministry of Communications and started to research wireless telegraph in 1896.

From the fundamental research and the resultant developments in wireless telegraphy, the application of wireless telegraphy to mobile communication systems started from the 1920s. This period, which is called the pre-cellular era, began with the first land-based mobile wireless telephone system installed in 1921 by the Detroit Police Department to dispatch patrol cars, followed in 1932 by the New York City Police Department. These systems were operated in the 2MHz frequency band. In 1946, the first commercial mobile telephone system, operated in the 150MHz frequency band, was set up by Bell Telephone Laboratories in St. Louis. The demonstration system was a simple analog communication system with a manually operated telephone exchange. Subsequently, in 1969, a mobile duplex communication system was realized in the 450MHz frequency band. The telephone exchange of this modified system was operated automatically. The new system, called the Improved Mobile Telephone System (IMTS), was widely installed in the United States. However, because of its large coverage area, the system could not manage a large number of users or allocate the available frequency bands efficiently.

The cellular zone concept was developed to overcome this problem by using the propagation characteristics of radio waves. The cellular zone concept divided a large coverage area into many smaller zones. A frequency channel in one cellular zone is used in another cellular zone. However, the distance between the cellular zones that use the same frequency channels is sufficiently long to ensure that the probability of interference is quite low. The use of the new cellular zone concept launched the third era, known as the cellular era. So far, the evolution of the analog cellular mobile communication system is described. There were many problems and issues, for example, the incompatibility of the various systems in each country or region, which precluded roaming. In addition, analog mobile communication systems were unable to ensure sufficient capacity for the increasing number of users, and the speech quality was not good.

To solve these problems, the R&D of cellular mobile communication systems based on digital radio transmission schemes was initiated. These new mobile communication systems became known as the second generation (2G) of mobile communication systems, and the analog cellular era is regarded as the first generation (1G) of mobile communication systems [5,6]. 1G analog cellular system was actually a hybrid of analog voice channels and digital control channels. The analog voice channels typically used

Frequency Modulation (FM) and the digital control channels used simple Frequency Shift keying (FSK) modulation. The first commercial analog cellular systems include Nippon Telephone and Telegraph (NTT) Cellular – Japan, Advanced Mobile Phone Service (AMPS) – US, Australia, China, Southeast Asia, Total Access Communications system (TACS) - UK, and Nordic Mobile Telephone (NMT) – Norway, and Europe.

2G digital systems use digital radio channels for both voice (digital voice) and digital control channels. 2G digital systems typically use more efficient modulation technologies, including Global System for Mobile communications (GSM), which uses a standard 2-level Gaussian Minimum Shift Keying (GMSK). Digital radio channels offer a universal data transmission system, which can be divided into many logical channels that can perform different services. 2G also uses multiple access (or multiplexing) technologies to allow more customers to share individual radio channels or use narrow channels to allow more radio channels into a limited amount of radio spectrum band. The 3 basic types of access technologies used in 2G are: Frequency Division Multiple Access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). The technologies reduce the RF channel bandwidth (FDMA), share a radio channel by assigning users to brief timeslot (TDMA), or divide a wide RF channel into many different coded channels (CDMA). Improvements in modulation techniques and multiple access technologies amongst other technologies inadvertently led to 2.5G and 3G.

1.3 MOTIVATION:

Multimedia is effectively an infrastructure technology with widely different origins in computing, telecommunications, entertainment and publishing. New applications are emerging, not just in the wired environment, but also in the mobile one. At present, only low bit-rate data services are available to the mobile users. The radio environment is harsh, due to the many reflected waves and other effects. Using adaptive equalization techniques at the receiver could be the solution, but there are practical difficulties in operating this equalization in real-time at several Mb/s with compact, low-cost hardware.

A promising candidate that eliminates a need for the complex equalizers is the Orthogonal Frequency Division Multiplexing (OFDM), a multiple carrier modulation technique. OFDM is robust in adverse channel conditions and allows a high level of spectral efficiency. It effectively mitigates performance degradations due to multipath and is capable of combating deep fades in part of the spectrum. The OFDM waveform can be easily modified to adjust to the delay spread of the channel. OFDM can handle large delay spreads easier to the independence of the carriers and the flexibility of varying the cyclic prefix length. OFDM allows efficient operation in both FDD and TDD mode as very short or no pre-ambles are needed. Multiple access techniques which are quite developed for the single carrier modulations (e.g. TDMA, FDMA) had made possible of sharing one communication medium by multiple number of users. Multiple techniques schemes are used to allow many mobile users to share simultaneously a finite amount of radio spectrum. The sharing is required to achieve high capacity by simultaneously allocating the available bandwidth (or the available amount of channels) to multiple users. For the quality communications, this must be done without severe degradation in the performance of the system. FDMA, TDMA and CDMA are the well known multiplexing techniques used in wireless communication systems.

While working with the wireless systems using these techniques various problems encountered are (1) multi-path fading (2) time dispersion which lead to inter symbol interference (ISI) (3) lower bit rate capacity (4) requirement of larger transmit power for high bit rate and (5) less spectral efficiency. Disadvantage of FDMA technique is its Bad Spectrum Usage. Disadvantages of TDMA technique is Multipath Delay spread problem. In a typical terrestrial broadcasting, the transmitted signal arrives at the receiver using various paths of different lengths. Since multiple versions of the signal interfere with each other, it becomes difficult to extract the original information. The use of orthogonal frequency division multiplexing (OFDM) technique provides better solution for the above mentioned problems.

1.4 OFDM:

Orthogonal Frequency Division Multiplexing (OFDM) is simply defined as a form of multi-carrier modulation where the carrier spacing is carefully selected so that each sub carrier is orthogonal to the other sub carriers. Two signals are orthogonal if their dot product is zero. That is, if you take two signals multiply them together and if their integral over an interval is zero, then two signals are orthogonal in that interval. 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. The major advantages of OFDM are its ability to convert a frequency selective fading channel into several nearly flat fading channels and high spectral efficiency.

However, one of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes attenuation and rotation of subcarriers, and Inter carrier interference (ICI). The undesired ICI degrades the performance of the system.

Orthogonal frequency division multiplexing (OFDM) is emerging as the preferred modulation scheme in modern high data rate wireless communication systems. OFDM has been adopted in the European digital audio and video broadcast radio system and is being investigated for broadband indoor wireless communications. Standards such as HIPERLAN2 (High Performance Local Area Network) and IEEE 802.11a and IEEE 802.11g have emerged to support IP-based services. Such systems are based on OFDM and are designed to operate in the 5 GHz band. OFDM is a special case of multi-carrier modulation. Multi-carrier modulation is the concept of splitting a signal into a number of signals, modulating each of these new signals to several frequency channels, and combining the data received on the multiple channels at the receiver.

In OFDM, the multiple frequency channels, known as sub-carriers, are orthogonal to each other. A well known problem of OFDM, however, is its sensitivity to frequency offset 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. This carrier frequency offset causes loss of Orthogonality between sub-carriers and the signals transmitted on each carrier are not independent of each other, leading to inter-carrier interference (ICI).

Researchers have proposed various methods to combat the ICI in OFDM systems. The existing approaches that have been developed to reduce ICI can be categorized as frequency-domain equalization, time-domain windowing, and the ICI self-cancellation (SC) scheme. In addition, statistical approaches have also been explored to estimate and cancel ICI. In this project, the effects of ICI have been analyzed and two solutions to combat ICI have been presented. The first method is a self-cancellation scheme, in which redundant data is transmitted onto adjacent sub-carriers such that the ICI between adjacent sub-carriers cancels out at the receiver. The other technique Extended Kalman filter (EKF) method, statistically estimate the frequency offset and correct the offset using the estimated value at the receiver.

1.5 OBJECTIVE AND OUTLINE OF THESIS:

The main objective of this thesis is to investigate different methods of ICI reduction. Several methods have been presented to reduce ICI, including frequency domain equalization [11, 12], windowing at the receiver [13, 14], ICI self-cancellation scheme [15, 16]. In this project, I have focused on the problem of ICI reduction using self cancellation and Extended Kalman Filter. Different modulation techniques are considered for ICI reduction and compared with each other for their performances. I have also briefly discussed OFDM and its advantages and disadvantages as compared to single carrier modulation technique. This report is organized as follows: In Chapter 2 Literature survey is presented. In Chapter 3 the applications, problems of OFDM is presented. In Chapter 4 Analysis of ICI is considered in detail. In chapter 5 Methods of ICI reduction is presented. In Chapter 6 work done is presented. Chapter 7 concludes the report and future works are also outlined. Chapter 8 contains references.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION:

It is well known that Chang proposed the original OFDM principles in 1966, and successfully achieved a patent in January of 1970. OFDM is a technique for transmitting data in parallel by using a large number of modulated sub-carriers. These sub-carriers divide the available bandwidth and are sufficiently separated in frequency so that they are orthogonal. The Orthogonality of the carriers means that each carrier has an integer number of cycles over a symbol period.

In 1971, Weinstein and Ebert proposed a modified OFDM system [7] in which the discrete Fourier Transform (DFT) was applied to generate the orthogonal subcarriers waveforms instead of the banks of sinusoidal generators. Their scheme reduced the implementation complexity significantly, by making use of the inverse DFT (IDFT) modules and the digital-to-analog converters. In their proposed model, baseband signals were modulated by the IDFT in the transmitter and then demodulated by DFT in the receiver. Therefore, all the subcarriers were overlapped with others in the frequency domain, while the DFT modulation still assures their Orthogonality.

Cyclic prefix (CP) or cyclic extension was first introduced by Peled and Ruiz in 1980 [8] for OFDM systems. In their scheme, conventional null guard interval is substituted by cyclic extension for fully-loaded OFDM modulation. As a result, the Orthogonality among the subcarriers was guaranteed. With the trade-off of the transmitting energy efficiency, this new scheme can result in a phenomenal ISI (Inter Symbol Interference) reduction. Hence it has been adopted by the current IEEE standards. In 1980,Hirosaki introduced an equalization algorithm to suppress both inter symbol interference (ISI) and ICI [9], which may have resulted from a channel distortion, synchronization error, or phase error. In the meantime, Hirosaki also applied QAM modulation, pilot tone, and trellis coding techniques in his high-speed OFDM system, which operated in voice-band spectrum.

In 1985, Cimini introduced a pilot-based method to reduce the interference emanating from the multipath and co-channels [10]. In the 1990s, OFDM systems have been exploited for high data rate communications. In the IEEE 802.11 standard, the carrier frequency can go up as high as 2.4 GHz or 5 GHz. Researchers tend to pursue OFDM operating at even much higher frequencies nowadays. For example, the IEEE 802.16 standard proposes yet higher carrier frequencies ranging from 10 GHz to 60 GHz. However, one of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes inter carrier interference (ICI). The undesired ICI degrades the performance of the system. Number of authors has suggested different methods for ICI reduction. These methods are investigated in this thesis and their performances are evaluated.

2.2 DESCRIPTION:

OFDM is a combination of modulation and multiplexing. Multiplexing generally refers to independent signals, those produced by different sources. In OFDM the question of multiplexing is applied to independent signals but these independent signals are a sub-set of the one main signal. In OFDM the signal itself is first split into independent channels, modulated by data and then re-multiplexed to create the OFDM carrier. If the FDM system above had been able to use a set of subcarriers that were orthogonal to each other, a higher level of spectral efficiency could have been achieved. The guard bands that were necessary to allow individual demodulation of subcarriers in an FDM system would no longer be necessary. The use of orthogonal subcarriers would allow the subcarriers spectra to overlap, thus increasing the spectral efficiency.

As long as Orthogonality is maintained, it is still possible to recover the individual subcarriers signals despite their overlapping spectrums. It can be seen that almost half of the bandwidth is saved by overlapping the spectra. As more and more carriers are added, the bandwidth approaches (N+1)/N Bits per Hz. Larger number of carriers gives better spectral efficiency. The main concept in OFDM is Orthogonality of the sub-carriers. The "orthogonal" part of the OFDM name indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. It is possible to arrange the carriers in an OFDM Signal so that the sidebands of the individual carriers overlap and the signals can still be received without adjacent carrier’s interference. In order to do this the carriers must be mathematically orthogonal. The Carriers are linearly independent (i.e. orthogonal) if the carrier spacing is a multiple of $1/T_s$. Where, T_s is the symbol duration.

The Orthogonality among the carriers can be maintained if the OFDM signal is defined by using Fourier transform procedures. The OFDM system transmits a large number of narrowband carriers, which are closely spaced. Note that at the central frequency of the each sub channel there is no crosstalk from other sub channels. In an OFDM system, the input bit stream is multiplexed into N symbol streams, each with symbol period T_s, and each symbol stream is used to modulate parallel, synchronous sub-carriers. The sub-carriers are spaced by $1/NT_s$ in frequency, thus they are orthogonal over the interval $(0, T_s)$. A typical discrete-time baseband OFDM transceiver system is shown in Figure 2.1. First, a serial-to-parallel (S/P) converter groups the stream of input bits from the source encoder into groups of $\log_2 M$ bits, where M is the alphabet of size of the digital modulation scheme employed on each sub-carrier. A total of N such symbols, X_m, are created. Then, the N symbols are mapped to bins of an inverse fast Fourier transform (IFFT). These IFFT bins correspond to the orthogonal sub-carriers in the OFDM symbol. Therefore, the OFDM symbol can be expressed as

$$x(n) = \frac{1}{N}\sum_{m=0}^{N-1} X_m e^{j\frac{2\pi mn}{N}} \qquad 0 \le n \le N-1 \tag{2.1}$$

Where X_m are the baseband symbols on each sub-carrier. The digital-to-analog (D/A) converter then creates an analog time-domain signal which is transmitted through the channel.

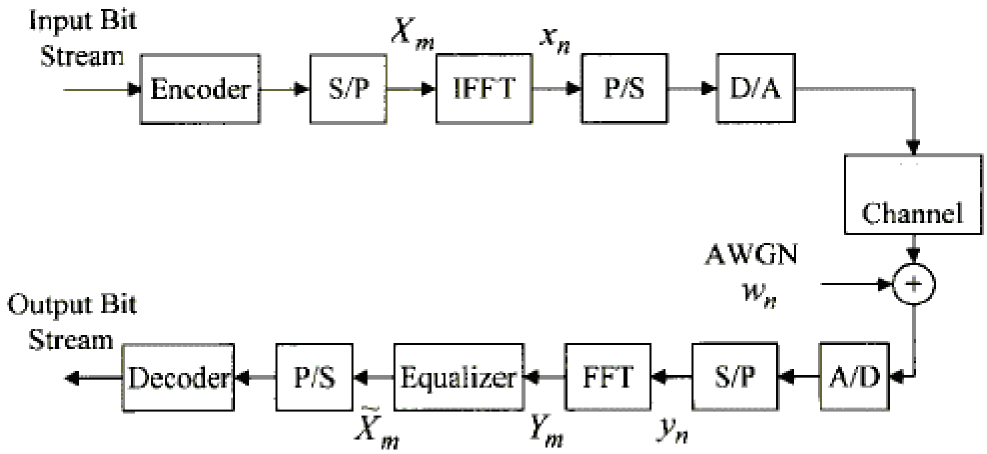


Figure 2.1: Baseband OFDM transceiver system.

At the receiver, the signal is converted back to a discrete N point sequence y(n), corresponding to each sub-carrier. This discrete signal is demodulated using an N-point fast Fourier transform (FFT) operation at the receiver. The demodulated symbol stream is given by:

$$Y(m) = \sum_{n=0}^{N-1} y(n) e^{-\frac{j2\pi mn}{N}} + W(m) \qquad 0 \le m \le N-1 \tag{2.2}$$

Where W (m) corresponds to the FFT of the samples of w (n), which is the Additive White Gaussian Noise (AWGN) introduced in the channel. The high speed data rates for OFDM are accomplished by the simultaneous transmission of data at a lower rate on each of the orthogonal sub-carriers. Because of the low data rate transmission, distortion in the received signal induced by multi-path delay in the channel is not as significant as compared to single-carrier high-data rate systems. For example, a narrowband signal sent at a high data rate through a multipath channel will experience greater negative effects of the multipath delay spread, because the symbols are much closer together. Multipath distortion can also cause inter-symbol interference (ISI) where adjacent symbols overlap with each other. This is prevented in OFDM by the insertion of a cyclic prefix between successive OFDM symbols. This cyclic prefix is discarded at the receiver to cancel out ISI. It is due to the robustness of OFDM to ISI and multipath distortion that it has been considered for various wireless applications and standards.

2.3 THEORY OF OFDM:

OFDM is a technique for transmitting data in parallel by using a large number of modulated sub-carriers. These sub-carriers (or sub-channels) divide the available bandwidth and are sufficiently separated in frequency (frequency spacing) so that they are orthogonal. The Orthogonality of the carriers means that each carrier has an integer number of cycles over a symbol period. Due to this, 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, although their spectra overlap.

The separation between carriers is theoretically minimal so there would be a very compact spectral utilization. OFDM systems are attractive for the way they handle ISI, which is usually introduced by frequency selective multipath fading in a wireless environment. Each sub-carrier is modulated at a very low symbol rate, making the symbols much longer than the channel impulse response. In this way, ISI is diminished. Moreover, if a guard interval between consecutive OFDM symbols is inserted, the effects of ISI can completely vanish. This guard interval must be longer than the multipath delay. Although each sub-carrier operates at a low data rate, a total high data rate can be achieved by using a large number of sub-carriers.

ISI has very small or no effect on the OFDM systems hence an equalizer is not needed at the receiver side. In the OFDM system, Inverse Fast Fourier Transform/Fast

Fourier Transform (IFFT /FFT) algorithms are used in the modulation and demodulation of the signal. The length of the IFFT/FFT vector determines the resistance of the system to errors caused by the multipath channel. The time span of this vector is chosen so that it is much larger than the maximum delay time of echoes in the received multipath signal. OFDM is generated by firstly choosing the spectrum required, based on the input data, and modulation scheme used. Each carrier to be produced is assigned some data to transmit. The required amplitude and phase of the carrier is then calculated based on the 3 modulation scheme (typically differential BPSK, QPSK, or QAM). Then, the IFFT converts this spectrum into a time domain signal. The FFT transforms a cyclic time domain signal into its equivalent frequency spectrum. Finding the equivalent waveform, generated by a sum of orthogonal sinusoidal components, does this. The amplitude and phase of the sinusoidal components represent the frequency spectrum of the time domain signal.

2.4 PRINCIPLES OF OFDM:

The main features of a practical OFDM system are as follows:

1. Some processing is done on the source data, such as coding for correcting errors, interleaving and mapping of bits onto symbols. An example of mapping used is QAM.

2. The symbols are modulated onto orthogonal sub-carriers. This is done by using IFFT.

3. Orthogonality is maintained during channel transmission. This is achieved by adding a cyclic prefix to the OFDM frame to be sent. The cyclic prefix consists of the L last samples of the frame, which are copied and placed in the beginning of the frame. It must be longer than the channel impulse response.

4. Synchronization: the introduced cyclic prefix can be used to detect the start of each frame. This is done by using the fact that the L first and last samples are the same and therefore correlated. This works under the assumption that one OFDM frame can be considered to be stationary.

5. Demodulation of the received signal by using FFT.

6. Channel equalization: the channel can be estimated either by using a training sequence or sending known so-called pilot symbols at predefined sub-carriers.

7. Decoding and de-interleaving.

The OFDM signal generated by the system shown in above Figure 2.2 is at baseband; in order to generate a radio frequency (RF) signal at the desired transmit frequency filtering and mixing is required. OFDM allows for a high spectral efficiency as the carrier power and modulation scheme can be individually controlled for each carrier. However in broadcast systems these are fixed due to the one-way communication. OFDM is a multicarrier system and it uses discrete Fourier Transform/Fast Fourier Transform (DFT/FFT) and sin(x)/x spectra for subcarriers. Available bandwidth is divided into very many narrow bands and 2000-8000 for digital TV and 48 for Hiperlan2. Data is transmitted in parallel on these bands. Most broadband systems are subject to multipath transmission. Conventional solution to multipath is an equalizer in the receiver with high data rates - equalizers too complicated. With OFDM there is a simple way of dealing with multipath for relatively simple DSP algorithms. Multipath is more than one transmission path between transmitter and receiver. Received signal is the sum of many versions of the transmitted signal with varying delay and attenuation.

