CHANNEL ESTIMATION IN OFDM SYSTEMS

A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF TECHNOLOGY

IN

ELECTRONICS SYSTEMS AND COMMUNICATION

By

Mr. ANIL KUMAR PATTANAYAK

Department of Electrical Engineering

National institute of Technology

Rourkela-769008

2007

CHANNEL ESTIMATION IN OFDM SYSTEMS

A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF TECHNOLOGY

IN

ELECTRONICS SYSTEMS AND COMMUNICATION

By

Mr. ANIL KUMAR PATTANAYAK

Under the Guidance of

Dr. SUSMITA DAS

Department of Electrical Engineering

National institute of Technology

Rourkela-769008

2007

National institute of Technology
Rourkela

CERTIFICATE

This is to certify that the thesis entitled “**Channel Estimation in OFDM systems**” submitted by **Mr. Anil Kumar Pattanayak**, in partial fulfillment of the requirements for the award of Master of Technology in the Department of Electrical Engineering, with specialization in ‘**Electronics Systems and Communication’** 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 thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date:

Dr. Susmita Das
Asst. Professor
Department of Electrical Engineering
NATIONAL INSTITUTE OF TECHNOLOGY
Rourkela-769008

ACKNOWLEDGEMENTS

On the submission of my thesis report of “**Channel Estimation in OFDM Systems**”, I would like to extend my gratitude & my sincere thanks to my supervisor **Dr. Susmita Das**, Asst. Professor, Department of Electrical Engineering for her constant motivation and support during the course of my work in the last one year. I truly appreciate and value her esteemed guidance and encouragement from the beginning to the end of this thesis. I am indebted to her for having helped me shape the problem and providing insights towards the solution.

I express my gratitude to Dr.P.K.Nanda, Professor and Head of the Department, Electrical Engineering for his invaluable suggestions and constant encouragement all through the thesis work.

I will be failing in my duty if I do not mention the laboratory staff and administrative staff of this department for their timely help.

I would like to thank all whose direct and indirect support helped me completing my thesis in time.

This thesis 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.

Anil Kumar Pattanayak
M.Tech (Electronics System and Communication)

CONTENTS

1. INTRODUCTION

2. CHARACTERISTICS OF MOBILE RADIO CHANNELS AND BASICS OF OFDM

3. SYSTEM DESCRIPTION

4. CHANNEL ESTIMATION IN OFDM SYSTEMS

5. RESULT AND DISCUSSION

6. CONCLUSION AND FUTURE WORK

ABSTRACT

Orthogonal frequency division multiplexing (OFDM) provides an effective and low complexity means of eliminating intersymbol interference for transmission over frequency selective fading channels. This technique has received a lot of interest in mobile communication research as the radio channel is usually frequency selective and time variant. In OFDM system, modulation may be coherent or differential. Channel state information (CSI) is required for the OFDM receiver to perform coherent detection or diversity combining, if multiple transmit and receive antennas are deployed. In practice, CSI can be reliably estimated at the receiver by transmitting pilots along with data symbols. Pilot symbol assisted channel estimation is especially attractive for wireless links, where the channel is time-varying. When using differential modulation there is no need for a channel estimate but its performance is inferior to coherent system.

In this thesis we investigate and compare various efficient pilot based channel estimation schemes for OFDM systems. The channel estimation can be performed by either inserting pilot tones into all subcarriers of OFDM symbols with a specific period or inserting pilot tones into each OFDM symbol. In this present study, two major types of pilot arrangement such as block-type and comb-type pilot have been focused employing Least Square Error (LSE) and Minimum Mean Square Error (MMSE) channel estimators. Block type pilot sub-carriers is especially suitable for slow-fading radio channels whereas comb type pilots provide better resistance to fast fading channels. Also comb type pilot arrangement is sensitive to frequency selectivity when comparing to block type arrangement. The channel estimation algorithm based on comb type pilots is divided into pilot signal estimation and channel interpolation. The pilot signal estimation is based on LSE and MMSE criteria, together with channel interpolation using linear interpolation and spline cubic interpolation. The symbol error rate (SER) performances of OFDM system for both block type and comb type pilot subcarriers are presented in the thesis.

LIST OF ACRONYMS

AMPS	Advanced Mobile Phone Services
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
D-AMPS	Digital AMPS
DFT	Discrete Fourier Transform.
DVD	Digital Video Broadcast
FDMA	Frequency Division Multiple Access
EM	Expectation Maximization
GSM	Global System for Mobile Communication
IDFT	Inverse Discrete Fourier Transform
ISI	Inter Symbol Interference
LS	Least Square
MCM	Multicarrier Modulation
MMSE	Minimum Mean Square Estimation
OFDM	Orthogonal Frequency Division Multiplexing
PSK	Phase Shift Keying
PSMA	Pilot Symbol Assisted Modulation
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RECT	Rectangular
SCM	Single Carrier Modulation
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunication System
VLSI	Very Large Scale Integration
W-CDMA	Wideband Code Division Multiplexing

LIST OF FIGURES

Cntd.

CHAPTER 1

INTRODUCTION

Literature Survey

Motivation

Objective

1.1 INTRODUCTION

Radio transmission has allowed people to communicate without any physical connection for more than hundred years. When Marconi managed to demonstrate a technique for wireless telegraphy, more than a century ago, it was a major breakthrough and the start of a completely new industry. May be one could not call it a mobile wireless system, but there was no wire! Today, the progress in the semiconductor technology has made it possible, not to forgot affordable, for millions of people to communicate on the move all around the world.

The Mobile Communication Systems are often categorized as different generations depending on the services offered. The fist generation comprises the analog frequency division multiple access (FDMA) systems such as the NMT and AMPS (Advanced Mobile Phone Services) [1]. The second generation consists of the first digital mobile communication systems such as the time division multiple access (TDMA) based GSM (Global System for Mobile Communication), D-AMPS (Digital AMPS), PDC and code division multiple access (CDMA) based systems such as IS-95. These systems mainly offer speech communication, but also data communication limited to rather low transmission rates. The third generation started operations on 1st October 2002 in Japan.

During the past few years, there has been an explosion in wireless technology. This growth has opened a new dimension to future wireless communications whose ultimate goal is to provide universal personal and multimedia communication without regard to mobility or location with high data rates. To achieve such an objective, the next generation personal communication networks will need to be support a wide range of services which will include high quality voice, data, facsimile, still pictures and streaming video. These future services are likely to include applications which require high transmission rates of several Mega bits per seconds (Mbps).