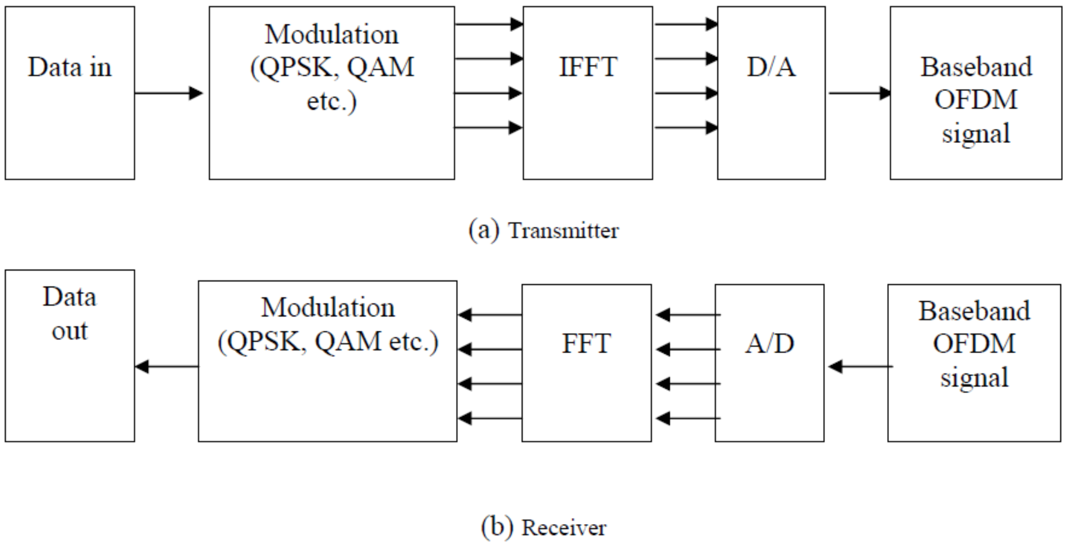


Figure 2.2: Basic OFDM System.

2.5 BLOCK DIAGRAM OF AN OFDM SYSTEM:

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. Usually, the bits are mapped into the 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 is provided between the OFDM symbols and the guard time is 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 efficient spectrum reuse by providing spatial diversity. At the receiver, first RF demodulation is performed. Then, the signal is digitized using an ADC and timing and frequency synchronization are performed. Synchronization will be dealt with in the later sections. 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.

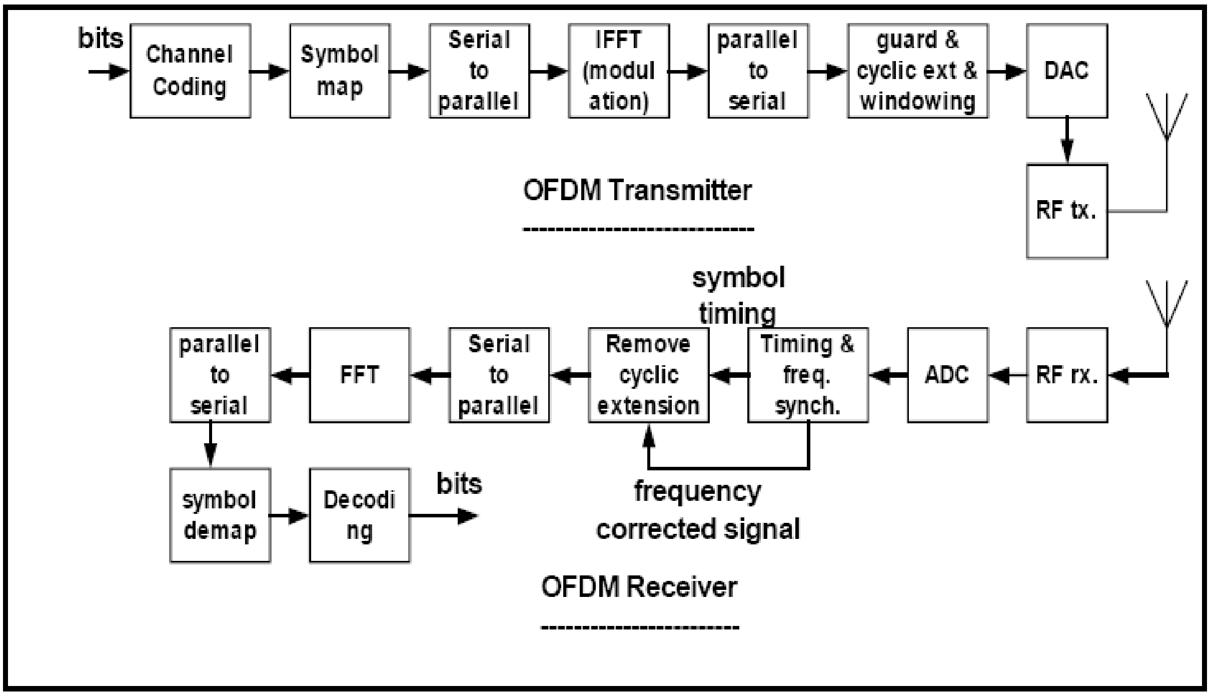


Figure 2.3: OFDM System Block Diagram.

2.6 BASICS OF OFDM:

2.6.1 Introduction:

Orthogonal Frequency Division Multiplexing (OFDM) has grown to be the most popular communications systems in high speed communications in the last decade. In fact, it has been said by many industry leaders that OFDM technology is the future of wireless communications. Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier transmission technique, which divides the bandwidth into many carriers, each one is modulated by a low rate data stream. In term of multiple access technique, OFDM is similar to FDMA in that the multiple user access is achieved by subdividing the available bandwidth into multiple channels that are then allocated to users. However, OFDM uses the spectrum much more efficiently by spacing the channels much closer together. This is achieved by making all the carriers orthogonal to one another, preventing interference between the closely spaced carriers. Late 1997, Lucent and NTT submitted proposals to the IEEE for a high speed wireless standard for local area networks (LAN). Eventually, the two companies combined their proposals and it was accepted as a draft standard in 1998 and as a standard now known as IEEE802.11a standard, in 1999.

2.6.2 Evolution of OFDM:

The evolution of OFDM can be divided into three parts. There are consists of Frequency Division Multiplexing (FDM), Multicarrier Communication (MC) and Orthogonal Frequency Division Multiplexing.

2.6.2.1 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 center frequency of transmission. To ensure that the signal of one channel did not overlap with the signal from an adjacent one, some gap or guard band was left between different channels. Obviously, this guard band will lead to inefficiencies which were exaggerated in the early days since the lack of digital filtering is made it difficult to filter closely packed adjacent channels.

2.6.2.2 Multicarrier Communication (MC):

The concept of Multi carrier (MC) communications uses a form of FDM technologies but only between a single data source and a single data receiver. As multicarrier communications was introduced, it enabled an increase in the overall capacity of communications, thereby increasing the overall throughput. Referring to MC as FDM, however, is somewhat misleading since the concept of multiplexing refers to the ability to add signals together. MC is actually the concept of splitting a signal into a number of signals, modulating each of these new signals over its own frequency channel, 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.

2.6.2.3 Orthogonal Frequency Division Multiplexing:

Orthogonal Frequency Division Multiplexing (OFDM) is simply defined as a form of multi-carrier modulation where the carrier spacing is carefully selected so that each sub-carrier is orthogonal to the other sub-carriers. Orthogonality can be achieved by carefully selecting the sub-carrier frequencies. One of the way is to select sub-carrier frequencies such that they are harmonics to each other.

2.6.3 Principle of OFDM transmission technology:

As stated above OFDM is a multi-carrier modulation technology where every sub-carrier is orthogonal to each other. The "orthogonal" part of the OFDM name indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. It is possible to arrange the carriers in an OFDM Signal so that the sidebands of the individual carriers overlap and the signals can still be received without adjacent carrier's interference. In order to do this the carriers must be mathematically orthogonal. Two signals are orthogonal if their dot product is zero. That is, if we take two signals multiply them together and if their integral over an interval is zero, then two signals are orthogonal in that interval. Since the carriers are all sine/cosine wave, we know that area under one period of a sine or a cosine wave is zero which is as shown below.

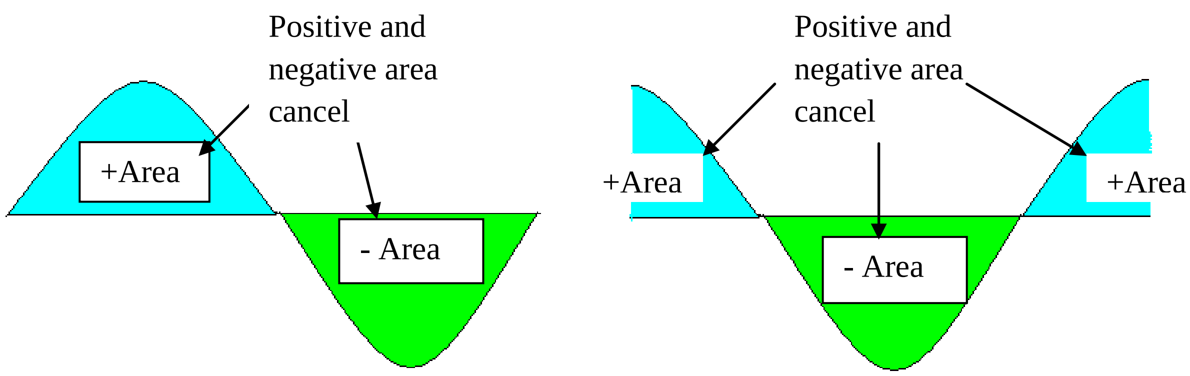


Fig. 2.4 :The area under a sine and a cosine wave over one period is always zero.

If a sine wave of frequency m is multiplied by a sinusoid (sine or cosine) of a frequency n, then the product is given by

$$f(t) = \sin mwt \times \sin nwt \tag{2.3}$$

Where both m and n are integers. By simple trigonometric relationship, this is equal to a sum of two sinusoids of frequencies (n-m) and (n+m). Since these two components are each a sinusoid, the integral is equal to zero over one period. The integral or area under this product is given by

$$= \int_0^{2\pi} \tfrac{1}{2}\cos(m-n)wt - \int_0^{2\pi} \tfrac{1}{2}\cos(m+n)wt$$

$$= 0 - 0$$

So when a sinusoid of frequency n multiplied by a sinusoid of frequency m, the area under the product is zero. In general for all integers n and m, sinmx cosmx, cosnx, sinnx are all orthogonal to each other. These frequencies are called harmonics.

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. The Orthogonality allows simultaneous transmission on a lot of sub-carriers in a tight frequency space without interference from each other as shown in Figure 2.6.

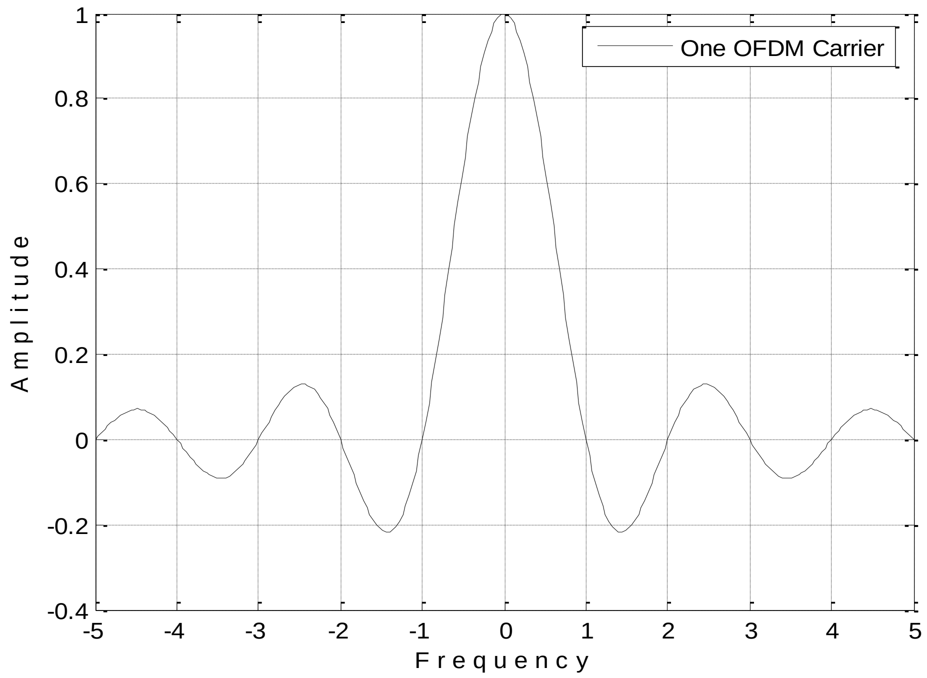


Fig. 2.5: Single Carrier of OFDM Signal.

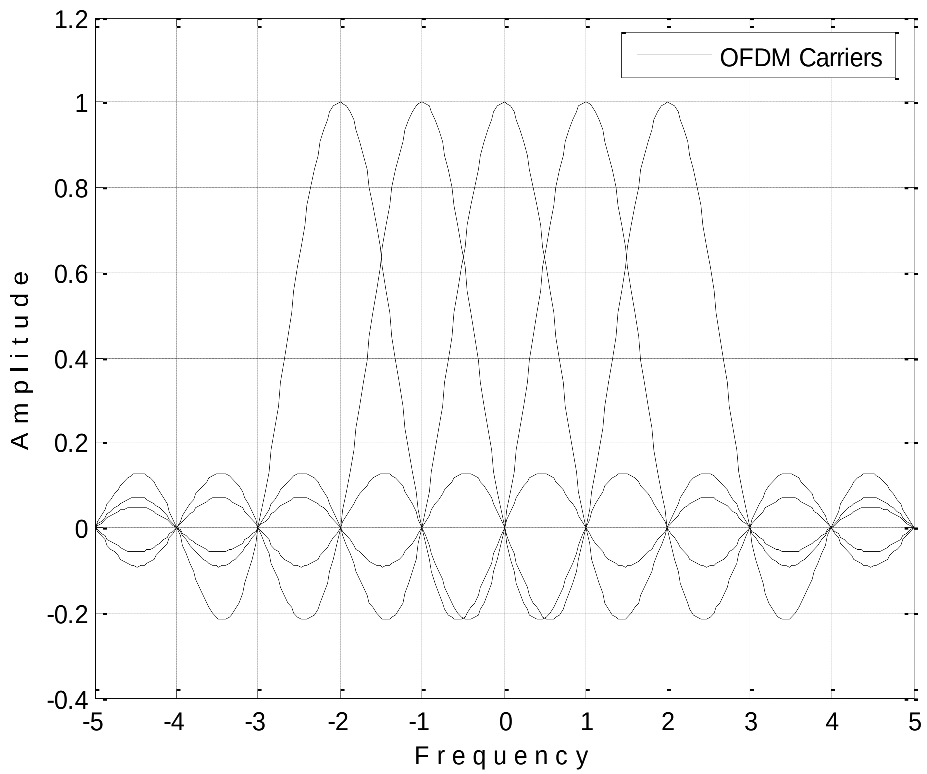


Fig. 2.6: 5 carriers of OFDM Signal.

So in the receiver side easily we can extract the individual sub-carriers. But in traditional FDM systems overlapping of carriers are not possible, rather a guard band is provided between each carrier to avoid inter-carrier interference which is as shown below.

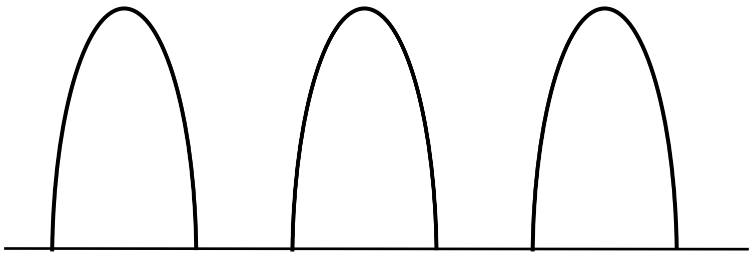


Fig. 2.7: Spectrum of FDM.

2.6.4 OFDM generation and reception:

Figure 2.8 shows the block diagram of a typical OFDM transceiver. The transmitter section converts digital data to be transmitted, into a mapping of subcarrier amplitude and phase. It then transforms this spectral representation of the data into the time domain using an Inverse Discrete Fourier Transform (IDFT). The Inverse Fast Fourier Transform (IFFT) performs the same operations as an IDFT, except that it is much more computationally efficiency, and so is used in all practical systems. In order to transmit the OFDM signal the calculated time domain signal is then mixed up to the required frequency. The receiver performs the reverse operation of the transmitter, mixing the RF signal to base band for processing, then using a Fast Fourier Transform (FFT) to analyze the signal in the frequency domain. The amplitude and phase of the subcarriers is then picked out and converted back to digital data. The IFFT and the FFT are complementary function and the most appropriate term depends on whether the signal is being received or generated. In cases where the signal is independent of this distinction then the term FFT and IFFT is used interchangeably. The binary data sent at the transmitter side is compared with the binary data received at the receiver. Bit error rate is calculated by comparing both the transmitted binary data and received binary data. Here channel is considered to be additive white Gaussian and DAC (digital to analog converter) is not considered. Similarly ADC(analog to digital converter) is not necessary but given in the block diagram.

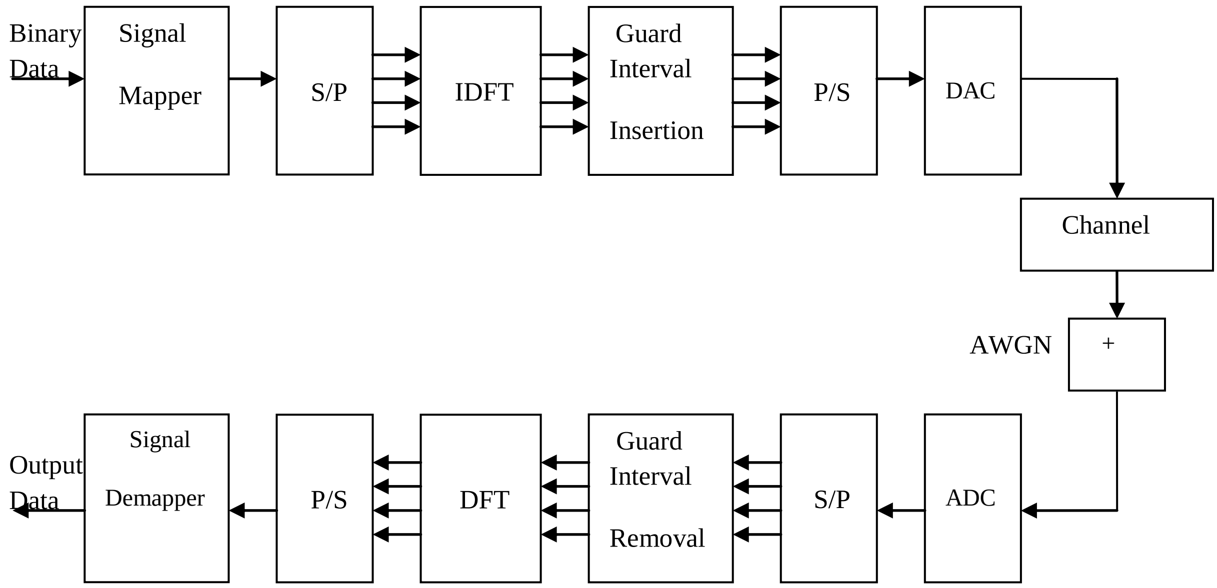


Fig. 2.8: The basic block diagram of an OFDM system in AWGN channel.

Signal Mapping:

A large number of modulation schemes are available allowing the number of bits transmitted per carrier per symbol to be varied. Digital data is transferred in an OFDM link by using a modulation scheme on each subcarrier. A modulation scheme is a mapping of data words to a real (In phase) and imaginary (Quadrature) constellation, also known as an IQ constellation. For example 256-QAM (Quadrature Amplitude Modulation) has 256 IQ points in the constellation constructed in a square with 16 evenly spaced columns in the real axis and 16 rows in the imaginary axis. The number of bits that can be transferred using a single symbol corresponds to log2(M), where M is the number of points in the constellation, thus 256-QAM transfers 8 bits per symbol. Increasing the number of points in the constellation does not change the bandwidth of the transmission, thus using a modulation scheme with a large number of constellation points, allows for improved spectral efficiency. For example 256-QAM has a spectral efficiency of 8 b/s/Hz, compared with only 1 b/s/Hz for BPSK. However, the greater the number of points in the modulation constellation, the harder they are to resolve at the receiver.

Serial to Parallel Conversion:

Data to be transmitted is typically in the form of a serial data stream. In OFDM, each symbol typically transmits 40 - 4000 bits, and so a serial to parallel conversion stage is needed to convert the input serial bit stream to the data to be transmitted in each OFDM symbol. The data allocated to each symbol depends on the modulation scheme used and the number of subcarriers. For example, for a subcarrier modulation of 16-QAM each subcarrier carries 4 bits of data, and so for a transmission using 100 subcarriers the number of bits per symbol would be 400. At the receiver the reverse process takes place, with the data from the subcarriers being converted back to the original serial data stream.

Frequency to Time Domain Conversion:

The OFDM message is generated in the complex baseband. Each symbol is modulated onto the corresponding subcarrier using variants of phase shift keying (PSK) or different forms of quadrature amplitude modulation (QAM). The data symbols are converted from serial to parallel before data transmission. The frequency spacing between adjacent subcarriers is $N\pi/2$, where N is the number of subcarriers. This can be achieved by using the inverse discrete Fourier transform (IDFT), easily implemented as the inverse fast Fourier transform (IFFT) operation . As a result, the OFDM symbol generated for an N-subcarrier system translates into N samples, with the ith sample being

$$x_i = \sum_{n=0}^{N-1} C_n \exp\left\{ j \frac{2\pi i n}{N} \right\}, \qquad 0 \le i \le N-1 \tag{2.4}$$

At the receiver, the OFDM message goes through the exact opposite operation in the discrete Fourier transform (DFT) to take the corrupted symbols from a time domain form into the frequency domain. In practice, the baseband OFDM receiver performs the fast Fourier transform (FFT) of the receive message to recover the information that was originally sent.

Inter symbol interference:

In a multipath environment, a transmitted symbol takes different times to reach the receiver through different propagation paths. From the receivers point of view, the channel introduces time dispersion in which the duration of the received symbol is stretched. Extending the symbol duration causes the current received symbol to overlap previous received symbols and results in inter symbol interference (ISI). In OFDM, ISI usually refers to interference of an OFDM symbol by previous OFDM symbols. For a given system bandwidth the symbol rate for an OFDM signal is much lower than a single carrier transmission scheme.

For example for a single carrier BPSK modulation, the symbol rate corresponds to the bit rate of the transmission. However for OFDM the system bandwidth is broken up into N subcarriers, resulting in a symbol rate that is N times lower than the single carrier transmission. This low symbol rate makes OFDM naturally resistant to effects of Inter-Symbol Interference (ISI) caused by multipath propagation. Multipath propagation is caused by the radio transmission signal reflecting off objects in the propagation environment, such as walls, buildings, mountains, etc. These multiple signals arrive at the receiver at different times due to the transmission distances being different. This spreads the symbol boundaries causing energy leakage between them.

Guard period:

The effect of ISI on an OFDM signal can be further improved by the addition of a guard period to the start of each symbol. This guard period is a cyclic copy that extends the length of the symbol waveform. Each subcarrier, in the data section of the symbol, (i.e. the OFDM symbol with no guard period added, which is equal to the length of the IFFT size used to generate the signal) has an integer number of cycles.

Because of this, placing copies of the symbol end-to-end results in a continuous signal, with no discontinuities at the joins. Thus by copying the end of a symbol and appending this to the start results in a longer symbol time. Figure 2.9 shows the insertion of a guard period. The total length of the symbol is $T_s = T_g + T_{fft}$, where T_s is the total length of the symbol in samples, T_g is the length of the guard period in samples, and T_{fft} is the size of the IFFT used to generate the OFDM signal. In addition to protecting the OFDM from ISI, the guard period also provides protection against time-offset errors in the receiver. This guard period is useful in eliminating inter symbol interference(ISI) and generally it contains last one fourth samples of OFDM symbol.

The most effective guard period to use is a cyclic extension of the symbol. If a mirror in time, of the end of the symbol waveform is put at the start of the symbol as the guard period, this effectively extends the length of the symbol, while maintaining the Orthogonality of the waveform. Using this cyclic extended symbol the samples required for performing the FFT (to decode the symbol), can be taken anywhere over the length of the symbol. This provides Multi path immunity as well as symbol time synchronization tolerance.

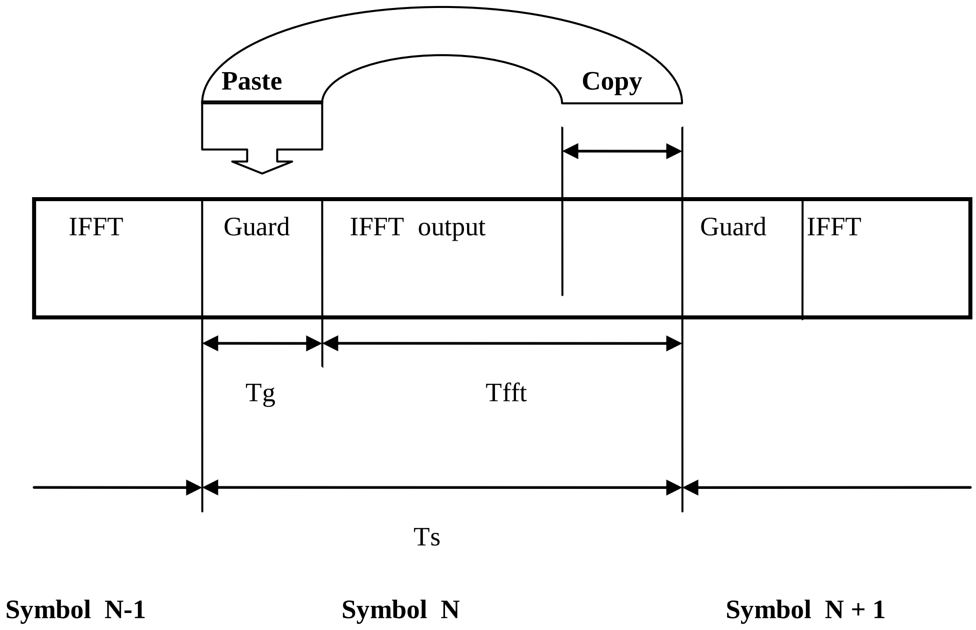


Fig. 2.9 :Guard period insertion in OFDM.

Effect of AWGN on OFDM:

Noise exists in all communications systems operating over an analog physical channel, such as radio. The main sources are thermal background noise, and electrical noise in the receiver amplifiers, and inter-cellular interference. In addition to this noise can also be generated internally to the communications system as a result of Inter-Symbol Interference (ISI), Inter-Carrier Interference (ICI), and Inter- Modulation Distortion (IMD). These sources of noise decrease the Signal to Noise Ratio (SNR), ultimately limiting the spectral efficiency of the system. Noise, in all its forms, is the main detrimental effect in most radio communication systems.

It is therefore important to study the effects of noise on the communications error rate and some of the tradeoffs that exist between the level of noise and system spectral efficiency. Most types of noise present in radio communication systems can be modeled accurately using Additive White Gaussian Noise (AWGN). This noise has a uniform spectral density (making it white), and a Gaussian distribution in amplitude (this is also referred to as a normal distribution). Thermal and electrical noise from amplification, primarily have white Gaussian noise properties, allowing them to be modeled accurately with AWGN. Also most other noise sources have AWGN properties due to the transmission being OFDM. OFDM signals have a flat spectral density and a Gaussian amplitude distribution provided that the number of carriers is large (greater than about 20 subcarriers), because of this the inter-cellular interference from other OFDM systems have AWGN properties. For the same reason ICI, ISI, and IMD also have AWGN properties for OFDM signals.

2.7 ADVANTAGES OF OFDM:

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, I will discuss some of these advantages.

2.7.1 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) is removed completely.

2.7.2 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.

2.7.3 Efficient modulation and demodulation:

Modulation and Demodulation of the sub-carriers is done using IFFT and FFT methods respectively, which are computationally efficient. By performing the modulation and demodulation in the digital domain, the need for highly frequency stable oscillators is avoided. OFDM makes efficient use of the spectrum by allowing overlap.

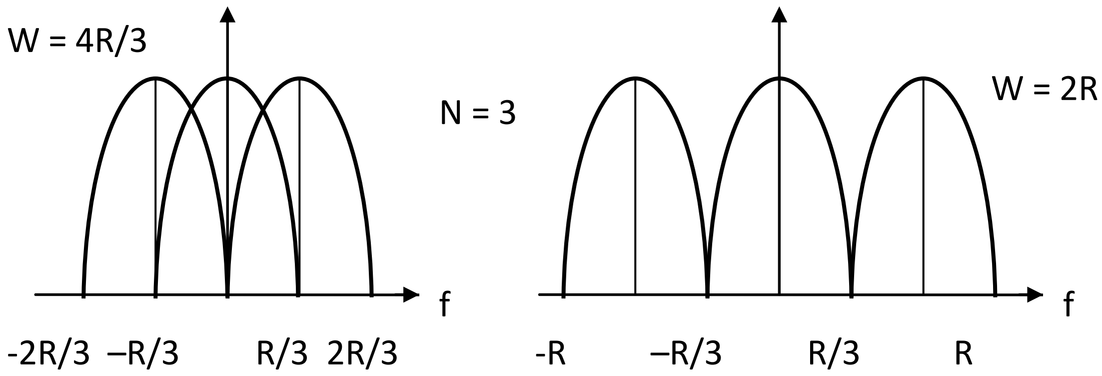


Fig. 2.10 : Spectrum Efficiency of OFDM Compared to FDM.

OFDM achieves high spectral efficiency by allowing the sub-carriers to overlap in the frequency domain. If the number of subcarriers is N and T_s is symbol duration, then total bandwidth required is

$$BW_{total} = \frac{(N+1)}{T_s} \tag{2.5}$$

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

$$BW_{total} = \frac{2N}{T_s} \tag{2.6}$$

2.7.4 Robustness to Frequency Selective Fading channels:

In a multipath channel the reflected signals that are delayed, add to the main signal and cause either gains in the signal strength or loss (deep fade) in the signal strength. Deep fade means the signal is nearly wiped out. In a channel where deep fades occurs at selected frequencies is called a frequency selective fading channel (Fig. 2.12) & those frequencies depends upon the environment.

In a single carrier system the entire signal is lost during the fading intervals. But as in case of OFDM the signal consists of many sub-carriers, so only few sub-carriers are affected during the fading intervals (Fig. 2.13) & hence a very small percentage of the signal is lost which can be easily recovered.

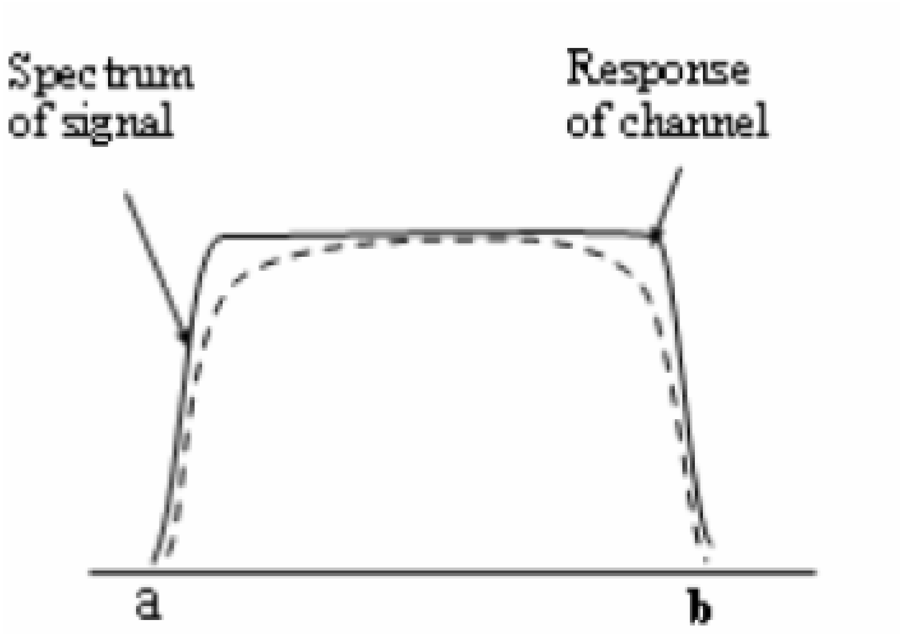


Fig. 2.11 :The signal and the channel frequency response.

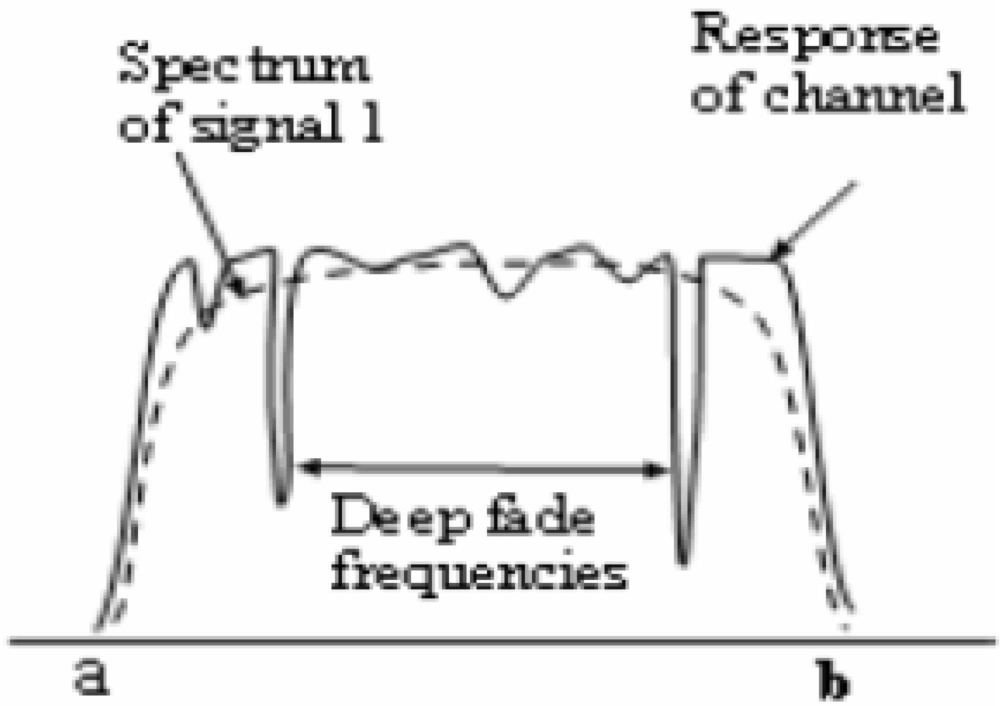


Fig. 2.12 :A fading channel frequency response.

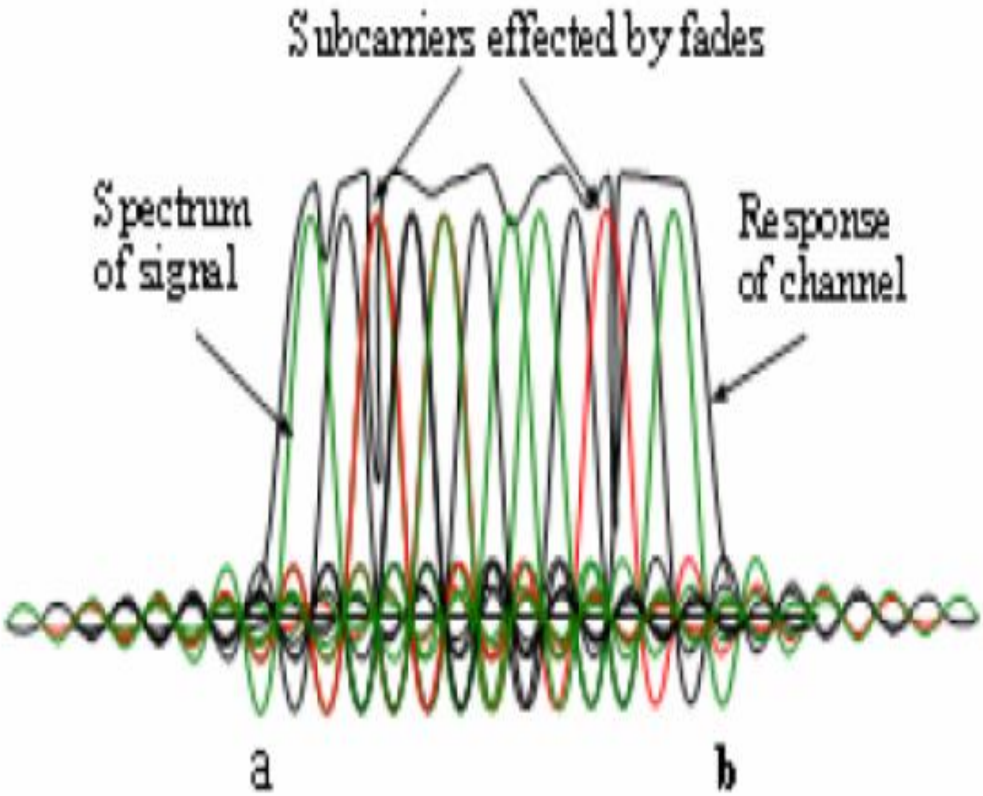


Fig. 2.13 :Robustness of OFDM to Frequency Selective Fading channel.

Makes efficient use of the spectrum by allowing overlap by dividing the channel into narrowband flat fading sub channels, OFDM is more resistant to frequency selective fading than single carrier systems i.e. robustness to frequency selective fading channels. Eliminates ISI through use of a cyclic prefix. Using adequate channel coding and interleaving one can recover symbols lost due to the frequency selectivity of the channel.

Channel equalization becomes simpler than by using adaptive equalization techniques with single carrier systems. It is possible to use maximum likelihood decoding with reasonable complexity. OFDM is computationally efficient by using FFT techniques to implement the modulation and demodulation functions. It is less sensitive to sample timing offsets than single carrier systems. Provides good protection against co channel interference and impulsive parasitic noise.

CHAPTER 3

APPLICATIONS AND PROBLEMS OF OFDM

3.1 APPLICATIONS OF OFDM:

3.1.1 General:

We have seen that OFDM is digital transmission technique well suited for wideband, high data rate transmissions. The main advantage is that less equalization is necessary. A consequence of that is OFDM is not a very good solution for one to one communications with several users on shared channels, because of the problem of frequency allocation. However on super high frequency bands (SHF) and Extremely high frequency bands (EHF) where occupied bandwidth is not a great problem, OFDM may be a good solution for one to one communications. But, nowadays, OFDM is mainly used for one to many (broadcast) communications like radio or television broadcasting. That's why we find OFDM on several new digital broadcasting systems such as DAB and DVB.

3.1.2 Digital Audio Broadcasting (DAB):

Digital Audio Broadcasting (DAB) is an international, standardized digital broadcasting system developed by the European EUREKA-147 Project. The system should completely replace, in the future, the well-known analog FM (Frequency Modulation) radio system on the 88-108 MHz frequency band. The DAB system is digital and provides CD-like audio quality. DAB is much more robust to interferences and is well suited for mobile reception like in a car. New possibilities are available on receivers like for example multimedia features (image and texts). The transmission scheme used for DAB is OFDM modulation.DAB is being deployed around Europe and some other countries nowadays, receivers are still expensive like CD players in the beginning of eighties but we might expect to see a wide use of it in the next 5 years.

3.1.3 What bandwidth to use for OFDM?

The wider the bandwidth, the more probably that the system overcome the correlation bandwidth of the channel. Problem to overcome: Short delay echoes are the main problems to overcome, and as these are always present there is no hard bound. The narrower the bandwidth, the more likely it is that the whole signal will be affected. There is a tradeoff between bandwidth and transmitter power.

Bandwidth: 7MHz few problems and 2 MHz degradation of 1dB in performance at each point and less than 1.5MHz degradation starts to increase and 200 KHz used for FM sound, then the margin required would be an additional 6dB or so.