In the current and future mobile communications systems, data transmission at high bit rates is essential for many services such as video, high quality audio and mobile integrated service digital network. When the data is transmitted at high bit rates, over mobile radio channels, the channel impulse response can extend over many symbol periods, which leads to inter symbol interference (ISI). Orthogonal Frequency Division Multiplexing (OFDM) is one of the promising candidate to mitigate the ISI. In an OFDM signal the bandwidth is divided into many narrow subchannels which are transmitted in parallel. Each subchannel is typically chosen narrow enough to eliminate the effect of delay spread. By combining OFDM with Turbo Coding and antenna diversity, the link budget and dispersive-fading limitations of the cellular mobile radio environment can be overcomed and the effects of co-channel interference can be reduced.

1.1.1 Digital Communication Systems

A digital communication system is often divided into several functional units as shown in Figure 1.1. The task of the source encoder is to represent the digital or analog information by bits in an efficient way. The bits are then fed into the channel encoder, which adds bits in a structured way to enable detection and correction of transmission errors. The bits from the encoder are grouped and transformed to certain symbols, or waveforms by the modulator and waveforms are mixed with a carrier to get a signal suitable to be transmitted through the channel. At the receiver the reverse function takes place. The received signals are demodulated and soft or hard values of the corresponding bits are passed to the decoder. The decoder analyzes the structure of received bit pattern and tries to detect or correct errors. Finally, the corrected bits are fed to the source decoder that is used to reconstruct the analog speech signal or digital data input.

This thesis deals with the three blocks to the right in Figure 1.1: the modulator, the channel and the demodulator. The main question is how to design certain parts of the modulator and demodulator to achieve efficient and robust transmission through a mobile wireless channel. The wireless channel has some properties that make the design especially challenging: it introduces time varying echoes and phase shifts as well as a time varying attenuation of the amplitude (fade). This thesis focuses on the following parts in the modulator-demodulator chain.

Orthogonal Frequency Division Multiplexing (OFDM) has proven to be a modulation technique well suited for high data rates on time dispersive channels [2]. There are some specific requirements when designing wireless OFDM systems, for example, how to choose the bandwidth of the sub-channels used for transmission and how to achieve reliable synchronization. The latter is especially important in packet-based systems since synchronization has to be achieved within a few symbols.

In order to achieve good performance the receiver has to know the impact of the channel. The problem is how to extract this information in an efficient way. Conventionally, known symbols are multiplexed into the data sequence in order to estimate the channel. From these symbols, all channel attenuations are estimated with an interpolation filter.

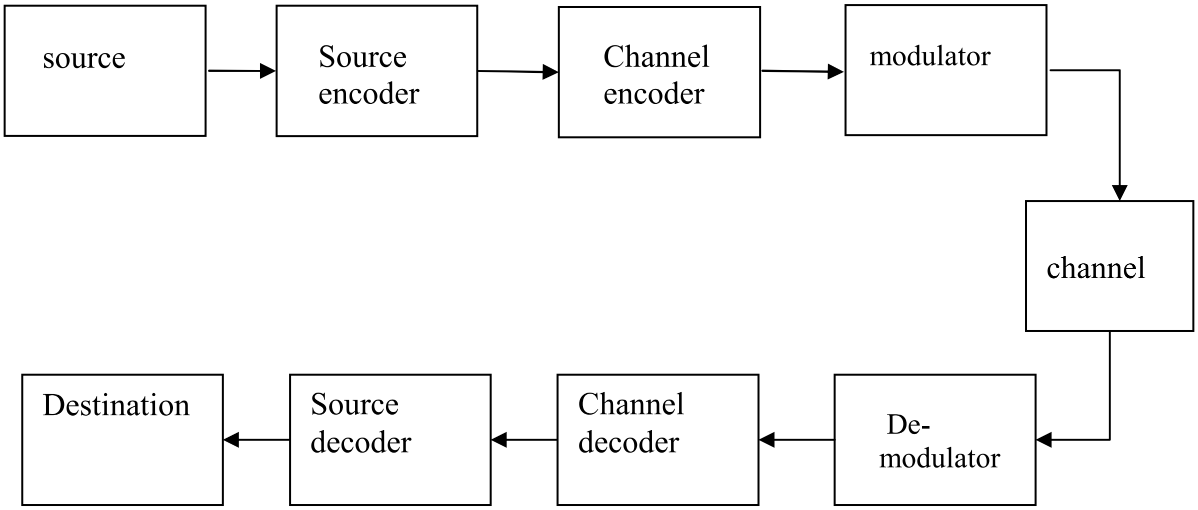

Fig1.1: Functional Block in a Communication System

For mobile or wireless applications, the channel is often described as a set of independent multipath components. The time varying impulse response can be described by [7]

$$h(t) = \sum_{i=1}^{M} a_i(t)\delta(\tau - \tau_i(t)) \qquad 1.1$$

Where $a_i(t)$ denotes the complex valued tap gain for path number i, $\tau_i(t)$ is the delay of tap i, and δ is the Dirac delta function. Among the most important parameters when choosing the modulation scheme are the delay and the expected received power for different delays. Large delays for stronger paths mean that the interference between the different received signal parts can severe, especially when the symbol rate is high so that the delay exceeds several symbols. In that case one have to introduce an equalizer to mitigate the effects of intersymbol interference (ISI). Another alternative is to use many parallel channels so that the symbol time on each of the channels is long. This means that only a small part of the symbol is affected by ISI and this is the idea behind orthogonal frequency division multiplexing, OFDM.

1.1.2 Wireless Systems

Wireless Systems are operating in an environment which has some specific properties compared to fixed wireline systems and these call for special design considerations. In a wired network, there are no fast movements of terminals or reflection points and the channel parameters are changing very slowly. In addition, time dispersion is less severe in a wired system, though it might still be a hard problem due to high data rates. In a mobile system the terminals are moving around, the received signal strength as well as the phase of the received signal, are changing rapidly. Further, the signal transmitted over the radio channel is reflected by buildings and other means of transportation on the ground, leading to different paths to the receiver, as shown in Figure 1.2.