Trade off: 1.5MHz for the type of propagation conditions that apply to mobile and portable radio reception.

Bit-rate: On each carrier the modulation system used is QPSK, the carriers are separated by a gap of around $1/T_s$, where T_s is symbol period. The maximum bit rate available is so 2bit/s/Hz of the bandwidth. This figure is reduced by the inefficiency (signal redundancy) of the guard interval, the null symbol and the error coding. For DAB, this brings the useful bit-rate down about 1 bit/s/Hz of the bandwidth. Therefore a DAB system will provide just less than 1.5Mbit/s of useful data. This is considerably more than 256kbit/s that needed for high-quality stereophonic program, so the implication is that several broadcast programs will share the same multiplex.

3.1.4 ASDL:

Asymmetric Digital Subscriber Line (ADSL) is a technique to transmit high data rates (up to 6 Mb/s downlink, 640kb/s uplink) on Subscriber Lines (telephone lines). Such lines consist of twisted copper wires. The idea is to use the full capacity of the line instead of using only 4 kHz needed to transmit voice. Occupied bandwidth goes to 1.1 MHz The main problem is that the characteristics of the line change among users. They change with distance, presence of bridged taps in the line, neighborhood of other lines. The results are reflections at certain frequencies which cause attenuation, velocity dependant of the frequency which causes ISI. The situation is very similar to wireless channels.

There are 2 possible modulation schemes usable for ADSL: CAP (Carrier less amplitude phase) that is similar to QAM and Discrete Multi tone (DMT) that is another appellation for OFDM. Nowadays, it seems that DMT is the retained candidate for ADSL. The downlink consists of 222 tones (carriers) and uplink is spitted in 24 tones. 2 to 15 bits are coded by tone. The transmission rate is optimized with respect to line conditions. If transmission on one of the tone is disrupted because of strong reflections and interferences at the frequency band, transmission is suspended on that tone by modem.

3.1.5 HIPERLAN2:

HiperLAN2 is the all new high performance radio technology, specifically suited for operating in LAN environments. HiperLAN2 is a technology being developed within the European Telecommunications Standardisation Institute (ETSI) and a final specification is due to be finalised at the end of 1999 or beginning of 2000.HiperLAN2 operates in the unlicensed 5 GHz frequency band, which has been specifically allocated to wireless LANs. In contrast to the IEEE 802.11 wireless Ethernet technology, HiperLAN2 is connection-oriented. Connections over the air are time-division multiplexed. Connections can also be assigned different Quality of Service (QOS) This QOS support allows for the transmission of a mix of different types of technologies, e.g. voice, video, and data. There are also specific connections for Unicast, multicast, and broadcast transmission.HiperLAN2 allows for interconnection into virtually any type of fixed network technology. Thus, HiperLAN2 can carry, for example, Ethernet frames, ATM cells, IP packets, etc. A likely first scenario for HiperLAN2 is to use it between a mobile terminal such as a laptop, and an access point.

OFDM is the modulation used in the physical layer of HiperLAN2, with a 64 point Fast Fourier Transform. For the subcarrier modulation we have choice between BPSK, QPSK, and 16-64 QAM; the symbol period used is 3.6μs with a guard interval of 0.8μs (optionally 0.4μs). The demodulation is coherent. OFDM obviously provides intentionally wide frequency band and a potential bit-rate of 54Mbit/s.

Domestic electronics like televisions, cameras, stereo equipment and computers can all be interconnected by HiperLAN2 using small H2 modules which automatically establish connectivity. HiperLAN2 allows multimedia equipment to be intelligently controlled from any computing device in the home without the need for network cables. HiperLAN2 also has strong security support, including both authentication and encryption and has a built-in facility for automatic frequency allocation, removing the need for frequency planning.

3.1.6 Other Applications:

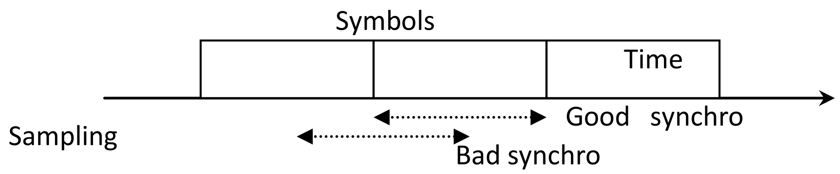
1. Wireless ATM transmission system.

2. IEEE802.11a and IEEE802.11g.

3.2 PROBLEMS IN OFDM:

3.2.1 Synchronization:

One of the crucial problems in the receiver is to sample the incoming signal correctly. If the wrong sequence of samples is processed, the Fast Fourier Transform shall not correctly recover the received data on the carriers. The problem is more embarrassing when the receiver is switched on. There is therefore a need for acquiring timing lock. If the signal transmitted is really time domain periodic, as required for the FFT to be correctly applied, then the effect of the time displacement is to modify the phase of all carriers by a known amount. This is due to the time shift theorem in convolution transform theory.



However, the signal is not really repetitive, we have cheated and performed the mathematical transform as if it were repetitive, but then chosen different symbols and transmitted them one after the other. The effect of the time shift would then be not only to add the phase shift referred to above, but also to add some Inter symbol interference with adjacent symbols. This interference could hardly degrade reception. To avoid these problems, we decide to transmit more than one complete sequence of time samples in order to increase the tolerance in timing. It's an additional data guard interval. It is built by repeating a set as long as channel memory of last samples taken in the original sequence. One technique used to obtain good synchronization is to add between each OFDM symbol a null (zero samples) symbol. This technique is used in DAB for time Synchronization.

3.2.2 Phase noise:

At the receiver, a local oscillator can add phase noise to an OFDM signal, for example. The phase noise could so have two effects those are: Common Phase Error (CPE) due to a rotation of the signal constellation and, Inter Carrier Interference (ICI), similar to additive Gaussian noise. The BBC R&D have made analysis of the effects of phase noise on an OFDM signal, this analysis shows that CPE arises simultaneously on all carriers. Indeed, the signal constellation within a given symbol is subject to the same rotation for all carriers and this effect can be corrected by using reference information within the same symbol. Unfortunately, ICI is more difficult to overcome, due to the additive noise, which is different for all carriers.

3.2.3 Frequency error:

An OFDM system can be subject to two types of frequency error. They are Frequency offset (as might be caused by the tolerance of the local oscillator frequency) and, Error in the receiver master clock frequency (which will cause the spacing of the demodulating carriers to be different from those transmitted). Before to find solutions to those problems, the system designer needs to determine how much residual frequency error is permissible, and understand exactly how errors affect the received signal. Both of these error situations have been analyzed so; a frequency offset affects most carriers equally, with the very edge carrier less affected. ICI resulting from a fixed absolute frequency offset increases with the number of carriers, if the system bandwidth is kept constant. About error in the receiver clock frequency, in absence of frequency offset, it affects carriers unequally (the center carrier suffers a little while the worst affected carrier lies close to, but not at, the edge).

3.2.4 Disadvantages of OFDM compared to single carrier:

The OFDM signal has a noise like amplitude with a very large dynamic range; therefore it requires RF power amplifiers with a high peak to average power ratio. It is more sensitive to carrier frequency offset and drift than single carrier systems are due to leakage of the DFT.

3.2.5 Intra symbol interference:

The guard interval is not used in practical systems because it does not prevent an OFDM symbol from interfering with itself. This type of interference is called intra symbol interference. The solution to the problem of intra symbol interference involves a discrete time property. Recall that in continuous-time, a convolution in time is equivalent to a multiplication in the frequency-domain. This property is true in discrete-time only if the signals are of infinite length or if at least one of the signals is periodic over the range of the convolution. It is not practical to have an infinite-length OFDM symbol; however, it is possible to make the OFDM symbol appear periodic.

3.3 OFDM ANALYSIS:

3.3.1 Channel:

When doing radio transmission on high frequencies (VHF and higher) we are often confronted to a multipath environment. Such environment is found mostly in urban areas where buildings reflect waves.

3.3.2 Frequency Selectivity:

One problem of multipath is that the resultant of waves from different paths can be constructive or destructive depending on the position, so signal change over time when moving. You can experiment that when listening on FM radios while driving in a city: signal is cut by noise when moving. Generally we speak of a frequency selective channel. Characteristics may change fast when moving. That’s why the channel is also time varying. The aim of equalization is to compensate the problems introduced by frequency selectivity.

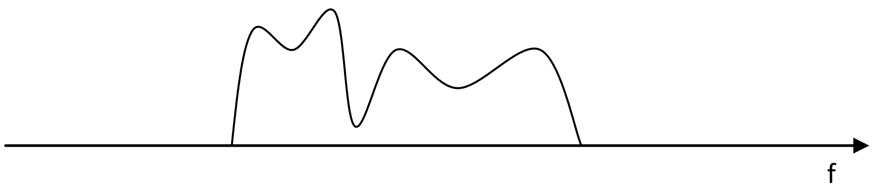


Figure 3.1: Typical frequency response of a channel suffering from multipath propagation.

3.3.3 Delay Spread:

Another effect that affects digital transmission is that the signal coming from different paths has different time delays depending on the length of path.

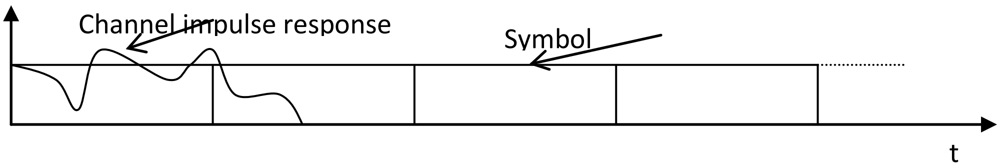


Figure 3.2: Delay Spread.

3.3.4 The problem of wideband transmission on a single carrier:

When transmitting wideband on frequency selective channels, equalization must be performed in order to avoid inter symbol interference. Equalization try to make the channel flat. In order to do that channel state information is needed. Training sequences have then to be transmitted periodically to estimate channel. Channel estimation is performed by several calculations and is then CPU time consuming. So when data rate is high and when characteristics of channel change rapidly CPU power needed is high and system become expensive. Also is the symbol period very small compared to the channel memory. That cause strong Inter symbol Interference (ISI) and equalization is needed to correct that problem.

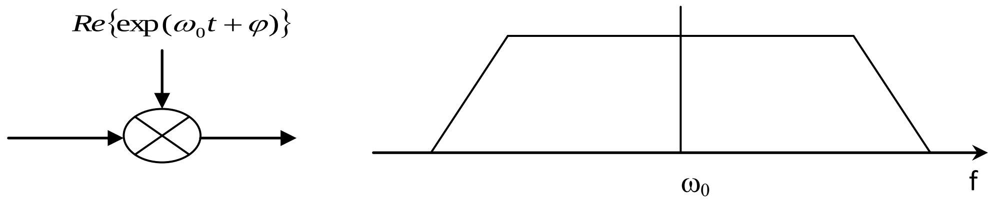


Figure 3.3 : Equalization.

3.3.5 Multi carrier transmission :

The idea of multicarrier transmission is to divide bandwidth in several narrow band transmissions so that the channel looks flat on each carrier. The data stream to transmit is then split among the carriers instead of being transmitted on one carrier with large signal bandwidth. That's what is meant by Frequency Division Multiplex (FDM). The advantage is that no or less complex equalization is needed. The symbol period on each carrier become large and the effect of channel memory (length of channel impulse response) become less destructive on the symbols, so inter symbol interference (ISI) is reduced and less equalization is needed.

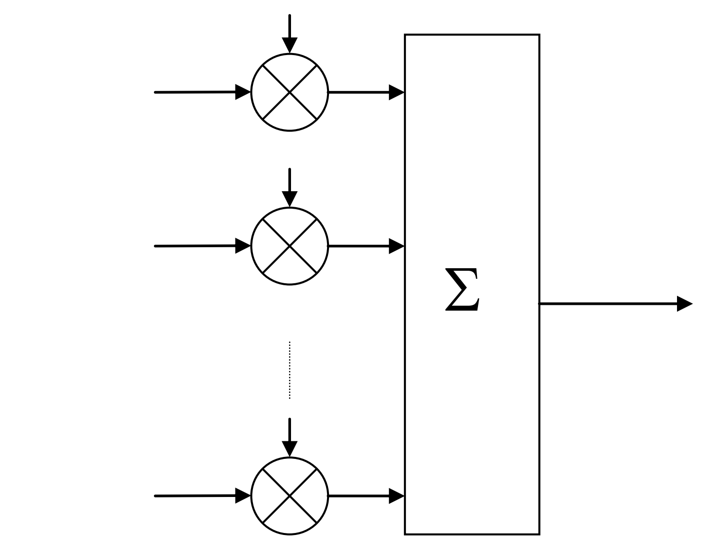


Figure 3.4: Multi Carrier Transmission.

CHAPTER 4

ANALYSIS OF INTER CARRIER INTERFERENCE

4.1 ICI MECHANISM OF STANDARD OFDM SYSTEMS:

The main disadvantage of OFDM, however, is its susceptibility to small differences in frequency at the transmitter and receiver, normally referred to as frequency offset. This frequency offset can be caused by Doppler shift due to relative motion between the transmitter and receiver, or by differences between the frequencies of the local oscillators at the transmitter and receiver. In this project, the frequency offset is modeled as a multiplicative factor introduced in the channel, as shown in Figure 4.1.

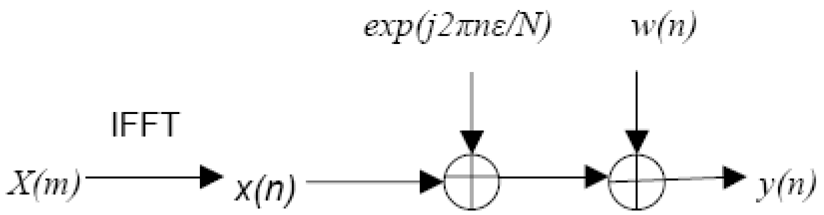


Figure 4.1: Frequency Offset Model.

The received signal is given by,

$$y(n) = x(n)e^{j2\pi n\frac{\varepsilon}{N}} + w(n) \tag{4.1}$$

Where ε the normalized frequency offset, and is given by $\Delta f N T_s$, Δf is the frequency difference between the transmitted and received carrier frequencies and T_s is the subcarrier symbol period. $w(n)$ is the AWGN introduced in the channel.

The effect of this frequency offset on the received symbol stream can be understood by considering the received symbol $Y(k)$ on the kth sub-carrier.

$$Y(k) = X(k)S(0) + \sum_{l=0, l\neq k}^{N-1} X(l)S(l-k) + n_k \qquad k = 0,1,2,......N-1 \tag{4.2}$$

Where N is the total number of subcarriers, $X(k)$ is the transmitted symbol (M-ary phase-shift keying (M-PSK), for example) for the kth subcarrier, n_k is the FFT of $w(n)$ and $S(l-k)$ are the complex coefficients for the ICI components in the received signal. The ICI components are the interfering signals transmitted on sub-carriers other than the kth sub-carrier. The complex coefficients are given by

$$S(l-k)=\frac{\sin(\pi(l+\varepsilon-k))}{N\sin(\pi(l+\varepsilon-k)/N)}\exp(j\pi(1-\frac{1}{N})(l+\varepsilon-k)) \qquad (4.3)$$

To analyze the effect of ICI on the received signal, we consider a system with N =16 carriers. The frequency offset values used are 0.2 and 0.4, and l is taken as 0, that is, we are analyzing the signal received at the sub-carrier with index 0. The complex ICI coefficients $S(l-k)$ are plotted for all sub-carrier indices in below Figures 4.2, 4.3 and 4.4.

This figure 4.2 shows that for a larger ε, the weight of the desired signal component, $S(0)$ decreases, while the weights of the ICI components increases. We can also notice that the adjacent carrier has the maximum contribution to the ICI. This fact is used in the ICI self-cancellation technique described in below section.

The carrier-to-interference ratio (CIR) is the ratio of the signal power to the power in the interference components. It serves as a good indication of signal quality. It has been derived from $Y(k)$ equation and is given below. The derivation assumes that the standard transmitted data has zero mean and the symbols transmitted on the different sub-carriers are statistically independent. In deriving the Theoretical CIR expression, the additive noise is omitted. The desired received signal power on the k th sub carrier can be represented as

$$\mathrm{E}\left[|C(k)|^2\right]=\mathrm{E}\left[|X(k)S(0)|^2\right] \qquad (4.4)$$

The ICI power is represented as

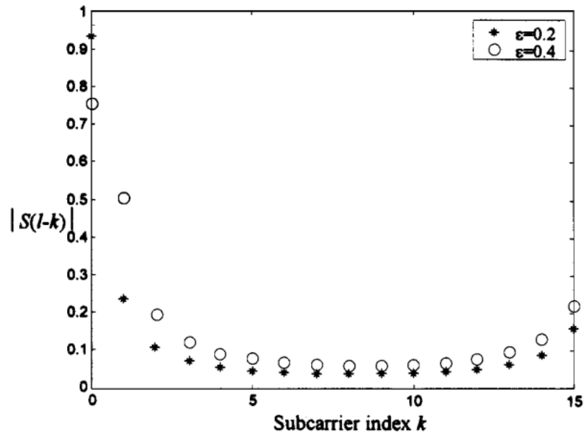
$$\mathrm{E}\left[|\mathrm{I}(k)|^2\right]=\mathrm{E}\left[\left|\sum_{l=0,l\neq k}^{N-1}\mathrm{X}(l)\mathrm{S}(l-k)\right|^2\right] \qquad (4.5)$$

CIR is given by below equation

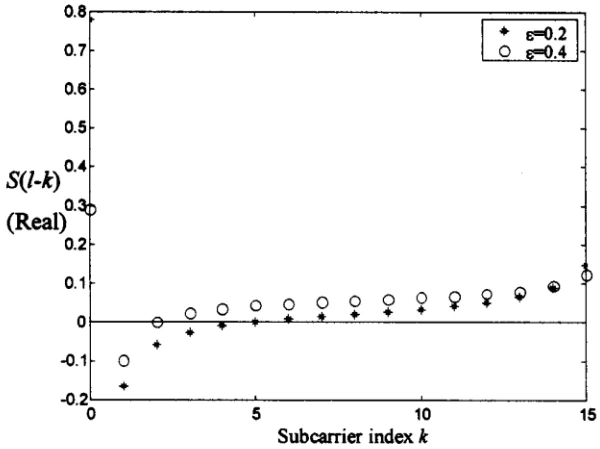
$$\mathrm{CIR}=\frac{\mathrm{S}(k)^2}{\sum_{l=0,l\neq k}^{N-1}\mathrm{S}(l-k)^2}=\frac{\left|\mathrm{S}(0)^2\right|}{\sum_{l=1}^{N-1}\mathrm{S}(l)^2} \qquad (4.6)$$

The carrier-to-interference power ratio (CIR) can be increased by 15 and 30 dB when the group size is two or three, respectively, for a channel with a constant frequency offset**.**

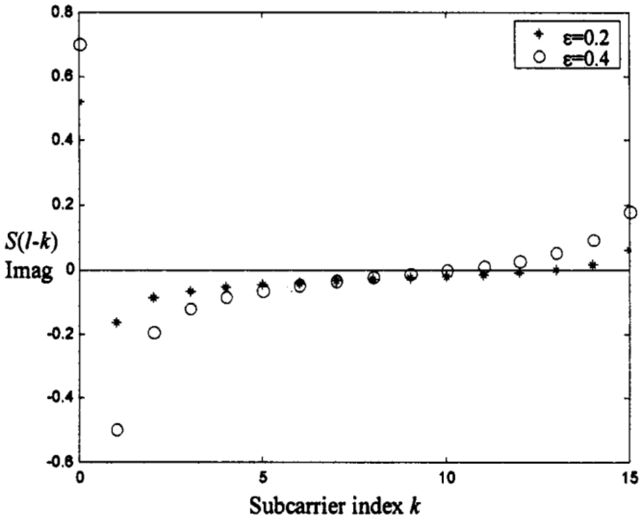
4.2 Amplitude of $S(l-k)$



4.3 Real part of $S(l-k)$



4.4 Imaginary part of $S(l-k)$



CHAPTER 5

METHODS OF ICI REDUCTION

Some of the methods for ICI reduction available in literature are:

- **Frequency domain equalization**
- **Time domain windowing**
- **Pulse shaping**
- **ICI self cancellation**
- **Maximum likelihood Estimation**
- **Extended Kalman Filtering**

From the above Six methods the first two methods are the initial approach, and the next two methods are very effective and the last two methods are good for higher modulation and frequency offsets.

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.

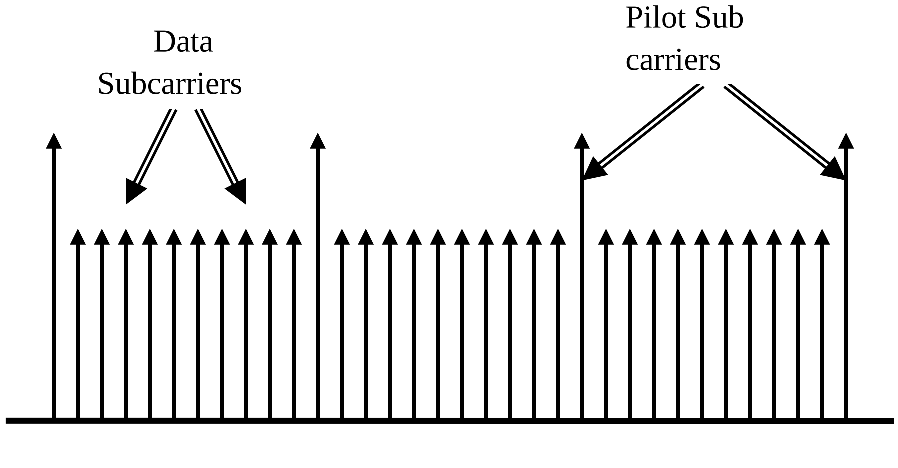


Figure 5.1: Pilot Subcarrier Arrangement.

Drawbacks:

It 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, and the Doppler shift. 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 the method is not effective one.

5.2 TIME DOMAIN WINDOWING:

We know that 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.

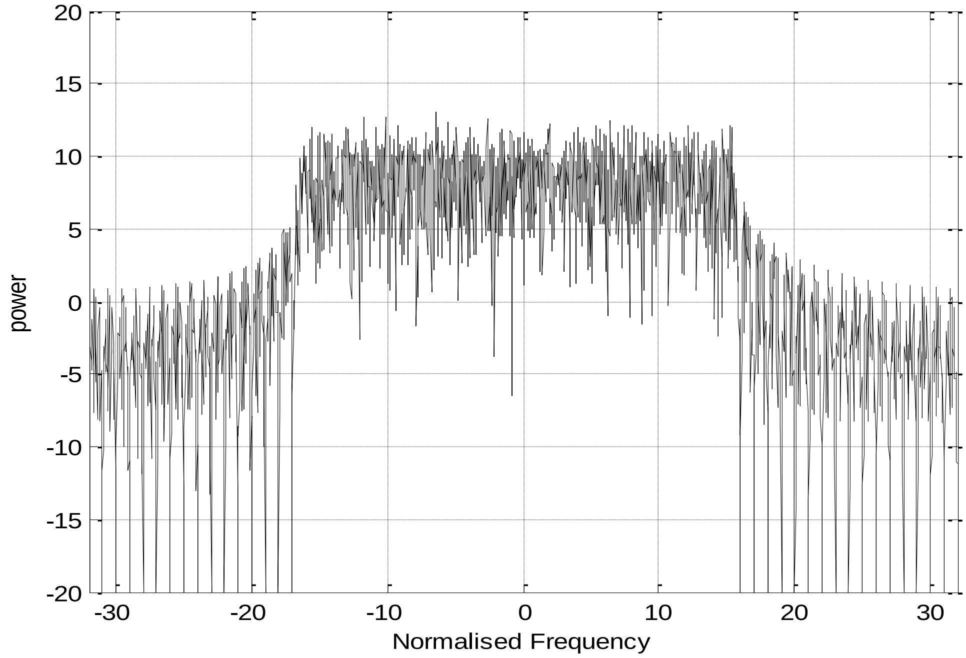


Fig. 5.2: Spectrum of a 64 subcarrier OFDM.

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 ICI will be eliminated if the product of the window functions satisfies the Nyquist vestigial symmetry criterion.

Frame by frame windowing:

The conventional frame-by-frame time limited orthogonal multicarrier signal S(t) can be expressed as:

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{n=0}^{N-1} w(t-kT) a_{n,k} \exp(jnw_{\Delta}(t-kT)) \tag{5.1}$$

Where $\{a_{n,k}\}$ is a complex sequence, $n\omega_{\Delta}$ $\{n = 0,1,......, N-1\}$ are carrier frequencies and they are equally spaced with ω_{Δ} . The window function w(t) has a length of T and it modifies the waveform of the multicarrier signal in each frame. The ICI for this multicarrier signal can be avoided if the window function w(t) and the carrier separation ω_{Δ} are correctly chosen. In order to provide a matched receiver for the transmitted signal, the window functions in both the transmitter and the receiver are selected to be equal. The ICI can be determined by examining the cross correlation between two carriers of the transmitted signals. For a complex sequence $\{a_{n,k}\}$, the condition for

The ICI is given by

$$a_{n,k} a_{m,k}^{*} \int_{-T/2}^{T/2} w^2(t) \exp(-jw_{\Delta}(n-m)t) dt = 0 \qquad for\ m \neq n \tag{5.2}$$

If the function $w^2(t)$ meets the Nyquist vestigial symmetry criterion, this condition will be satisfied. If T' is a time parameter and T/2 ≤ T' ≤ T . Then the window function w(t) which satisfies the Nyquist criterion will be described by

$$w^2(t) = \begin{cases} x(t) + y(t) & -T/2 \leq t \leq T/2 \\ 0 & otherwise \end{cases} \tag{5.3}$$

Here x(t) is a rectangular window function over [-T'/2 , T'/2] and y(t) is an even function with odd symmetry about –T'/2 and T'/2 . It is known that the raised cosine function satisfies the Nyquist criterion, and so this function can be considered as y(t) .

Here T is defined as T = T'(1+α) and α is the roll-off parameter of the raised cosine function. The ICI free condition requires the frequency separation between adjacent carriers to be

$$w_{\Delta} = \frac{2\pi(1+\alpha)}{T} \tag{5.4}$$

So, the total required bandwidth for N carriers is about $(1+\alpha)/T_S$ where T_S is the symbol interval of the input sequence and $T = NT_S$

Drawbacks:

It can only reduce 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. The above method cannot address to it.

Windowing is done frame by frame & hence it reduces the spectral efficiency to a large extent. Hence the method is not effective one.

5.3 PULSE SHAPING:

As we have seen in the OFDM spectrum that each carrier consist 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 exist a spectral null. That is at that point the component of all other carriers is zero. Hence the individual carrier is easily separated.

When there is a frequency offset the Orthogonality is lost because now the 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. Now the purpose of pulse shaping is to reduce the side lobes. If we can reduce the side lobe significantly then the ICI power will also be reduced significantly. Hence a number of pulse shaping functions are proposed having an aim to reduce the side lobe as much as possible.

The significant pulse shaping functions are

(a) Rectangular pulse (REC)

(b) Raised cosine pulse (RC)

(c) Better then raised cosine pulse (BTRC)

(d) Sinc power pulse (SP)

(e) Improved Sinc power pulse (ISP)

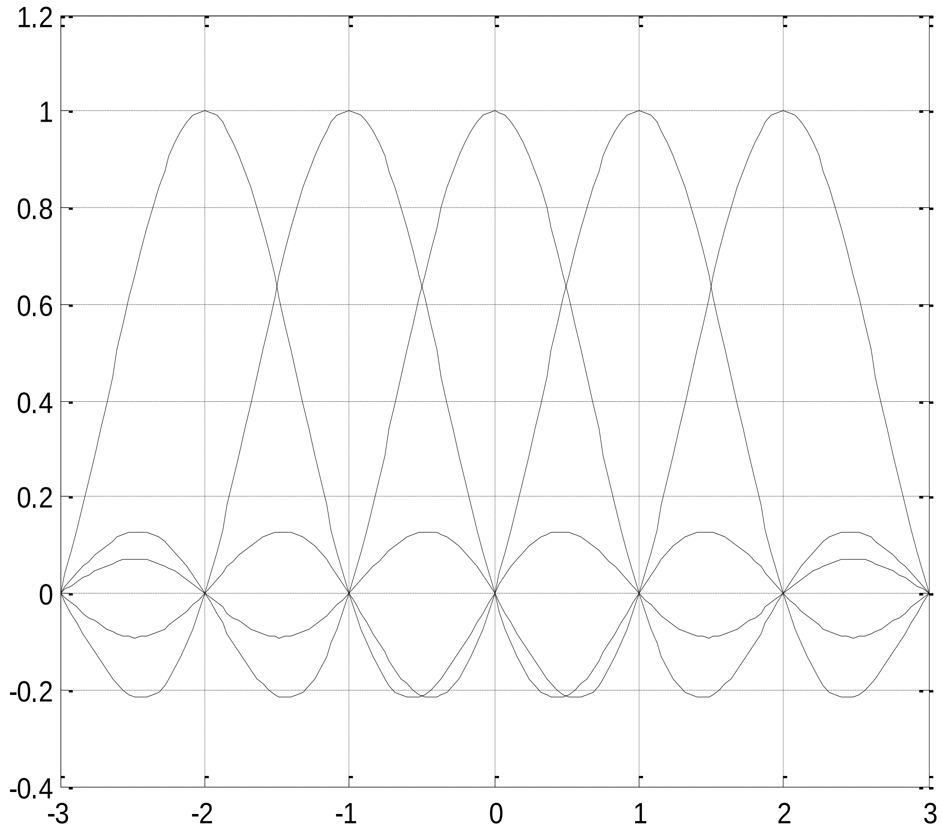


Figure 5.3: Sub-carrier Spacing in OFDM Signal.

5.4 MAXIMUM LIKELIHOOD ESTIMATION:

Another method for frequency offset correction i.e. ML estimation in OFDM systems was suggested by Moose. In this approach, the frequency offset is first statistically estimated using a maximum likelihood algorithm and then cancelled at the receiver. This technique involves the replication of an OFDM symbol before transmission and comparison of the phases of each of the subcarriers between the successive symbols.

When an OFDM symbol of sequence length N is replicated, the receiver receives, in the absence of noise, the $2N$ point sequence $r(n)$ is given by

$$r(n) = \frac{1}{N}\left[\sum_{k=-K}^{K} X(k)H(k)e^{j2\pi n(k+\varepsilon)/N}\right] \tag{5.5}$$

$$k = 0,1,2.........N-1, N \geq 2K+1$$

Where $X(k)$ are the $2k+1$ complex modulation values used to modulate $2k+1$ subcarriers, $H(k)$ is the channel transfer function for the kth carrier and ε is the normalized frequency offset of the channel. The first set of N symbols is demodulated using an N-point FFT to yield the sequence $R_1(k)$, and the second set is demodulated using another N-point FFT to yield the sequence $R_2(k)$. The frequency offset is the phase difference between $R_1(k)$ and $R_2(k)$, that is $R_2(k) = R_1(k)e^{j2\pi\varepsilon}$.

Adding the AWGN yields

$$
\begin{aligned}
&Y_1(k) = R_1(k) + W_1(k) \\
&Y_2(k) = R_1(k)e^{j2\pi\varepsilon} + W_2(k) \qquad (5.6) \\
&k = 0,1,2........N-1
\end{aligned}
$$

The maximum likelihood estimate of the normalized frequency offset is given by:

$$
\hat{\varepsilon} = \left(\frac{1}{2\pi}\right)\tan^{-1}\left\{\frac{\left(\sum_{k=-K}^{K} \mathrm{Im}\left[Y_2(k)Y_1^*(k)\right]\right)}{\left(\sum_{k=-K}^{K} \mathrm{Re}\left[Y_2(k)Y_1^*(k)\right]\right)}\right\} \qquad (5.7)
$$

This maximum likelihood estimate is a conditionally unbiased estimate of the frequency offset and was computed using the received data .Once the frequency offset is known, the ICI distortion in the data symbols is reduced by multiplying the received symbols with a complex conjugate of the frequency shift and applying the FFT,

$$
\hat{x}(n) = FFT\left\{ y(n)e^{-j\frac{2\pi n\varepsilon}{N}} \right\} \qquad (5.8)
$$

From below Figure 5.4, it can be seen that the results of the maximum likelihood estimation of the frequency offset are quite accurate over a varying range of SNR values.

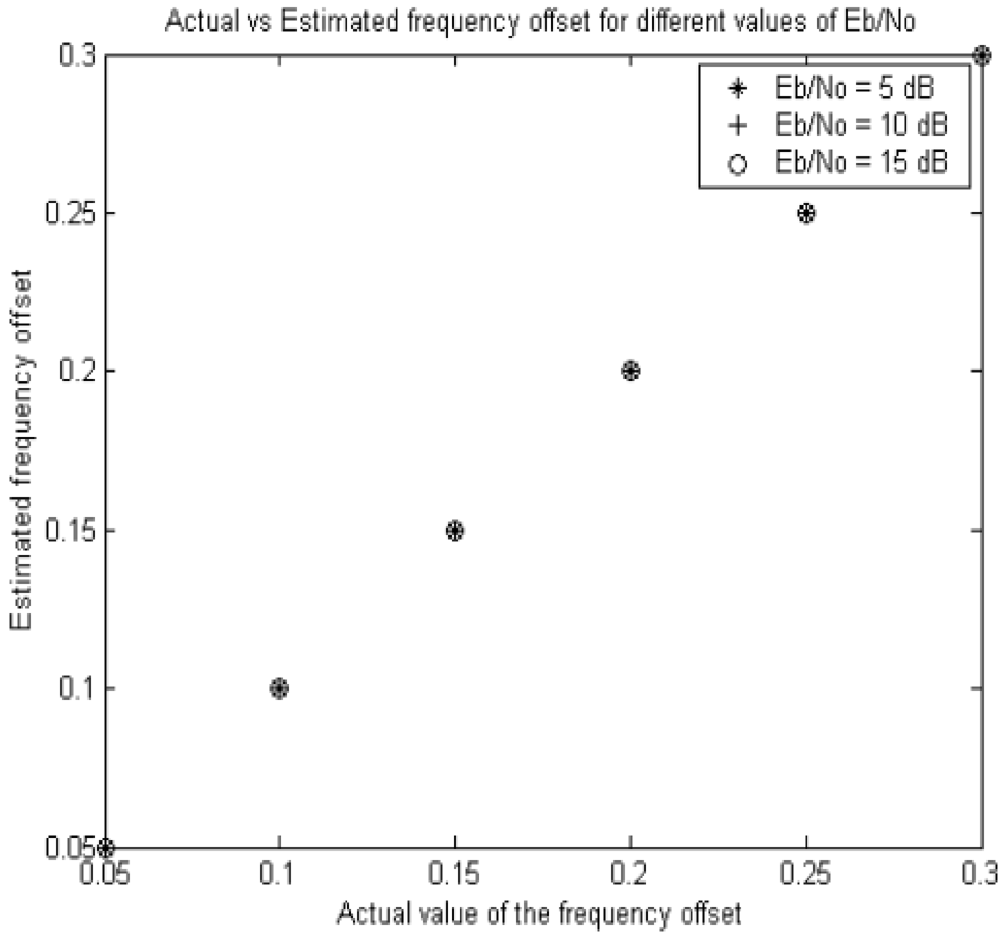


Figure 5.4: Actual vs. ML estimation of frequency offset for various values of Eb/No.

CHAPTER 6

WORK DONE

6.1 ICI SELF CANCELLATION SCHEME:

ICI self cancellation is a scheme that was introduced by Zhao and Sven-Gustav in 2001 to combat and suppress ICI in OFDM. Succinctly, the main idea is to modulate the input data symbol onto a group of subcarriers with predefined coefficients such that the generated ICI signals within that group cancel each other, hence the name self- cancellation. It is seen that the difference between the ICI co-efficient of two consecutive sub-carriers are 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. 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. This method is also suitable for flat channels. The method is simple, less complex & effective. The major drawback of this method is the reduction in band width efficiency as same symbol occupies two sub-carrier.

6.1.1 ICI Cancelling Modulation:

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

$$Y(k) = X(k)S(0) + \sum_{l=0, l\neq k}^{N-1} X(l)S(l-k) + n_k, \qquad k = 0,1,......, N-1 \tag{6.1}$$

Where N is the total number of the sub carriers, $X(k)$ denotes the transmitted symbol for the kth subcarrier and n_k is an additive noise sample. The first term in the right-hand side of (6.1) represents the desired signal. The second term is the ICI component. The sequence $S(l-k)$ is defined as the ICI coefficient between lth and kth subcarriers, which can be expressed as

$$S(l-k) = \frac{\sin(\pi(l+\varepsilon-k))}{N\sin\left(\frac{\pi}{N}(l+\varepsilon-k)\right)}.\exp\left(j\pi\left(1-\frac{1}{N}\right)(l+\varepsilon-k)\right) \tag{6.2}$$

It is seen that the difference of ICI coefficient between two consecutive subcarrier{(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 .

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

$$Y'(k) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[S(l-k) - S(l+1-k)] + n_k \tag{6.3}$$

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

$$Y'(k+1) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[S(l-k-1) - S(l-k)] + n_{k+1} \tag{6.4}$$

In such a case, the ICI coefficient is denoted as

$$S'(l-k) = S(l-k) - S(l+1-k) \tag{6.5}$$

It is found that $S'(l-k) << S(l-k)$, which is shown in figure 6.1.

6.1.2 ICI Cancelling Demodulation:

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*+1th 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

$$\begin{aligned} Y''(k) &= Y'(k) - Y'(k+1) \\ &= \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[-S(l-k-1) + 2S(l-k) - S(l-k+1)] + n_k - n_{k+1} \end{aligned} \tag{6.6}$$

The corresponding ICI coefficient then becomes

$$S''(l-k) = -S(l-k-1) + 2S(l-k) - S(l-k+1) \tag{6.7}$$

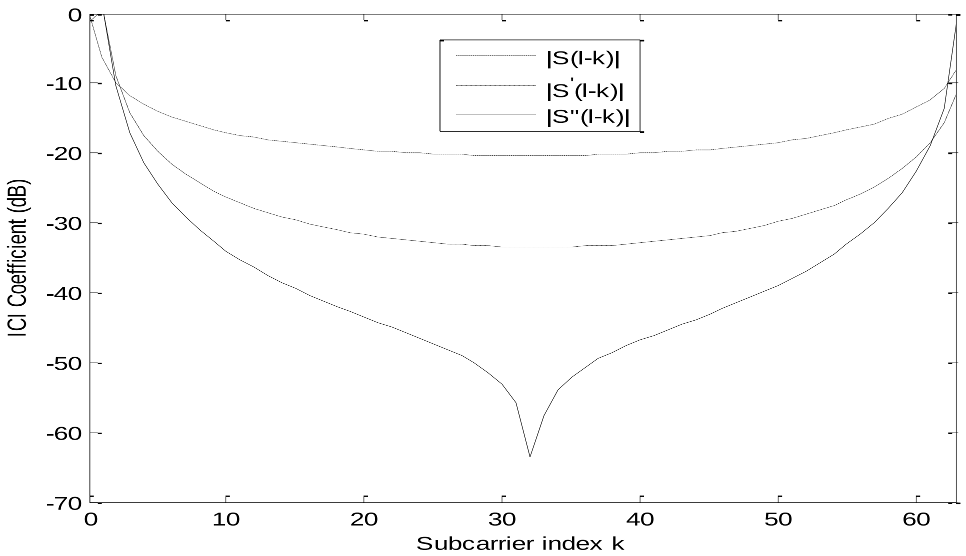


Fig. 6.1 Comparison between $|S(l-k)|$, $|S'(l-k)|$ and $|S''(l-k)|$

Figure 6.1 shows the amplitude comparison of $|S(l-k)|$, $|S'(l-k)|$ and $|S''(l-k)|$ for N = 64 and ε = 0.3. For the majority of (*l-k*) values, $|S'(l-k)|$ is much smaller than $|S(l-k)|$, and the $|S''(l-k)|$ is even smaller than $|S'(l-k)|$.