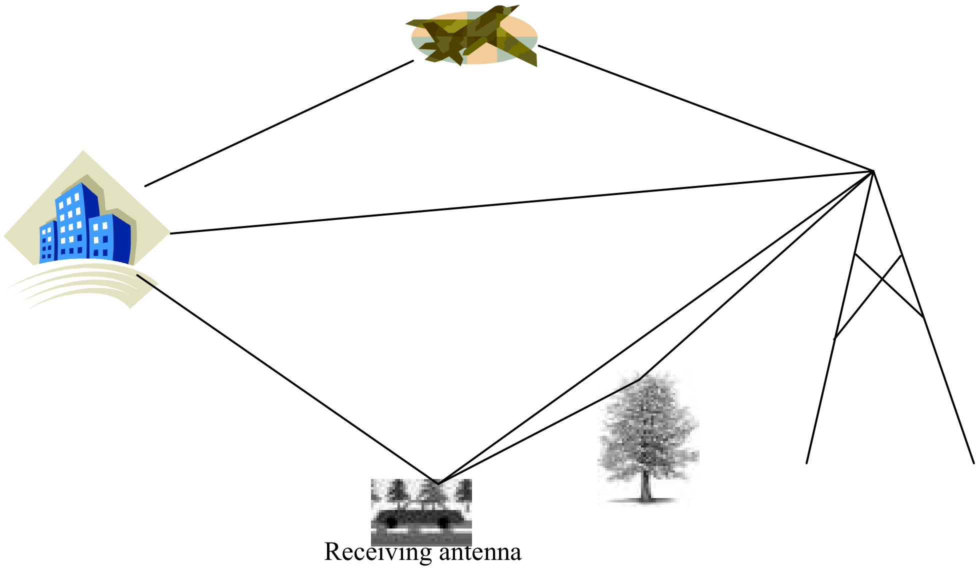

Fig. 1.2: Multipath Reception

If the length of the paths differ, the received signal will contain several delayed versions of the transmitted signal according to the channel impulse response defined in Equation (1.1).The delays make it necessary to use complex receiver structures. In a mobile wireless system, the terminals are of course intended to be portable. This means that power consumption is important since batteries sometimes will power the equipment. Therefore, low complexity and low power consumption are properties that are even more desirable in wireless systems than in a wired system.

1.1.3 Packet-Based Versus Circuit-Switched Systems

A wireless system can either be packet-based or circuit switched. In a packet based system the information bits are grouped and transmitted in packets, and transmission occur only when there is a need for communication. These systems are suitable for bursty traffic conditions, such as data communication. In circuit switched systems, a physical or virtual connection is established and occupied as long as communication proceeds. Circuit switched systems are well suited for real time traffic when delay is a limiting factor. In packet based systems, the receiver has to achieve synchronization in a very short time. It is hard to track channel variations between the packets, and therefore fast acquisition algorithms are required. In circuit switched systems, the receiver needs to enter in acquisition mode more seldom due to transmission over steady channels, therefore requirements on fast acquisition can be loosened in these systems. In circuit switched systems, we also require continuous channel tracking. Today there is a trend towards more and more packet based systems due to increased data traffic. For example, both the third generation mobile systems based on W-CDMA and the HiperLAN/2 system based on OFDM use packet-based communication for data traffic.

1.1.4 Coherent Versus Non-Coherent Systems

In general, coherent systems result in better detection performance compared to differential systems, but these require channel estimation in order to form time and phase references for the decisions. Differential schemes on the other hand require no channel estimation, but there is a performance loss compared to coherent detection.

In coherent schemes, the channel estimates are often achieved by multiplexing known, so called, pilot symbols into the data sequence and this technique is called Pilot Symbol Assisted Modulation (PSAM). PSAM was introduced by Moher and Lodge [3] and analyzed by Cavers [4] for single carrier systems. The receiver observes the influence of the channel on the pilot symbols and uses interpolation to get an estimate of the channel impact on data symbols. The receiver then removes that impact in order to make decisions. The pilot symbols transmit no data and therefore there is a small overhead causing a bandwidth expansion and an energy loss. Both these looses depends on the pilot-to-data symbol ratio.

1.1.5 Third Generation Wireless Networks

The expansion of the use of digital networks has led to the need for the design of new higher capacity communications networks. The demand for cellular-type systems in Europe is predicted to be between 15 and 20 million users by the year 2000, and is already over 30 million (1995) in the U.S. [1]. Wireless services have been growing at a rate greater than 50% per year [2], with the current second generation European digital systems (GSM) being expected to be filled to capacity by the early 2000s. The telecommunications industry is also changing, with a demand for a greater range of services such as video conferencing, Internet services, and data networks, and multimedia. This demand for higher capacity networks has led to the development of third generation telecommunications systems.

One of the proposed third generation telecommunication systems is the Universal Mobile Telecommunications System (UMTS), with the aim of providing more flexibility, higher capacity, and a more tightly integrated service. Other systems around the world are being developed, however many of these technologies are expected to be combined into the UMTS.

The World Wide Web (WWW) has become an important communications media, as its use has increased dramatically over the last few years. This has resulted in an increased demand for computer networking services. In order to satisfy this, telecommunications systems are now being used for computer networking, Internet access and voice communications. A WWW survey revealed that more than 60% of users access the Internet from residential locations, where the bandwidth is often limited to 28.8 kbps. This restricts the use of the Internet, preventing the use of real time audio and video capabilities. Higher speed services are available, such as integrated-services digital network (ISDN). These provide data rates up to five times as fast, but at a much increased access cost. This has led to the demand of a more integrated service, providing faster data rates, and a more universal interface for a variety of services. The emphasis has shifted away from providing a fixed voice service to providing a general data connection that allows for a wide variety of applications, such as voice, Internet access, computer networking, etc.

The increased reliance on computer networking and the Internet has resulted in an increased demand for connectivity to be provided any where, any time, leading to an increase in the demand for wireless systems. This demand has driven the need to develop new higher capacity, high reliability wireless telecommunications systems. The development and deployment of third generation telecommunication systems aim to overcome some of the shortcomings of current wireless systems by providing a high capacity, integrated wireless network. There are currently several third generation wireless standards, including IMTS-CDMA, IMTS-TDD, IMTS-TF etc.

1.1.6 Evolution of Telecommunication Systems

Many mobile radio standards have been developed for wireless systems throughout the world, with more standard likely to emerge. Most first generations systems were introduced in the mid 1980s, and can be characterized by the use of analog transmission techniques, and the use of simple multiple access techniques such as Frequency Division Multiple Access (FDMA). First generation telecommunications systems such as Advanced Mobile Phone Service (AMPS), only provided voice communications. They also suffered from a low user capacity, and security problems due to the simple radio interface used.