Thus, the ICI signals become smaller when applying ICI cancelling modulation. On the other hand, the ICI cancelling demodulation can further reduce the residual ICI in the received signals. This combined ICI cancelling modulation and demodulation method is called the ICI self-cancellation scheme. Until now, three types of ICI coefficients are obtained: 1) $S(l-k)$ for the standard OFDM system 2) $S'(l-k)$ for ICI cancelling modulation and 3) $S''(l-k)$ for combined ICI cancelling modulation and demodulation.

On the other hand, the ICI cancelling demodulation can further reduce the residual ICI in the received signals. This combined ICI cancelling modulation and demodulation method is called the ICI self-cancellation scheme. It is worth mentioning that the proposed ICI cancelling demodulation also improves the system signal-to-noise ratio. The signal level increases by a factor of 2, due to coherent addition, whereas the noise level is proportional to $\sqrt{2}$ because of non coherent addition of the noise on different subcarriers. Using ICI coefficient given by (6.7), the theoretical CIR of the ICI self-cancellation scheme can be derived as

$$CIR = \frac{\left|-S(-1)+2S(0)-S(1)\right|^2}{\sum_{l=2,4,6,\ldots}^{N-1}\left|-S(l-1)+2S(l)-S(l+1)\right|^2} \tag{6.8}$$

Figure 6.2 shows the theoretical CIR curve calculated by above CIR equation together with simulation results. As a reference, the CIR of a standard OFDM system is also shown. Such an ICI cancellation scheme gives more than 15-dB CIR improvement in the range $0 \leq \varepsilon \leq 0.5$. Especially for small to medium frequency offsets in the range $0 \leq \varepsilon \leq 0.2$, the CIR improvement can reach 17 dB.

Due to the repetition coding, the bandwidth efficiency of the ICI self-cancellation scheme is reduced by half. To fulfill the demanded bandwidth efficiency, it is natural to use a larger signal alphabet size. For example, using 4PSK modulation together with the ICI self-cancellation scheme can provide the same bandwidth efficiency as standard OFDM systems (1 bit/Hz/s). When the channel frequency offset is small, the use of a larger signal alphabet size might increase the system bit-error rate (BER) compared to a smaller alphabet size. However, for medium to large channel frequency offsets ($\varepsilon \geq 0.05$) significant BER improvement is obtained by using ICI self cancellation scheme. Figure 6.3 shows CIR improvement for different group lengths.

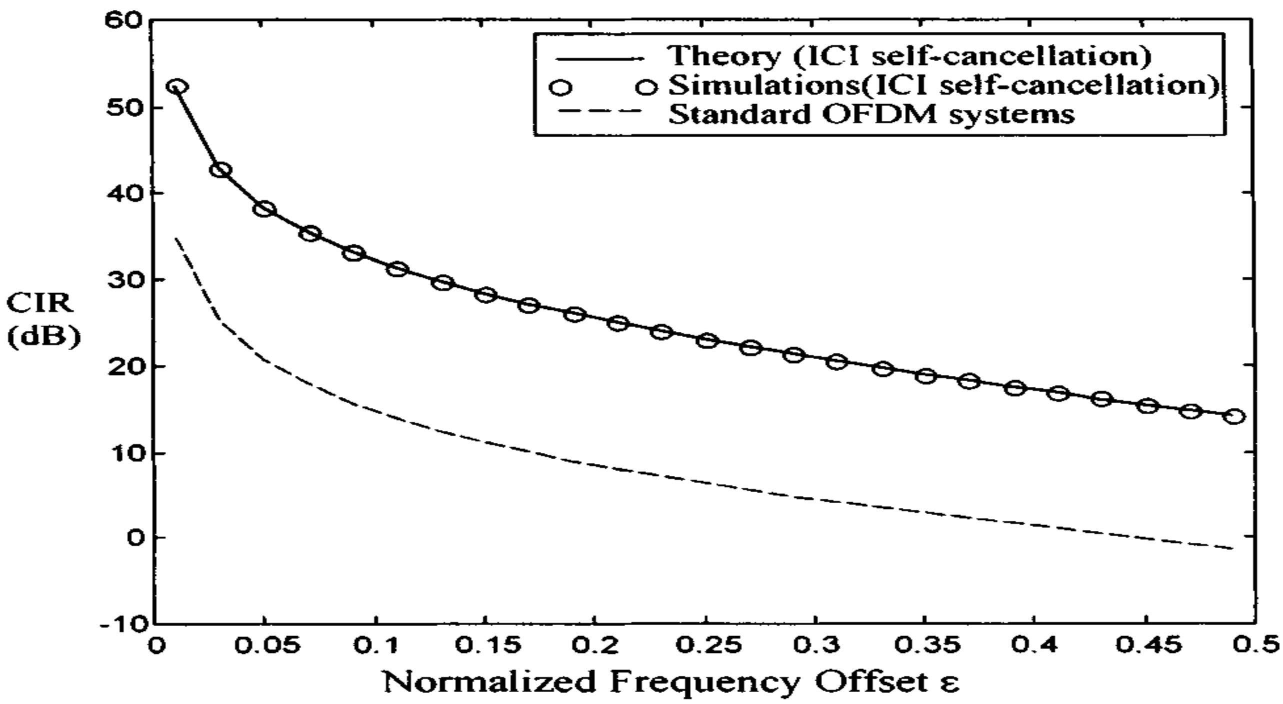


Figure 6.2: CIR improvement using ICI self-cancellation scheme.

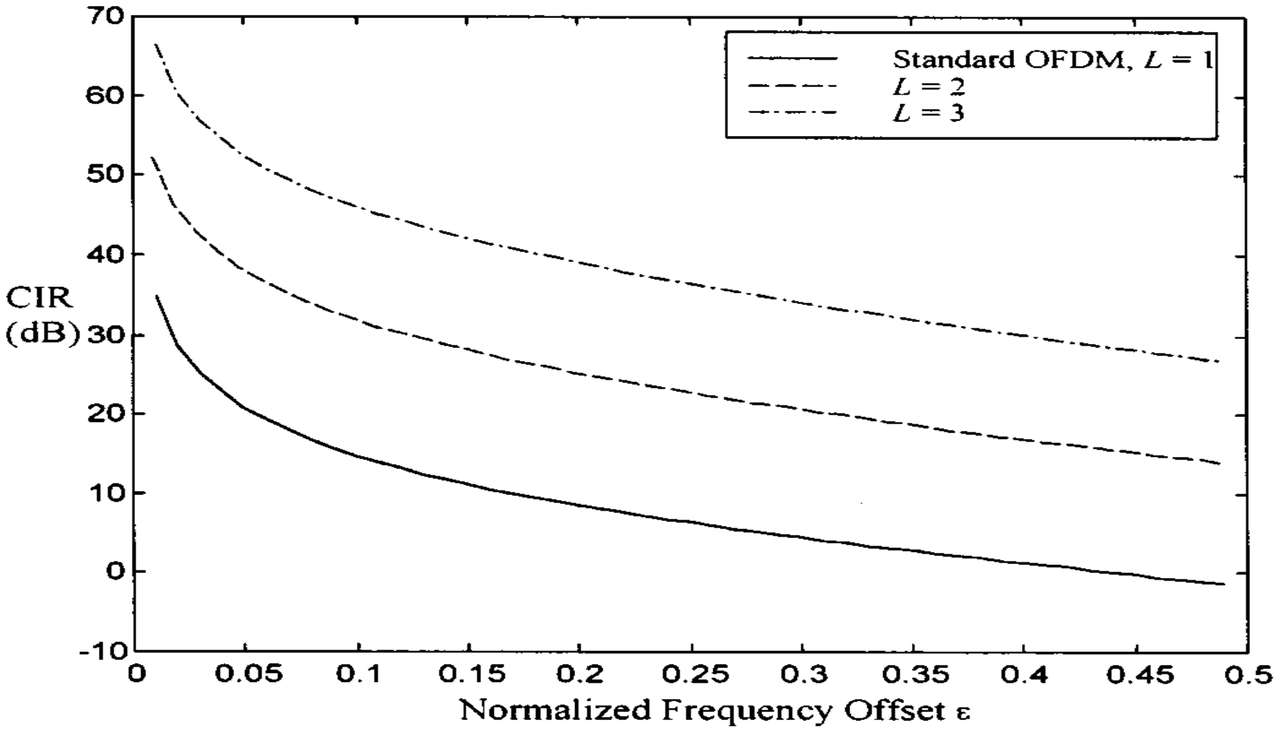


Figure 6.3: CIR improvement for different group lengths.

6.2 EXTENDED KALMAN FILTER:

Kalman filters are common in communications and signal processing literature. The Kalman filter is a remarkably versatile and powerful recursive estimation algorithm that has found various applications in communications, such as adaptive equalization of telephone channels, adaptive equalization of fading dispersive channels, and adaptive antenna arrays. As a recursive filter, it is particularly applicable to non-stationary processes such as signals transmitted in a time-variant radio channel. In estimating non-stationary processes, the Kalman filter computes estimates of its own performance as part of the recursion and use this information to update the estimate at each step. Therefore, the estimation procedure is adjusted to the time-variant statistical characteristics of the random process.

6.2.1 Problem Formulation:

A state-space model of the discrete Kalman filter is defined as

$$z(n) = a(n)d(n) + v(n) \tag{6.9}$$

In this model, the observation $z(n)$ has a linear relationship with the desired value $d(n)$. By using the discrete Kalman filter, $d(n)$ can be recursively estimated based on the observation of $z(n)$ and the updated estimation in each recursion is optimum in the minimum mean square sense. The received symbols are

$$y(n) = x(n)e^{j\frac{2\pi n'\varepsilon(n)}{N}} + w(n) \tag{6.10}$$

It is obvious that the observation $y(n)$ is in a nonlinear relationship with the desired value $\varepsilon(n)$, i.e.

$$y(n) = f(\varepsilon(n)) + w(n) \tag{6.11}$$

Where

$$f(\varepsilon(n)) = x(n)e^{j\frac{2\pi n'\varepsilon(n)}{N}} \tag{6.12}$$

In order to estimate $\varepsilon(n)$ efficiently in computation, we build an approximate linear relationship using the first-order Taylor's expansion:

$$y(n) \approx f(\hat{\varepsilon}(n-1)) + f'(\hat{\varepsilon}(n-1))\left[\varepsilon(n) - \hat{\varepsilon}(n-1)\right] + w(n) \tag{6.13}$$

Where $\hat{\varepsilon}(n-1)$ is the estimation of $\varepsilon(n-1)$

$$f'(\hat{\varepsilon}(n-1)) = \frac{\partial f(\varepsilon(n))}{\partial(\varepsilon(n))}\bigg|_{\varepsilon(n) = \hat{\varepsilon}(n-1)} = j\frac{2\pi n'}{N}x(n)e^{j\frac{2\pi n'\hat{\varepsilon}(n-1)}{N}} \tag{6.14}$$

Define

$$\begin{aligned} z(n) &= y(n) - f(\hat{\varepsilon}(n-1)) \\ d(n) &= \varepsilon(n) - \hat{\varepsilon}(n-1) \end{aligned} \tag{6.15}$$

and the following relationship:

$$z(n) = f'(\varepsilon(n-1))d(n) + w(n) \tag{6.16}$$

Which has the same form as (6.9), i.e., $z(n)$ is linearly related to $d(n)$. Hence the normalized frequency offset $\varepsilon(n)$ can be estimated in a recursive procedure similar to the discrete Kalman filter. As linear approximation is involved in the derivation, the filter is called the extended Kalman filter (EKF). The derivation of the EKF is omitted in this report for the sake of brevity. The EKF provides a trajectory of estimation for $\varepsilon(n)$. The error in each update decreases and the estimate becomes closer to the ideal value during iterations. It is noted that the actual error in each recursion between $\varepsilon(n)$ and $\hat{\varepsilon}(n)$ does not strictly obey above (6.16). Thus there is no guarantee of optimal MMSE estimates in the EKF scheme. However it has been proven that EKF is a very useful method of obtaining good estimates of the system state. Hence this has motivated us to explore the performance of EKF in ICI cancellation in an OFDM system.

6.2.2 Assumptions:

In the following estimation using the EKF, it is assumed that the channel is slowly time varying so that the time-variant channel impulse response can be approximated to be quasi-static during the transmission of one OFDM frame. Hence the frequency offset is considered to be constant during a frame. The preamble preceding each frame can thus be utilized as a training sequence for estimation of the frequency offset imposed on the symbols in this frame. Furthermore, in our estimation, the channel is assumed to be flat-fading and ideal channel estimation is available at the receiver. Therefore in our derivation and simulation, the one-tap equalization is temporarily suppressed.

6.2.3 ICI Cancellation:

There are two stages in the EKF scheme to mitigate the ICI effect: the offset estimation scheme and the offset correction scheme.

6.2.3.1 Offset Estimation Scheme:

To estimate the quantity $\varepsilon(n)$ using an EKF in each OFDM frame, the state equation is built as

$$\varepsilon(n) = \varepsilon(n-1) \tag{6.17}$$

i.e., in this case we are estimating an unknown constant ε. This constant is distorted by a non-stationary process $x(n)$, an observation of which is the preamble symbols preceding the data symbols in the frame. The observation equation is

$$y(n) = x(n)e^{j\frac{2\pi n'\varepsilon(n)}{N}} + w(n) \tag{6.18}$$

where $y(n)$ denotes the received preamble symbols distorted in the channel, $w(n)$ the AWGN, and $x(n)$ the IFFT of the preambles $X(k)$ that are transmitted, which are known at the receiver. Assume there are N_p preambles preceding the data symbols in each frame are used as a training sequence and the variance σ^2 the AWGN $w(n)$ is stationary. The computation procedure is described as follows.

1.Initialize the estimate $\hat{\varepsilon}(0)$ and corresponding state error $P(0)$.

2.Compute then $H(n)$, the derivative of $y(n)$ with respect to $\varepsilon(n)$ at $\hat{\varepsilon}(n-1)$, the estimate obtained in the previous iteration.

3.Compute the time-varying Kalman gain $K(n)$ using the error variance $P(n-1)$, $H(n)$, and σ^2.

4.Compute the estimate $\hat{y}(n)$ using $x(n)$ and $\hat{\varepsilon}(n-1)$, i.e. based on the observations up to time $n-1$, Compute the error between the true observation $y(n)$ and $\hat{y}(n)$.

5.Update the estimate $\hat{\varepsilon}(n)$ by adding the $K(n)$-weighted error between the observation $y(n)$ and $\hat{y}(n)$ to the previous estimation $\hat{\varepsilon}(n-1)$.

6.Compute the state error $P(n)$ with the Kalman gain $K(n)$, $H(n)$, and the previous error $P(n-1)$.

7.If n is less than N_p, increment n by 1 and go to step 2; otherwise stop.

It is observed that the actual errors of the estimation $\hat{\varepsilon}(n)$ from the ideal value $\varepsilon(n)$ are computed in each step and are used for adjustment of estimation in the next step.

The pseudo code of computation is summarized in Figure 6.4.

Initialize $P(n)$, $\hat{\varepsilon}(0)$.

For n=1,2,…….. N_p Compute

$$H(n) = \left.\frac{\partial y(x)}{\partial x}\right|_{x=\hat{\varepsilon}(n)} = j\frac{2\pi n'}{N} e^{j\frac{2\pi n'\hat{\varepsilon}(n-1)}{N}} x(n)$$

$$K(n) = P(n-1)H^{*}(n)\left[P(n-1)+\sigma^{2}\right]^{-1}$$

$$\hat{\varepsilon}(n) = \hat{\varepsilon}(n-1) + \mathrm{Re}\left\{K(n)\left[y(n) - x(n)e^{j\frac{2\pi n'\hat{\varepsilon}(n-1)}{N}}\right]\right\}$$

$$P(n) = \left[1 - K(n)H(n)\right]P(n-1)$$

Figure 6.4: Pseudo Code for EKF.

Through the recursive iteration procedure described above, an estimate of the frequency offset $\hat{\varepsilon}$ can be obtained. Figure 6.5 shows the estimates for various normalized frequency offsets ε. It is observed that the EKF technique offers fast convergence.

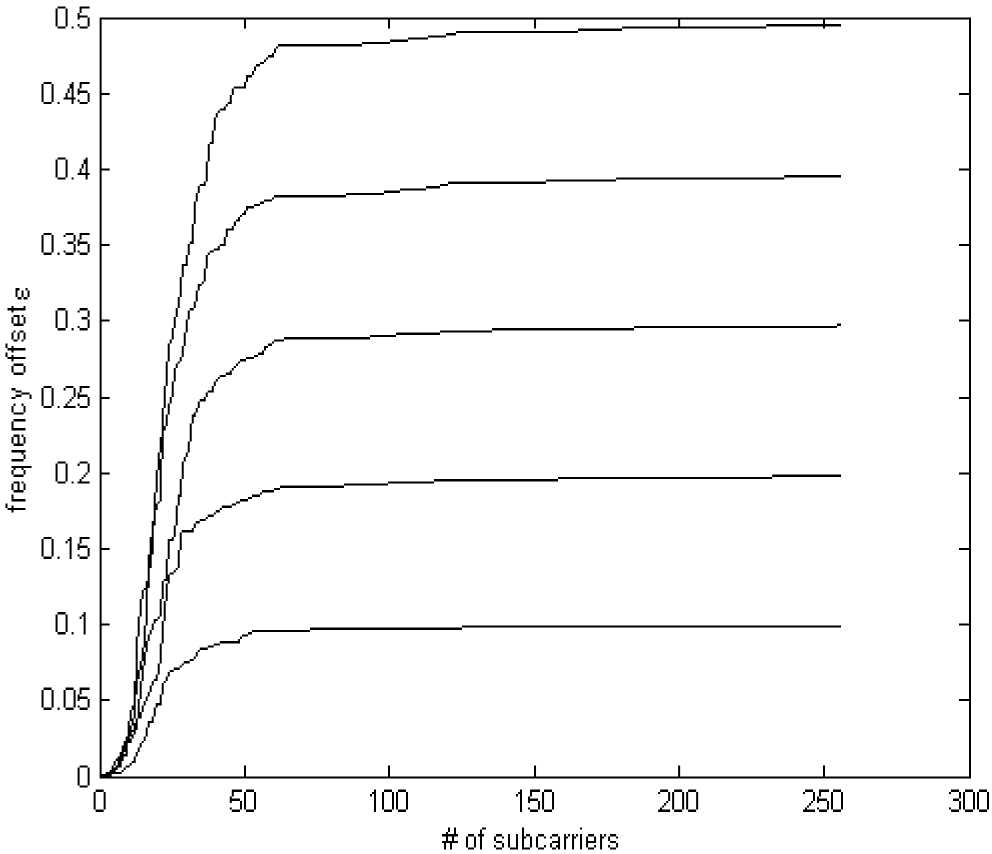


Figure 6.5: Recursive estimation of the normalized frequency offset ε, SNR = 20 dB.

6.2.3.2 Offset Correction Scheme:

The ICI distortion in the data symbols $x(n)$ that follow the training sequence can then be mitigated by multiplying the received data symbols $y(n)$ with a complex conjugate of the estimated frequency offset and applying FFT, i.e.

$$\hat{x}(n) = FFT\left\{ y(n)e^{-j\frac{2\pi n'\hat{\varepsilon}}{N}} \right\} \tag{6.19}$$

As the estimation of the frequency offset by the EKF scheme is pretty efficient and accurate, it is expected that the performance will be mainly influenced by the variation of the AWGN.

6.3 SIMULATION RESULTS AND COMPARISON:

Standard OFDM and ICI self cancellation methods:

Table 6.1:

Parameter	**Specifications**
FFT Size	64
Number of Carriers in OFDM symbol	52
Channel	AWGN
Doppler Shift	0, 0.05,0.15,0.2
Guard Length	12
Signal Constellation	BPSK,QPSK
OFDM symbols for one loop	1000

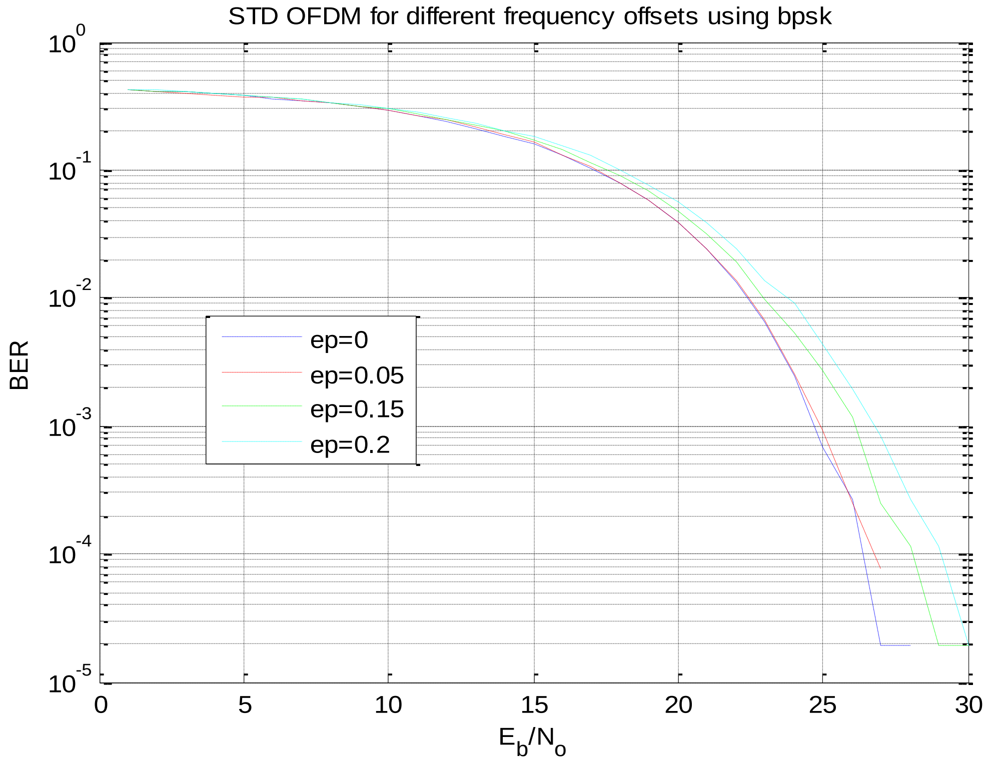
Extended Kalman Filter method:

Table 6.2:

Parameter	**Specifications**
FFT size	64
Preamble size	256
Sub carriers size	512
Signal Constellation	BPSK,QPSK
Number of OFDM frames	256

In order to compare the two different cancellation schemes, BER curves were used to evaluate the performance of each scheme. For the simulations in this project, MATLAB was employed with its Communications Toolbox for all data runs. The OFDM transceiver system was implemented as specified by Figure 2.1. Frequency offset was introduced as the phase rotation as given by (4.1). Modulation schemes of binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) were chosen as they are used in many standards such as 802.11a. Simulations for cases of normalized frequency offsets equal to 0, 0.05, 0.15, and 0.20 are given in Figure 6.6, 6.7.

From below figure 6.6 BER of Standard OFDM for different frequency offsets using bpsk is better than of standard OFDM for different frequency offsets using qpsk. Also when using higher modulation schemes BER is not improved as compared to lower modulation schemes. From below figure 6.7 BER of standard OFDM with ICI self cancellation using bpsk is better than BER of standard OFDM with ICI self cancellation using qpsk. ICI self cancellation scheme is used for lower frequency offset values and lower modulation schemes like bpsk.BER stands for bit error rate. As frequency offset increases BER will become more and for higher frequency offsets BER performance is very poor. Also here by using kalman filter method for higher frequency offsets ICI is completely removed as compared to ICI self cancellation method. In ICI self cancellation method ICI is not completely eliminated and there is some residual ICI in OFDM symbol.



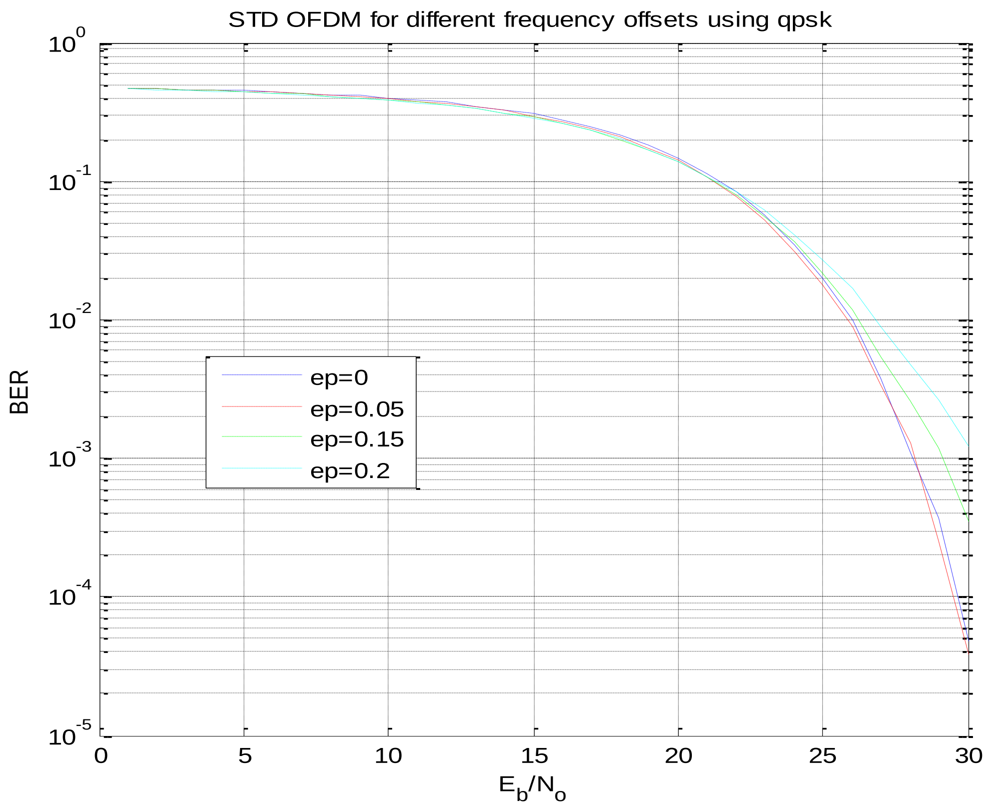
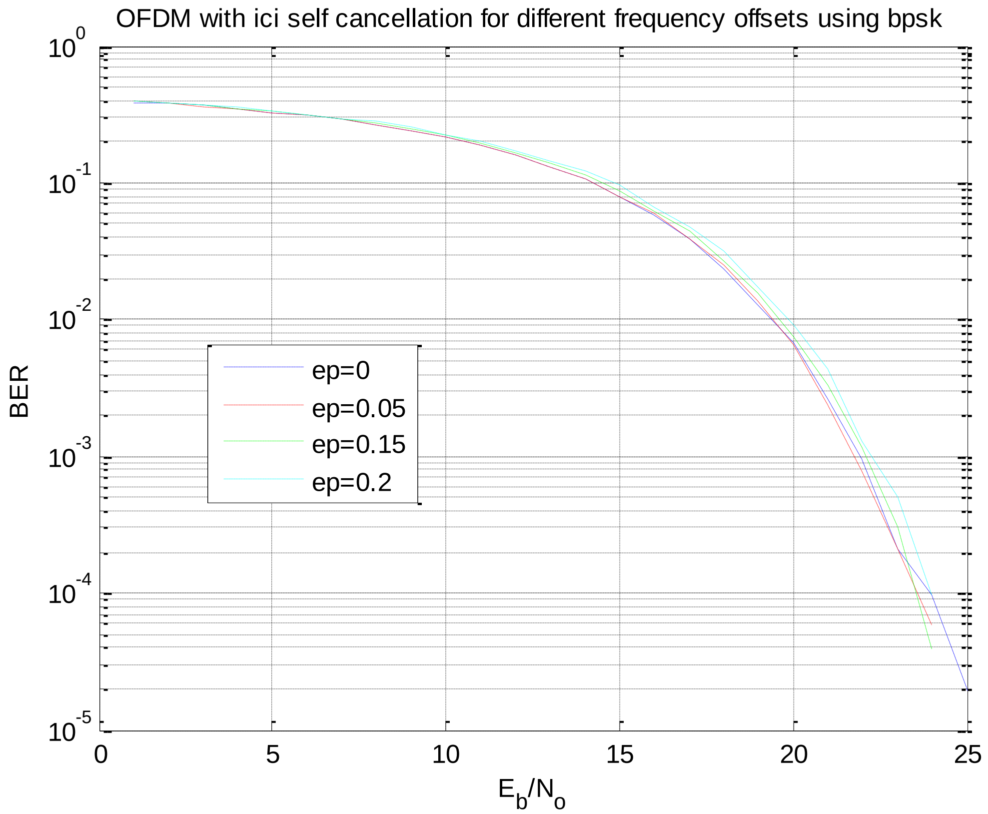


Figure 6.6: BER performance of a standard OFDM system without ICI cancellation.



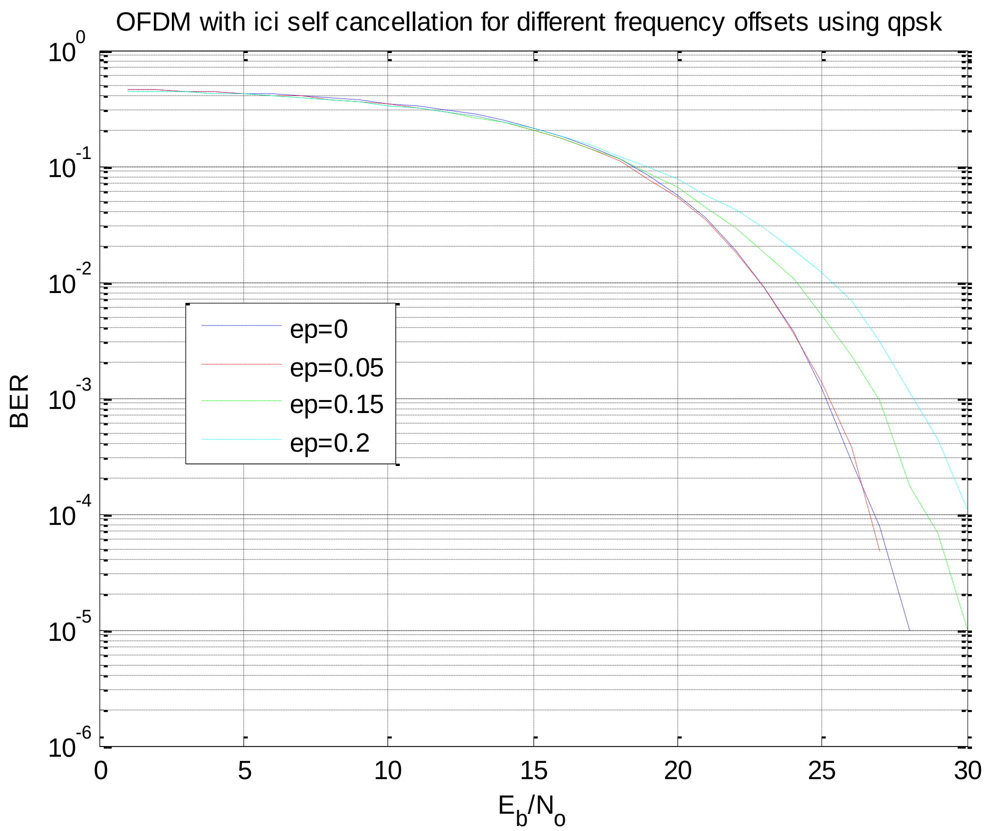
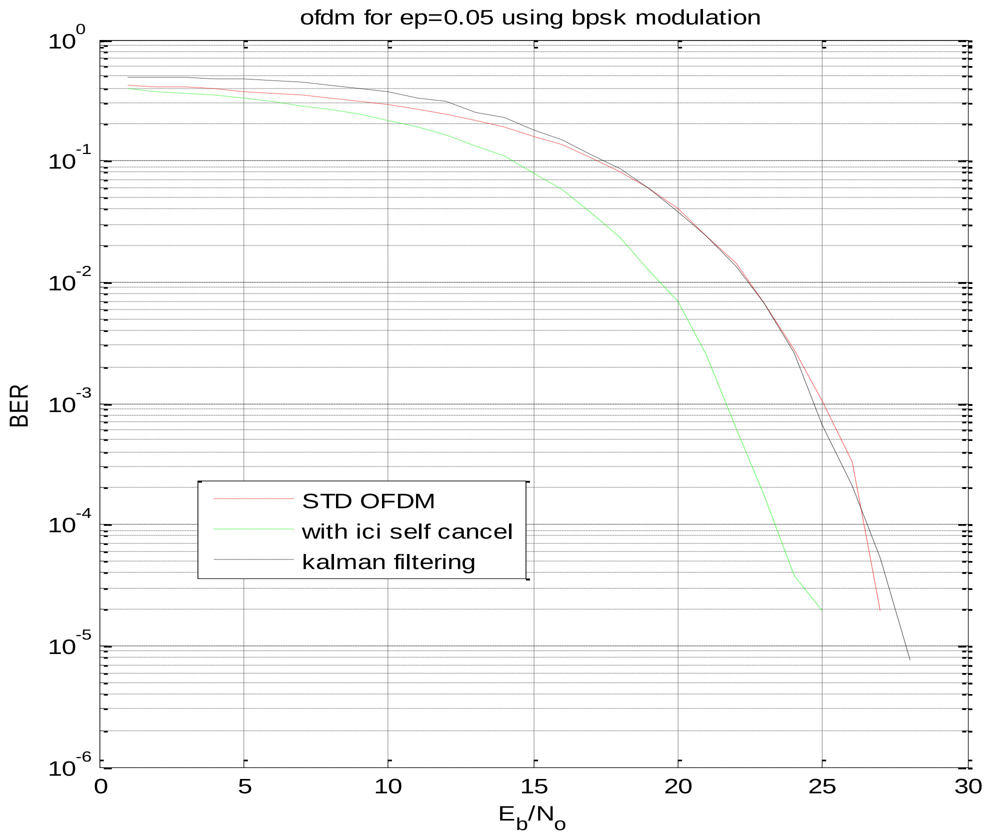


Figure 6.7: BER performance of a standard OFDM system with ICI cancellation.

These results show that degradation of performance increases with frequency offset. For the case of BPSK, even severe frequency offset of 0.30 does not deteriorate the performance too greatly. However, for QPSK with an alphabet of size 2, performance degrades more quickly. When frequency offset is small, the QPSK system has a lower BER than the BPSK system. But the BER of QPSK varies more dramatically with the increase the frequency offset than that of BPSK. Therefore it is concluded that larger alphabet sizes are more sensitive to ICI. Figures 6.8-6.10 provide comparisons of the performance of the SC, and EKF schemes for different alphabet sizes and different values of the frequency offset.



From below figure 6.8 BER of OFDM for ε=0.05 using bpsk, ICI self cancellation has better BER than kalman filter better than standard OFDM. Also BER of OFDM for ε=0.05 using qpsk, kalman filter has better BER than ICI self cancellation better than standard OFDM. From below figure 6.9 BER of OFDM for ε=0.15 using qpsk, kalman filter is better than ICI self cancellation which is better than standard OFDM. BER of OFDM for ε=0.15 using bpsk, ICI self cancellation is better than kalman filter which is better than standard OFDM. From below figure 6.10 BER of OFDM for ε=0.3 using qpsk, kalman filter is better than both ICI self cancellation and standard OFDM. BER of OFDM for ε=0.3 using bpsk, ICI self cancellation is better than kalman filter which is better than standard OFDM.

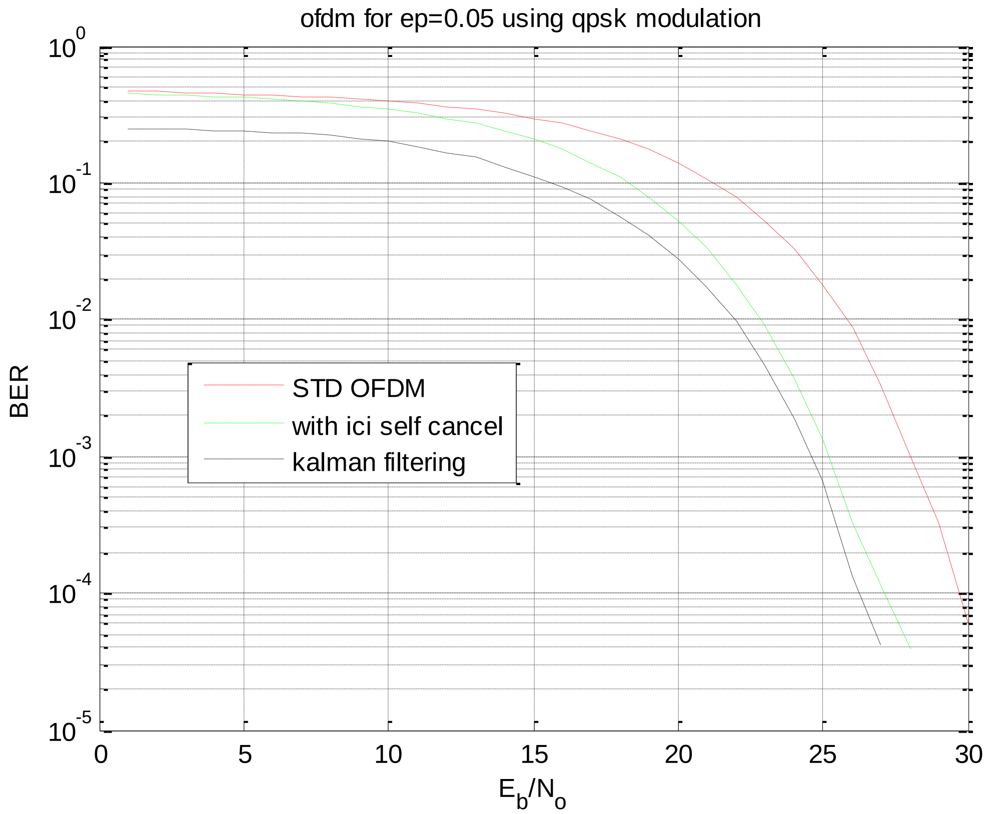
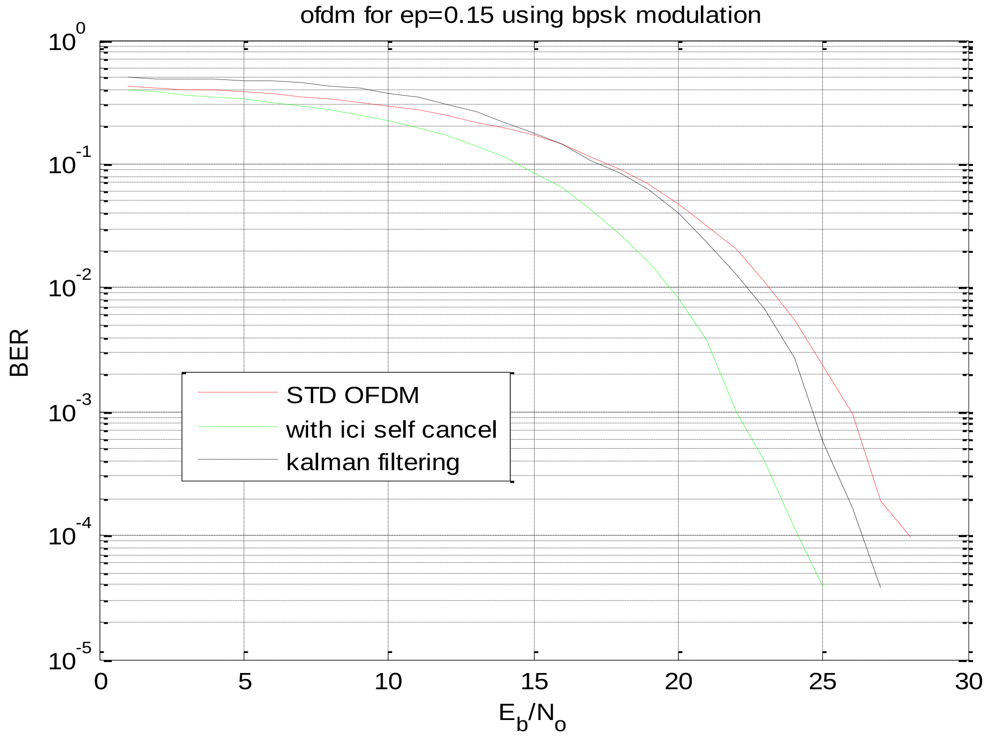


Figure 6.8: BER Performance with ICI Cancellation, ε=0.05.