Second generation systems were introduced in the early 1990s, and all use digital technology. This provided an increase in the user capacity of around three times [1]. This was achieved by compressing the voice waveforms before transmission.

Third generation systems are an extension on the complexity of second generation systems and are already introduced. The system capacity is expected to be increased to over ten times original first generation systems. This is going to be achieved by using complex multiple access techniques such as Code Division Multiple Access (CDMA), or an extension of TDMA, and by improving flexibility of services available.

Figure 1.3 shows the evolution of current services and networks to the aim of combining them into a unified third generation network. Many currently separate systems and services such as radio paging, cordless telephony, satellite phones, private radio systems for companies etc, will be combined so that all these services will be provided by third generation telecommunications systems.

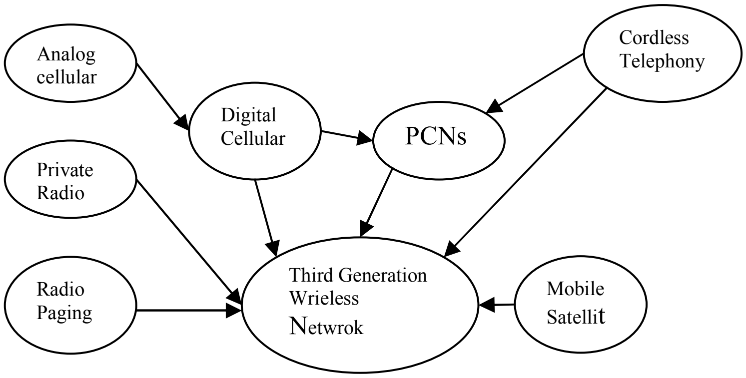

Fig 1.3: Evolution of current networks to the next generation of wireless networks

1.1.7 Fourth Generation Wireless Systems

Although carriers are reluctant to discuss 4G, vendors are always mapping future of 4G systems. It is still a decade away (at least), but 4G is already a big topic of discussion behind closed doors. Main advantages of 4G are its spectrum optimization, network capacity and faster data rates, however, carriers are still reluctant to discuss 4G, either because they refuse to take a public position on it when 3G roll-outs still are unfulfilled, or because they are in denial. But carriers soon will find that 4G is not going away. 3G systems are not enough for many services like data transfer between wireless phones or multimedia. Equipment vendors are coming together to speed the adoption of OFDM, which will be part of the 4G set of standards.

Orthogonal Frequency Division Multiplexing OFDM [2] is a multicarrier transmission technique, many carriers, each one being modulated by a low rate data stream share the transmission bandwidth. 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.

In FDMA each user is typically allocated a single channel of certain bandwidth, which is used to transmit all the user information. The allocated bandwidth is made wider than the minimum amount required to prevent channels from interfering with one another. This extra bandwidth is to allow for signals from neighboring channels to be filtered out, and to allow for any drift in the center frequency of the transmitter or receiver. In a typical system, up to 50% of the total spectrum is wasted due to the extra spacing between channels.

TDMA partly overcomes this problem by using wider bandwidth channels, which are used by several users. Multiple users access the same channel by transmitting in their data in time slots. Thus, many low data rate users can be combined together to transmit in a single channel which has a sufficient bandwidth so that the spectrum can be used efficiently.

There are however, two main problems with TDMA. There is an overhead associated with the change over between users due to time slotting on the channel. This limits the number of users that can be sent efficiently in each channel. In addition, the symbol rate of each channel is high (as the channel handles the information from multiple users) resulting in problems with multipath delay spread.

OFDM overcomes most of the problems with both FDMA and TDMA. OFDM splits the available bandwidth into many narrow band channels (typically 100-8000 Hz). The carriers for each channel are made orthogonal to one another, allowing them to be spaced very close together, with no overhead as in the FDMA example. Because of this there is no great need for users to be time multiplexed as in TDMA, thus there is no overhead associated with switching between users.

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 location of each of the other carriers in the system. This results in no interference between the carriers, allowing them to be as close as theoretically possible. This overcomes the problem of overhead carrier spacing required in FDMA. Each carrier in an OFDM signal has a very narrow bandwidth (i.e.1kHz), thus the resulting symbol rate is low. This results in the signal having a high tolerance to multipath delay spread, as the delay spread must be very long to cause significant inter-symbol interference (e.g. ≥ 500 μsec). We will discuss these aspects of OFDM system, in much detail, in Chapter 2.

1.2 LITERATURE SURVEY

The first OFDM scheme was proposed by Chang [2] in 1966 for dispersive fading channels, which has also undergone a dramatic evolution due to the efforts of [5]. Recently OFDM was selected as the high performance local area network transmission technique. A method to reduce the ISI is to increase the number of subcarriers by reducing the bandwidth of each subchannel while keeping the total bandwidth constant .The ISI can instead be eliminated by adding a guard interval at the cost of power loss and bandwidth expansion. These OFDM systems have been employed in military applications since the 1960's, for example by Bello [6], Zimmerman [7] and others. The employment of discrete Fourier transform (DFT) to replace the banks of sinusoidal generators and the demodulators was suggested by Weinstein and Ebert [5] in 1971, which significantly reduces the implementational complexity of OFDM modems. Hirosaki [8], suggested an equalization algorithm in order to suppress both intersymbol and intersubcarrier interference caused by the channel impulse response or timing and frequency errors. Simplified model implementations were studied by Peled [9] in 1980. Cimini [6] and Kelet [10] published analytical and early seminal experimental results on the performance of OFDM modems in mobile communication channels.

Most recent advances in OFDM transmission were presented in the impressive state of art collection of works edited by Fazel and Fettweis [11]. OFDM transmission over mobile communications channels can alleviate the problem of multipath propagation. Recent research efforts have focused on solving a set of inherent difficulties regarding OFDM, namely peak-to-mean power ratio, time and frequency synchronization, and on mitigating the effects of the frequency selective fading channels.

Channel estimation and equalization is an essential problem in OFDM system design. Basic task of equalizer is to compensate the influences of the channel [3]. This compensation requires, however, than an estimate of the channel response is available. Often the channel frequency response or impulse response is derived from training sequence or pilot symbols, but it is also possible to use nonpilot aided approaches like blind equalizer algorithms [12]. Channel estimation is one of the fundamental issue of OFDM system design, without it non coherent detection has to be used, which incurs performance loss of almost 3-4 dB compared to coherent detection [13]. If coherent OFDM system is adopted, channel estimation becomes a requirement and usually pilot tones are used for channel estimation.

A popular class of coherent demodulation for a wide class of digital modulation schemes has been proposed by Moher and Lodge [14], and is known as Pilot Symbol Assisted Modulation, PSAM. The main idea of PSAM channel estimation is to multiplex known data streams with unknown data. Conventionally the receiver firstly obtain tentative channel estimates at the positions of the pilot symbols by means of remodulation and than compute final channel estimates by means of interpolation. Aghamohammadi [15] et al. and Cavers [16] were among the first analyzing and optimizing PSAM given different interpolation filters. The main disadvantage of this scheme is the slight increase of the bandwidth. One class of such pilot symbol assisted estimation algorithms adopt an interpolation technique with fixed parameters (two dimensional and one dimensional) to estimate the frequency domain channel impulse response by using channel estimates obtained at the lattices assigned to the pilot tones. Linear, Spline and Gaussian filters have all been studied [17].

Channel estimation using superimposed pilot sequences is also a completely new area, idea for using superimposed pilot sequences has been proposed by various authors for different applications.In [18], superimposed pilot sequences are used for time and frequency synchronization. In [19], superimposed pilot sequences are introduced for the purpose of channel estimation, and main idea here is to linearly add a known pilot sequence to the transmitted data sequence and perform joint channel estimation and detection in the receiver.

In [20], expectation maximization (EM) algorithm was proposed, and in [21] EM algorithm was applied on OFDM systems for efficient detection of transmitted data as well as for estimating the channel impulse response. Here, maximum likelihood estimate of channel was obtained by using channel statistics via the EM algorithm. In [22], performance of low complexity estimators based on DFT has been analyzed. In [23], block and comb type pilot arrangements have been analyzed.

There are some other techniques, proposed for channel estimation and calculation of channel transfer function in OFDM systems. For example, the use of correlation based estimators working in the time domain and channel estimation using singular value decomposition [24]. Its basically based on pilot symbols but in order to reduce its complexity, statistical properties of the channel are used in a different way. Basically the structure of OFDM allows a channel estimator to use both time and frequency correlations, but particularly it is too complex. In [24], they analyzed a class of block oriented channel estimators for OFDM, where only the frequency correlation of the channel is used in estimation. Whatever, their level of performance, they suggested that they may be improved with the addition of second filter using the time correlation. In [25], they proposed a channel estimation algorithm based polynomial approximations of the channel parameters both in time and frequency domains. This method exploits both the time and frequency correlations of the channel parameters.

Use of the pilot symbols for channel estimation is basically an overhead of the system, and it is desirable to keep the number of pilot symbols to a minimum. In [26], Julia proposed a very good approach for OFDM symbol synchronization in which synchronization (correction of frequency offsets) is achieved simply by using pilot carriers already inserted for channel estimation, so no extra burden is added in the system for the correction of frequency offsets. Similarly in [27], it has been shown that the number of pilot symbols for a desired bit error rate and Doppler frequency is highly dependant on the pilot patterns used, so by choosing a suitable pilot pattern we can reduce the number of pilot symbols, but still retaining the same performance. Most common pilot patterns used in literature are block and comb pilot arrangements [23], [28]. Comb patterns perform much better than block patterns in fast varying environments [23].

1.3 MOTIVATION

The focus of future fourth-generation (4G) mobile systems is on supporting high data rate services and ensuring seamless provisioning of services across a multitude of wireless systems and networks, for indoor to outdoor, from one interface to another, and from private to public network infrastructure.

Higher data rates allow the deployment of multi-media applications which involve voice, data, pictures, and video over the wireless networks. At this moment, the data rate envisioned for 4G networks is 1 GB/s for indoor and 100Mb/s for outdoor environments. High data rate means the signal waveform is truly wideband, and the channel is frequency-selective from the waveform perspective, that is, a large number of resolvable multipaths are present in the environment. Orthogonal frequency division multiplexing (OFDM), which is a modulation technique for multicarrier communication systems, is a promising candidate for 4G systems since it is less susceptible to intersymbol interference introduced in the multipath environment.

It is not possible to make reliable data decisions unless a good channel estimate is available. Thus, an accurate and efficient channel estimation procedure is necessary to coherently demodulate the received data. As we mentioned earlier that although differential detection could be used to detect the transmitted signal in the absence of channel estimates, it would result in about 3-4dB loss [2] in signal to noise ratio compared to coherent detection. Moreover, as opposed to former standards using OFDM modulation, the new standards rely on QAM modulation and thus require channel estimation. Hence, the complexity of channel estimation is of crucial importance, especially for time varying channels, where it has to be performed periodically or even continuously. Several channel estimation techniques related with OFDM systems have been proposed in literature [29]. Number of pilot symbols for a desired error rate and Doppler frequency is highly dependent on how we transmit pilots [27] in OFDM systems.

Rearrangement of pilot symbols, in some cases, can handle 10 times higher Doppler frequencies alternatively reduce the needed pilot symbols the same amount, still retaining the same bit error rate [27].

1.4 OBJECTIVE AND OUTLINE OF THESIS

In this work, channel estimation in OFDM systems is investigated. The main objective of this thesis is to investigate the performance of channel estimation in OFDM systems and study different patterns of pilot symbols which already have been proposed in literature.

The main objectives of this thesis are: (1) Investigate the effectiveness of Orthogonal Frequency Division Multiplexing (OFDM) as a modulation technique for wireless radio applications. Main factors affecting the performance of an OFDM system are multipath delay spread and channel noise. The performance of OFDM is assessed using computer simulations performed using Matlab. It was found that OFDM performs extremely well, providing a very high tolerance to multipath delay spread and channel noise. (2) In pilot assisted channel estimation, we study different pilot arrangements, and investigate how to select a suitable pilot pattern for wireless OFDM transmission..

This thesis is organized as follows: In Chapter 2, characteristics of mobile radio channels and the basics of OFDM are presented. In Chapter 3, the description of OFDM system (base band) based on pilot estimation is given. In Chapter 4, an overview of different approaches of channel estimation in OFDM systems is presented. We also discuss different channel estimation and interpolation techniques in Chapter 4. Chapter 5 demonstrates Simulation Results and Discussion of Basic OFDM System employing a single antenna under AWGN, a 2-ray static multipath channel and rayleigh fading channel. Chapter 6 concludes the thesis and areas for future work are also suggested.