It is observed in the figures that each method has its own advantages. In the presence of small frequency offset and binary alphabet size, self cancellation gives the best results. However, for larger alphabet sizes and larger frequency offset such as QPSK and frequency offset of 0.30, self cancellation does not offer much increase in performance. The Kalman filter method indicates that for very small frequency offset, it does not perform very well, as it hardly improves BER.

However, for high frequency offset the Kalman filter does perform extremely well. It gives a significant boost to performance. Significant gains in performance can be achieved using the EKF method for a large frequency offset. For small alphabet sizes (BPSK) and for low frequency offset values, the SC technique has good performance in terms of BER. However, for higher order modulation schemes, the EKF method performs better. This is attributed to the fact that EKF method estimate the frequency offset very accurately and cancel the offset using this estimated value. However, the self-cancellation technique does not completely cancel the ICI from adjacent sub-carriers, and the effect of this residual ICI increases for larger alphabet sizes and offset values.



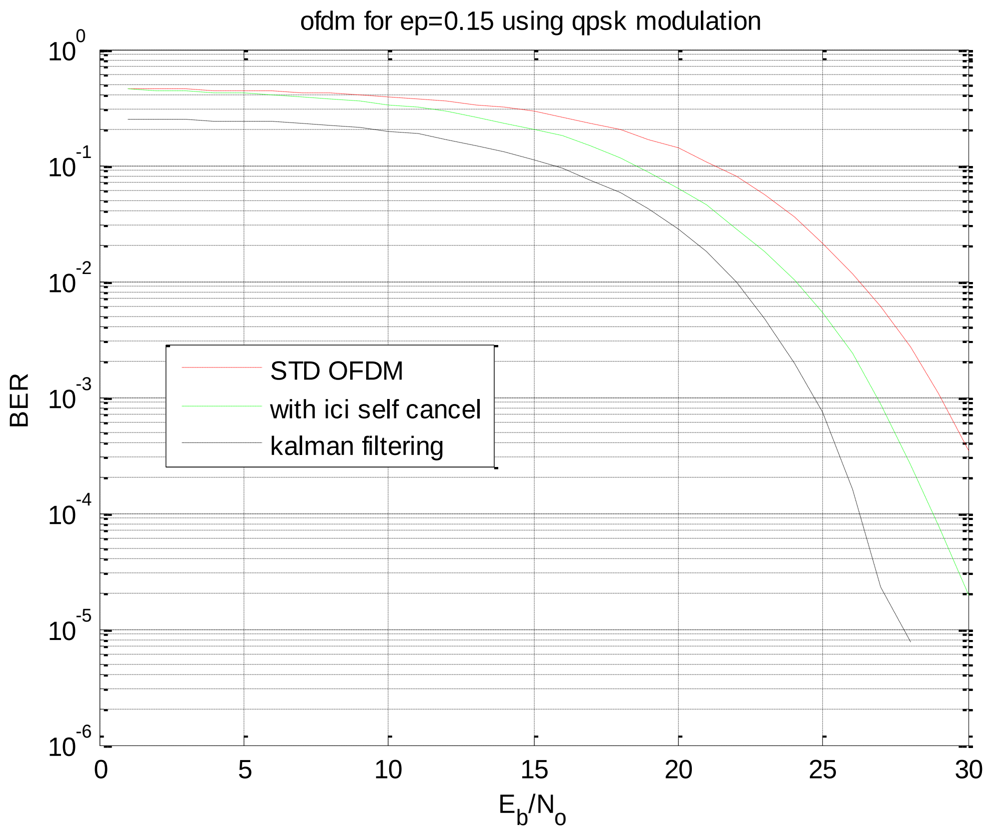
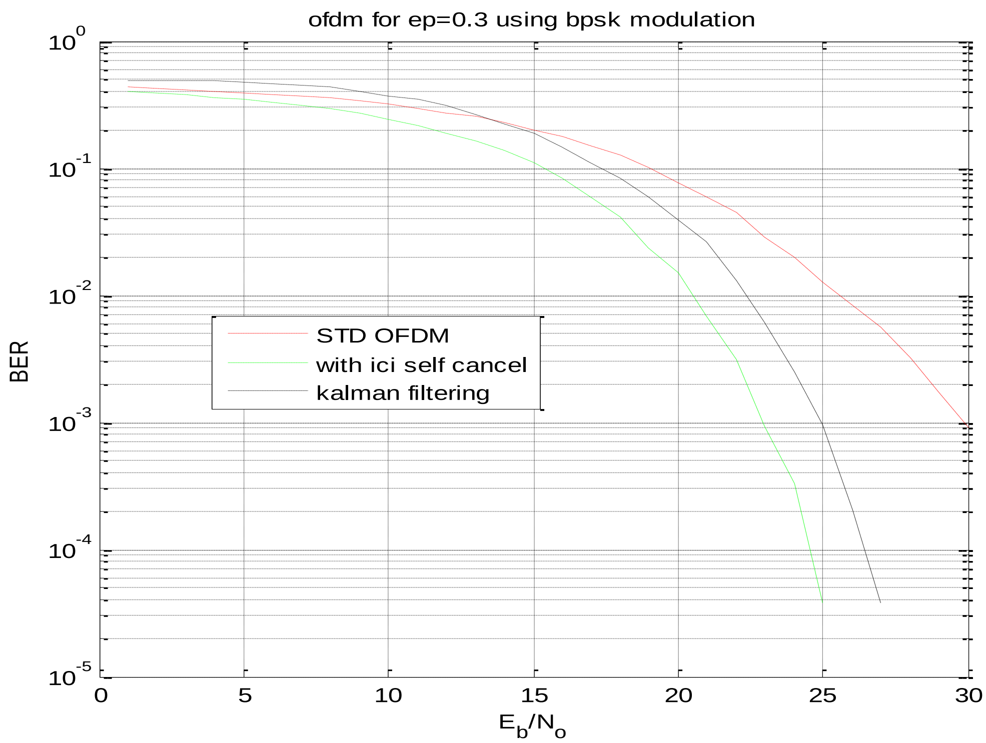


Figure 6.9: BER Performance with ICI Cancellation, ε=0.15.



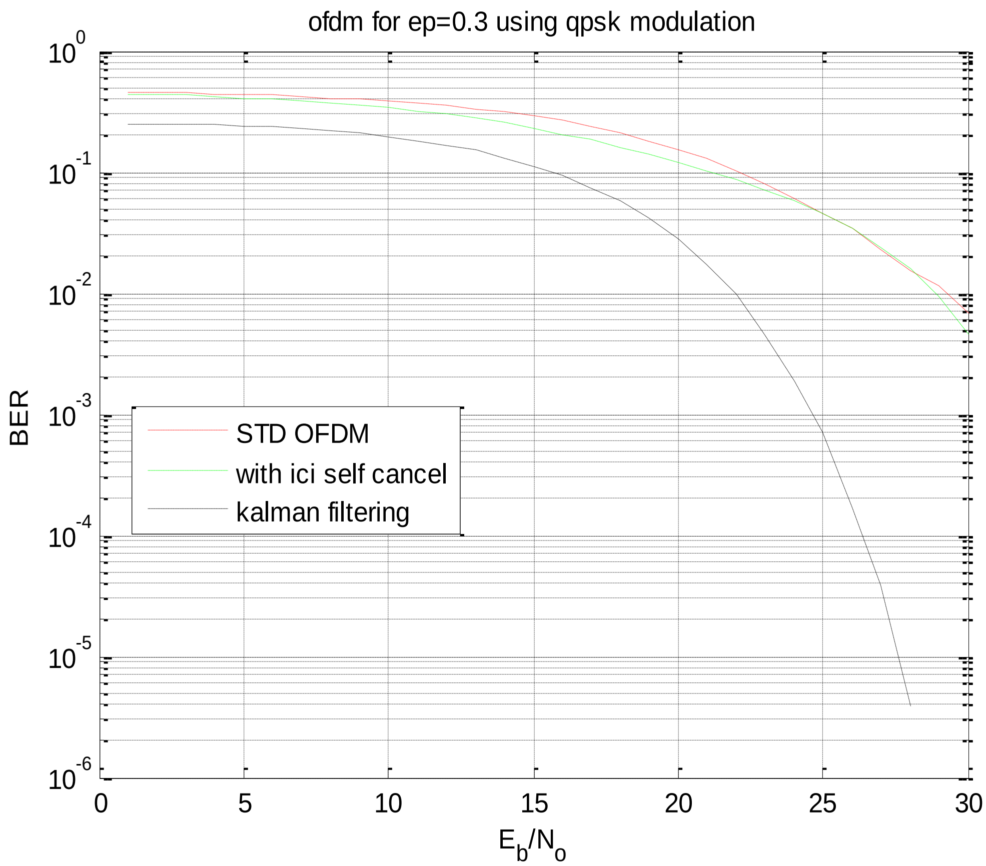


Figure 6.10: BER Performance with ICI Cancellation, ε=0.30.

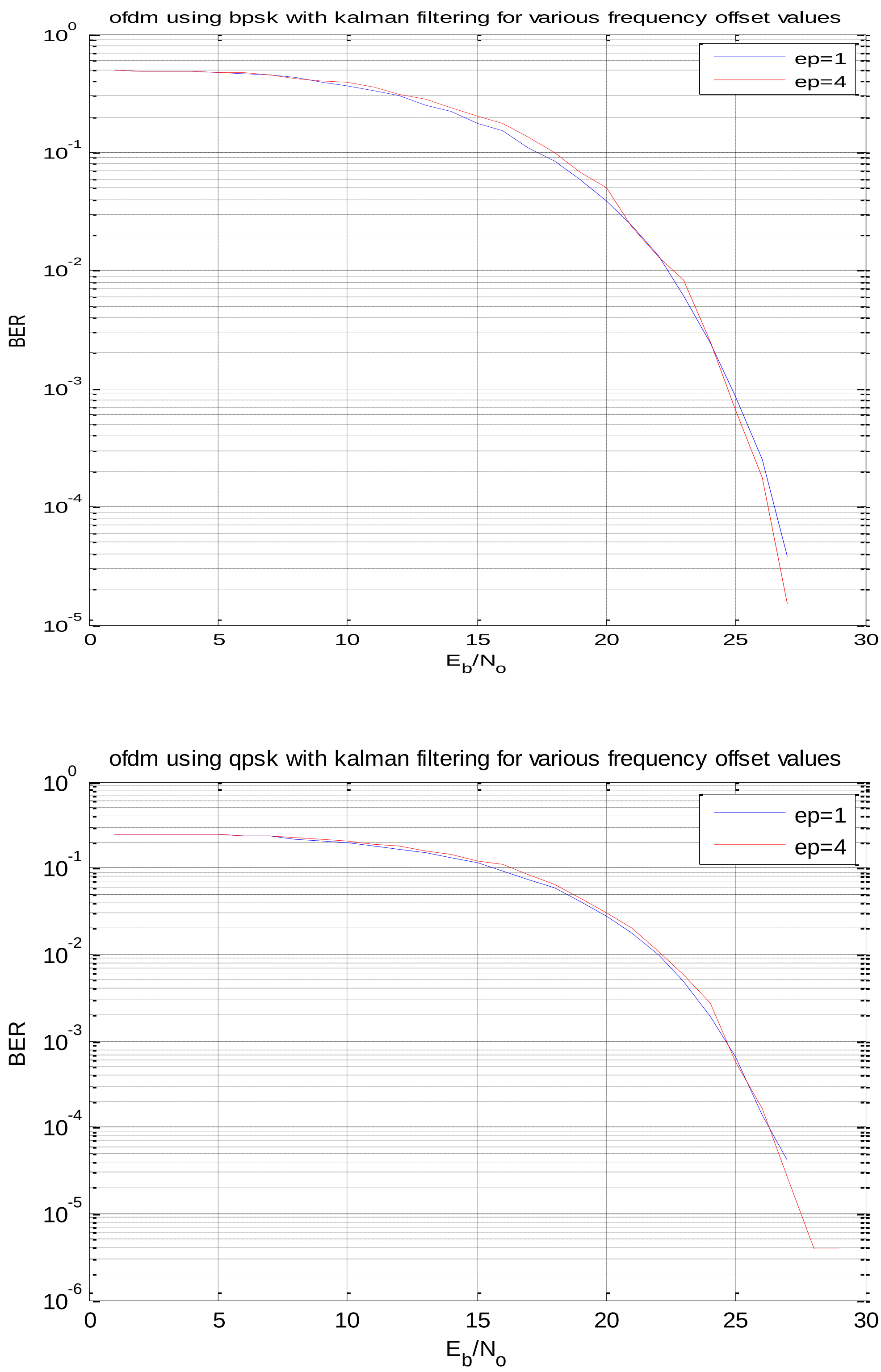


Figure 6.11: BER Performance with Kalman filter method ε=1and ε =4.

From above figure 6.11 for higher frequency offset values like ε=1and ε =4 BER performance of extended kalman filter is better for both bpsk and qpsk.

CHAPTER 7

CONCLUSION

7.1 CONCLUSION:

In this project, the performance of OFDM systems in the presence of frequency offset between the transmitter and the receiver has been studied in terms of the Carrier-to-Interference ratio (CIR) and the bit error rate (BER) performance. Inter-carrier interference (ICI) which results from the frequency offset degrades the performance of the OFDM system. Two methods were explored in this project for mitigation of the ICI. The ICI self-cancellation (SC) is proposed .

The extended Kalman filter (EKF) method for estimation and cancellation of the frequency offset has been investigated in this project, and comparison is made with these two existing techniques. The choice of which method to employ depends on the specific application. For example, self cancellation does not require very complex hardware or software for implementation. However, it is not bandwidth efficient as there is a redundancy of 2 for each carrier. The ML method also introduces the same level of redundancy but provides better BER performance, since it accurately estimates the frequency offset. Its implementation is more complex than the SC method. On the other hand, the EKF method does not reduce bandwidth efficiency as the frequency offset can be estimated from the preamble of the data sequence in each OFDM frame.

However, it has the most complex implementation of the two methods. In addition, this method requires a training sequence to be sent before the data symbols for estimation of the frequency offset. It can be adopted for the receiver design for IEEE 802.11a because this standard specifies preambles for every OFDM frame. The preambles are used as the training sequence for estimation of the frequency offset. In this project, the simulations were performed in an AWGN channel. This model can be easily adapted to a flat-fading channel with perfect channel estimation. Further work can be done by performing simulations to investigate the performance of these ICI cancellation schemes in multipath fading channels without perfect channel information at the receiver. In this case, the multipath fading may hamper the performance of these ICI cancellation schemes.

7.2 SCOPE OF FUTURE WORK:

Following are the areas of future study which can be considered for further research work.

1.In this work the BER performance of the OFDM system is evaluated considering BPSK and QPSK Modulation system. It can be tested with other modulation systems such as QAM and GMSK. ICI reduction using self cancellation technique can be used for COFDM (Coded OFDM) Systems.

2. This self cancellation technique and Extended Kalman filter method can also be applied under different channel conditions such as Rayleigh fading channel, urban area channel, rural area channel etc.

3. This self cancellation scheme can be extended to MIMO-OFDM systems and a Bayesian State–space approach (SIS) to combat inter-carrier interference in OFDM systems can be used.

4. The sequential Monte Carlo (SMC) method called sequential importance sampling (SIS) can be implemented which requires very lower computational complexity and estimates accurately high value frequency offsets. However, the SIS performs slightly better, which is expected due to the nonlinearity of the state–space and it is bandwidth efficiency scheme.

CHAPTER 8

REFERENCES

[1] J. Armstrong, “Analysis of new and existing methods of reducing inter carrier Interference due to carrier frequency offset in OFDM,” IEEE *Trans. Commun*., vol. 47, No. 3, pp. 365–369, Mar. 1999.

[2] P. H. Moose, A technique for orthogonal frequency division multiplexing frequency offset correction, *IEEE Trans. Commun*., vol. 42, no.10, pp. 2908–2914, 1994.

[3] H .Harada and R. Prasad, Simulation *& Software Radio for Mobile Communications*, Artech house Publisher, London, 2002.

[4] V. N. Richard and R. Prasad, OFDM *for Wireless Multimedia Communication*, Artech house Publisher, London, 2000.

[5] Wikipedia the Free encyclopedia: http://www.wikipedia.org/

[6] T. S. Rapp port, *Wireless Communications, principles and practice*, 2nd Edition, Prentice- Hall publications, 2002.

[7] S. Weinstein and P. Ebert, “Data Transmission by Frequency Division Multiplexing Using the Discrete Fourier Transform” IEEE *Trans. On Commun*. vol.19, Issue: 5, pp. 628–634, Oct.1971.

[8] A. Peled and A. Ruiz, “Frequency domain data transmission using reduced Computational complexity algorithms”, Acoustics, Speech, and Signal Processing, *IEEE International Conference on ICASSP '80*, vol. 5, pp.964 –967, Apr. 1980.

[9] B. Hirosaki, “An analysis of automatic equalizers for orthogonally multiplexed QAM Systems,” IEEE *Trans. Commun.* , vol. COM-28, pp.73-83, Jan.1980.

[10] L. J. Cimini, “Analysis and simulation of a digital mobile channel using orthogonal Frequency division multiplex”, *IEEE Trans. Communications*. Vol. COM- 33, pp. 665-675. July 1985.

[11] J. Ahn and H. S. Lee, “Frequency domain equalization of OFDM signal over frequency Non selective Rayleigh fading channels,” *Electron. Lett*, vol. 29, no. 16, pp. 1476–1477, Aug. 1993.

[12] N.A. Dhahi., “Optimum finite-length equalization for multicarrier transceivers,” *IEEE Trans. Commun.*, vol. 44, pp. 56–64, Jan. 1996.

[13] R. Li and G. Stette, "Time-limited orthogonal multicarrier modulation schemes," *IEEE Trans. Commun.*, vol. 43, pp. 1269–1272, 1995.

[14] C. Muschallik, Improving an OFDM reception using an adaptive Nyquist windowing, *IEEE Trans. Consum. Electron*, vol. 42, no. 3, pp. 259–269, 1996.

[15] Y. Zhao and S. G. Haggman, "Inter carrier interference self-cancellation scheme for OFDM Mobile communication systems," IEEE *Trans. Commun.*, vol. 49, no. 7, pp.1185–1191, July 2001.

[16] Y. Zhao and S. G. Haggman, "Sensitivity to Doppler shift and carrier frequency errors in OFDM systems—the consequences and solutions," in *Proc. IEEE 46th Vehicular Technology Conf.*, Atlanta, GA, Apr. 28–May 1, 1996, pp. 1564–1568.

[17] P. Tan, N.C. Beaulieu, "Reduced ICI in OFDM systems using the better than raised cosine Pulse," IEEE *Commun. Lett*, vol. 8, no. 3, pp. 135–137, Mar. 2004.

[18] H. M. Mourad, Reducing ICI in OFDM systems using a proposed pulse shape, *Wireless Person. Commun*, vol. 40, pp. 41–48, 2006.

[19] V. Kumbasar and O. Kucur, "ICI reduction in OFDM systems by using improved Sinc power pulse," *Digital Signal Processing*, vol.17, Issue 6, pp. 997-1006, Nov. 2007.

[20] Charan Langton, Orthogonal frequency division multiplexing (OFDM) tutorial. http://www.complextoreal.com/chapters/ofdm2.pdf

[21] L. Hanzo, M. Munster, B. J. Choi and T. Keller, *OFDM and MC-CDMA for broadband Multi-user Communications,* New York, IEEE press, 2000.

[22] A. R. S. Bahai, B. R. Saltzberg, *Multi-Carrier Digital Communication Theory and Applications of OFDM*, Plenum Publishing, New York, 1999.

[23] J. A. C. Bingham, "Multi Carrier Modulation for Data Transmission, an Idea Who's Time Has Come", *IEEE Communications Magazine, pp*., 5-14, May. 1990.

[24] Simon Haykin, *Digital Communications, Wiley* Publications Ltd, Singapore, 1988.

[25] Alex P. Palamides and Andreas M. Maras*, Member, IEEE, "*A Bayesian State–Space Approach to Combat Inter-Carrier Interference in OFDM Systems", IEEE signal Processing Letters, vol. 14, no. 10, October 2007.