CHAPTER 2

CHARACTERISTICS OF MOBILE RADIO CHANNELS AND BASICS OF OFDM

In this chapter the propagation characteristics of mobile radio channels and basics of OFDM are presented. Radio channel is the link between the transmitter and the receiver that carries information bearing signal in the form of electromagnetic waves. The radio channel is commonly characterized by scatterers (local to the receiver) and reflectors (local to the transmitter). Small scale fading, or simply fading, is used to describe the rapid fluctuations of the amplitude of a radio signal over a short period of time or travel distance, so that large scale path loss effects may be ignored. Characteristics of radio channel and a basic of OFDM such orthoganality principle, use of IFFT and DFT in OFDM, history of OFDM etc are described in below.

2.1 PROPAGATION CHARACTERISTICS OF MOBILE RADIO CHANNELS

In an ideal radio channel, the received signal would consist of only a single direct path signal, which would be a perfect reconstruction of the transmitted signal. However, in a real channel the signal is modified during transmission. The received signal consists of a combination of attenuated, reflected, refracted, and diffracted replicas of the transmitted signal. On top of all this, the channel adds noise to the signal and can cause a shift in the carrier frequency if either of the transmitter or receiver is moving (Doppler Effect). Understanding of these effects on the signal is important because the performance of a radio system is dependent on the radio channel characteristics.

Attenuation

Attenuation is the drop in the signal power when transmitting from one point to another. It can be caused by the transmission path length, obstructions in the signal path, and multipath effects. Any objects which obstruct the line of sight of the signal from the transmitter to the receiver, can cause attenuation. Shadowing of the signal can occur whenever there is an obstruction between the transmitter and receiver. It is generally caused by buildings and hills, and is the most important environmental attenuation factor. Shadowing is the most severe in heavily built up areas, due to the shadowing from buildings. However, hills can cause a large problem due to the large shadow they produce. Radio signals diffract off the boundaries of obstructions, thus preventing total shadowing of the signals behind hills and buildings. However, the amount of diffraction is dependent on the radio frequency used, with high frequencies scatter more than low frequency signals. Thus high frequency signals, especially, Ultra High Frequencies (UHF) and microwave signals require line of sight for adequate signal strength, because these scatter too much. To overcome the problem of shadowing, transmitters are usually elevated as high as possible to minimize the number of obstructions.

Multipath Effects

Rayleigh Fading

In a radio link, the RF signal from the transmitter may be reflected from objects such as hills, buildings, or vehicles. This gives rise to multiple transmission paths at the receiver. Figure 3.2 shows some of the possible ways in which multipath signals can occur. The relative phase of multiple reflected signals can cause constructive or destructive interference at the receiver. This is experienced over very short distances (typically at half wavelength distances), which is given the term fast fading. These variations can vary from 10-30dB over a short distance. The Rayleigh distribution is commonly used to describe the statistical time varying nature of the received signal power. It describes the probability of the signal level being received due to fading.

Frequency Selective Fading

In any radio transmission, the channel spectral response is not flat. It has dips or fades in the response due to reflections causing cancellation of certain frequencies at the receiver. Reflections off near-by objects (e.g. ground, buildings, trees, etc) can lead to multipath signals of similar signal power as the direct signal. This can result in deep nulls in the received signal power due to destructive interference. For narrow bandwidth transmissions if the null in the frequency response occurs at the transmission frequency then the entire signal can be lost. This can be partly overcome in two ways. By transmitting a wide bandwidth signal or spread spectrum as in the case of CDMA, any dips in the spectrum only result in a small loss of signal power, rather than a complete loss. Another method is to split the transmission up into many carriers carrying low rate data, as is done in a COFDM/OFDM

Delay Spread

The received radio signal from a transmitter consists of typically a direct signal plus signals reflected off object such as buildings, mountains, and other structures. The reflected signals arrive at a later time than the direct signal because of the extra path length, giving rise to a slightly different arrival time of the transmitted pulse. The signal energy confined to a narrow pulse is spreading over a longer time. Delay spread is a measure of how the signal power is spread over the time between the arrival of the first and last multipath signal seen by the receiver. In a digital system, the delay spread can lead to inter-symbol interference. This is due to the delayed multipath signal overlapping symbols that follows. This can cause significant errors in high bit rate systems, especially when using time division multiplexing (TDMA). As the transmitted bit rate is increased the amount inter symbol interference also increases. The effect starts to become very significant when the delay spread is greater then 50% of the bit time.

2.2 INTRODUCTION TO OFDM

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. Mathematically, suppose we have a set of signals ψ then

$$\begin{aligned} \int_0^T \psi_p(t)\psi_q^*(t) &= k \quad \mathit{for} \quad p = q \\ &= 0 \quad \mathit{for} \quad p \neq q \qquad 2.1 \end{aligned}$$

Where ψ_p and ψ_q are pth and qth elements in the set. The signals are orthogonal if the integral value is zero. where T is a symbol period. Since the carriers are orthogonal to each other the nulls of one carrier coincides with the peak of another sub carrier. As a result it is possible to extract the sub carrier of interest OFDM transmits a large number of narrowband subchannels. The frequency range between carriers is carefully chosen in order to make them orthogonal one another. In fact, the carriers are separated by an interval of 1/T, where T represents the duration of an OFDM symbol. The frequency spectrum of an OFDM transmission is illustrated in Figure 2.1. Each sinc of the frequency spectrum, in the Fig 2.2 corresponds to a sinusoidal carrier modulated by a rectangular waveform representing the information symbol. One could easily notice that the frequency spectrum of one carrier exhibits zero-crossing at central frequencies corresponding to all other carriers. At these frequencies, the intercarrier interference is eliminated, although the individual spectra of subcarriers overlap. It is well known, orthogonal signals can be separated at the receiver by correlation techniques. The receiver acts as a bank of demodulators, translating each carrier down to baseband, the resulting signal then being integrated over a symbol period to recover the data. If the other carriers all beat down to frequencies which, in the time domain means an integer number of cycles per symbol period (T), then the integration process results in a zero contribution from all these carriers. The waveform of some carriers in a OFDM transmission is illustrated in Fig 2.1. The figure indicates the spectrum of carriers significantly over laps over the other carrier. This is contrary to the traditional FDM technique in which a guard band is provided between each carrier. From the figures illustrated, it is clear that OFDM is a highly efficient system and hence is often regarded as the optimal version of multi-carrier transmission schemes. The number of sub channels transmitted is fairly arbitrary with certain broad constraints, but in practical systems, subchannels tend to be extremely numerous and close to each other. For example the number of carriers in 802.11 wireless LAN is 48 while for Digital Video Broadcast (DVB) it is as high as 6000 sub-carriers. If we consider a single OFDM carrier, we can model the transmitted pulse as a sinusoid multiplied by a RECT function. In the frequency domain, the resulting spectrum has a $\frac{\sin(x)}{x}$ shape centered at the carrier frequency as shown in the Figure 2.3.

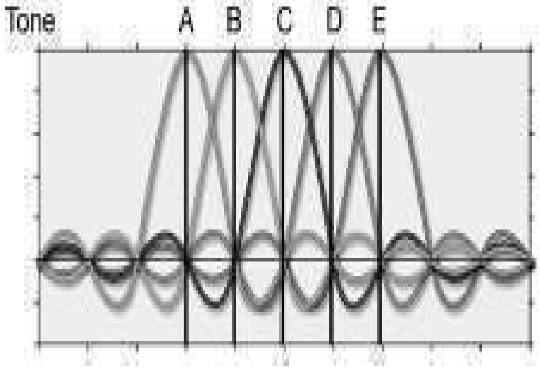

Fig 2.1: Spectrum of Orthogonal carriers

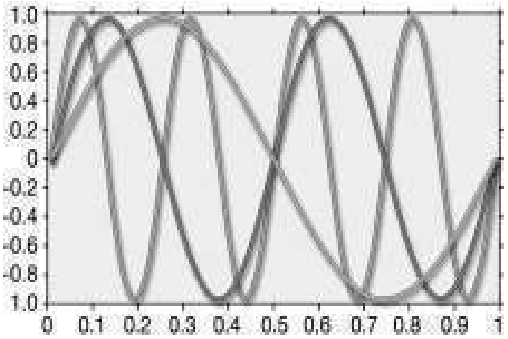

Fig. 2.2: Time domain representation of Orthogonal carriers

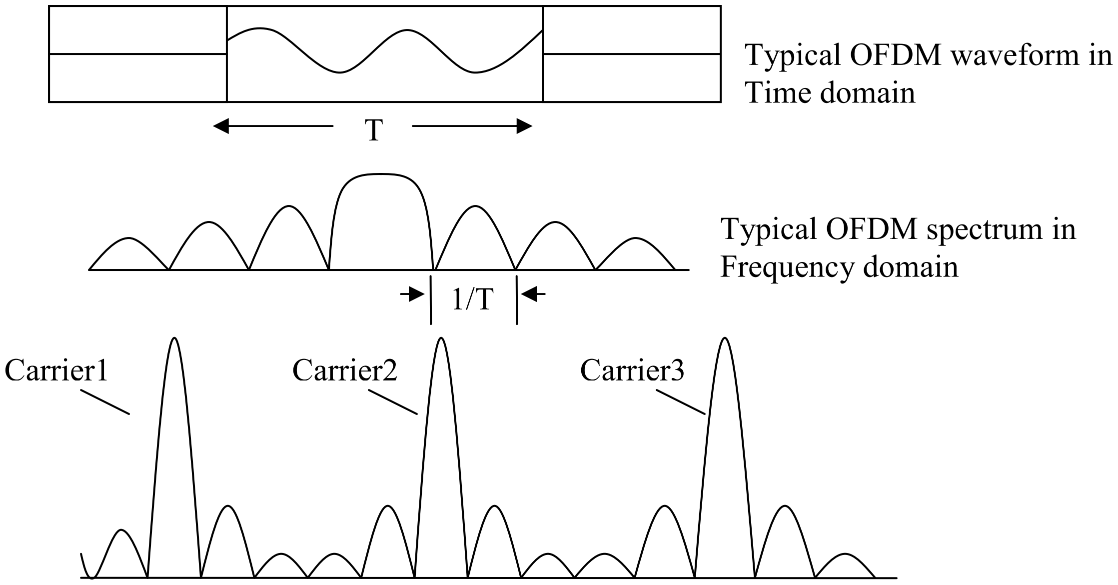

Fig. 2.3 A Single carrier of OFDM

It is worth mentioning here that relative to single carrier Modulation technique (SCM), the OFDM carriers occupy a significant amount of bandwidth of the spectrum relative to the symbol rate. This characteristic is not a problem given that the carriers overlap significantly. The slow sin (x)/x roll off, which implies a wider carrier bandwidth is only an issue at the edge of the channel spectrum. Standards like 802.11a, allow the RECT pulse to be modified such that the rising and falling edges are softer (Raised cosine) at the edge of their assigned spectrum. This helps constrain the spectrum without affecting data transmissions OFDM offers several advantages over single carrier system like better multipath effect immunity, simpler channel equalization and relaxed timing acquisition constraints. But it is more susceptible to local frequency offset and radio front-end nonlinearities. The frequencies used in OFDM system are orthogonal. Neighboring frequencies with overlapping spectrum can therefore be used. This results in efficient usage of BW. The OFDM is therefore able to provide higher data rate for the same BW introduced between the different carriers and in the frequency domain, which results in a lowering of spectrum efficiency.

Moreover, to eliminate the banks of subcarrier oscillators and coherent demodulators required by frequency-division multiplex, completely digital implementations could be built around special-purpose hardware performing the fast Fourier transform (FFT), which is an efficient implementation of the DFT. Recent advances in very-large-scale integration (VLSI) technology make high-speed, large-size FFT chips commercially affordable. Using this method, both transmitter and receiver are implemented using efficient FFT techniques that reduce the number of operations from N^2 in DFT down to $N \log N$. In the 1980s, OFDM was studied for high-speed modems, digital mobile communications, and high-density recording. One of the systems realized the OFDM techniques for multiplexed QAM using DFT and by using pilot tone, stabilizing carrier and clock frequency control and implementing trellis coding are also implemented. Moreover, various-speed modems were developed for telephone networks.

In the more conventional approach the traffic data is applied directly to the modulator with a carrier frequency at the center of the transmission band $f_0, f_1, ...f_{N-1}$,i.e., at $(f_{N-1} + f_0)/2$ and the modulated signal occupies the entire bandwidth *W*. When the data is applied sequentially the effect of a deep fade in a mobile channel is to cause burst errors. Figure 2.4 shows the serial transmission of symbols $S_0, S_1, ..., S_{N-1}$, while the solid shaded block indicates the position of the error burst which affects only *k* < *N* symbols.

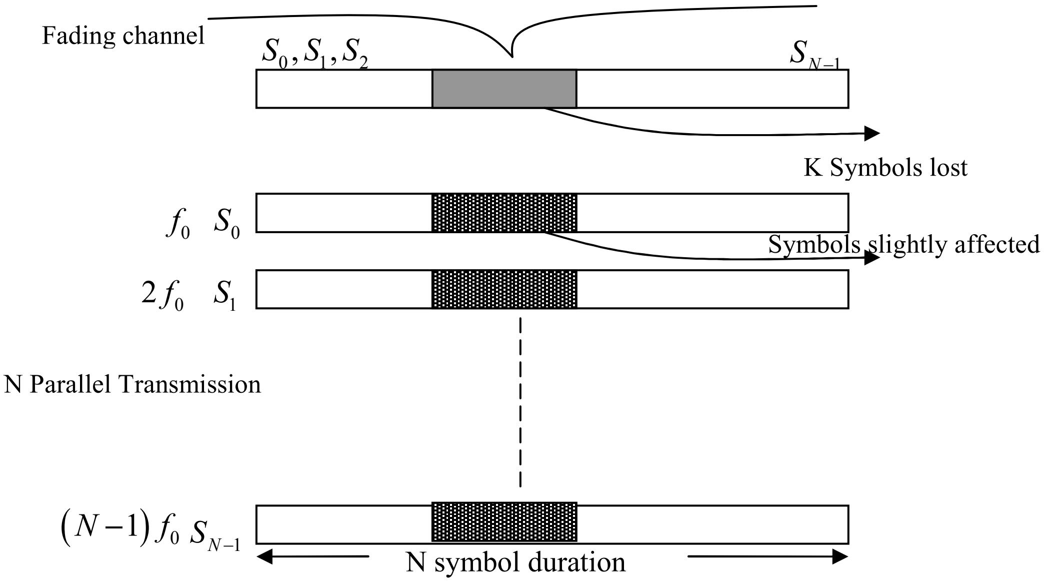

Fig 2.4: Effect of a fade on serial and parallel systems

By contrast, during the *N*-symbol period of the conventional serial system, each OFDM modulator carriers only one symbol, and the error burst causes sever signal degradation of the duration of *k*-serial symbols. This degradation is shown crosshatched. However, if the error burst is only a small fraction of the symbol period than each of the OFDM symbols may only be slightly affected by the fade and they can still be correctly demodulated. Thus while the serial system exhibits an error burst, no errors or few errors may occur using the OFDM approach.

A further advantage of OFDM is that because the symbol period has been increased, the channel delay spread is significantly a shorter fraction of a symbol period than in the serial system, potentially rendering the system less sensitive to ISI than the conventional serial system.

2.3 BRIEF HISTORY OF OFDM

The concept of using parallel data transmission by means of frequency division multiplexing (FDM) was published in mid 60's by Fazel & Fettwis [30],. Some early developers can be traced back in the 50's a U.S. patent was filled and issued in January, 1970. The idea was to use parallel data streams and FDM with overlapping subchannels to avoid the use of high speed equalization, and to combat impulsive noise, and multipath distortion as well as to fully use the available bandwidth. The initial applications were in the military communications. In the telecommunications field, the term of discrete Multitone, multi-channel modulation and multi-carrier modulation (MCM) are widely used and sometimes they are interchangeable with OFDM. In OFDM, each carrier is orthogonal to all other carriers. However, this condition is not always maintained in MCM. OFDM is an optimum version of multi carrier transmission schemes.

For a large number of subchannels, the arrays of sinusoidal generators and coherent demodulator require in parallel system become unreasonably expensive and complex. The receiver needs precise phasing of the demodulator carriers and sampling times in order to keep crosstalk between subchannels acceptable. Weinstein and Ebert [5] applied the discrete Fourier transform to parallel data as part of modulation and demodulation process. But the problem with FFT is that here we can use only limited frequencies, which are the integral multiples of 1/T , where T is the symbol time period. In the 1980's, OFDM was studied for high-speed modems, digital mobile communications [9] and high density recording. One of the systems used a pilot tone [31] for stabilizing carrier and clock frequency control and trellis coding was implemented. In 1990's, OFDM was exploited for wideband data communications over mobile radio FM channels, high bit-rate digital subscriber line, asymmetric digital subscriber line, very high speed digital subscriber lines, digital audio broadcasting (DAB) and HDTV terrestrial broadcasting.

2.4 GENERATION OF OFDM SYMBOLS

A baseband OFDM symbol can be generated in the digital domain before, modulating on a carrier for transmission. To generate a baseband OFDM symbol, a serial digitized data stream is first modulated using common modulation schemes such as he phase shift keying (PSK) or quadrature amplitude modulation (QAM). These data symbols are then converted to parallel streams before modulating subcarriers. Subcarriers are sampled with sampling rate N/T, where N is the number of subcarriers and T is the OFDM symbol duration. The frequency separation between two adjacent subcarriers is $2\pi/N$. Finally, samples on each subcarrier are summed together to form an OFDM sample. An OFDM symbol generated by an N-subcarrier OFDM system consists of N samples and the m-th sample of an OFDM symbol is given by

$$x_m = \sum_{n=1}^{N} X_n e^{j\frac{2\pi mn}{N}} \qquad 0 \le m \le N-1 \qquad 2.2$$

Where X_n is the transmitted data symbol on the nth carrier. Equation (2.2) is equivalent to the N-point inverse discrete Fourier transform (IDFT) operation on the data sequence with the omission of a scaling factor. It is well known that IDFT can be implemented efficiently using inverse fast Fourier transform (IFFT). Therefore, in practice, the IFFT is performed on the data sequence at an OFDM transmitter for baseband modulation and the FFT is performed at an OFDM receiver for baseband demodulation. Size of FFT and IFFT is N, which is equal to the number of sub channels available for transmission, but all of the channels needs to be active. The sub-channel bandwidth is given by

$$f_{sc} = \frac{1}{T} = \frac{f_{samp}}{N} \qquad 2.3$$

Where f_{samp} the sample rate and Ts is is the symbol time.

Finally, a baseband OFDM symbol is modulated by a carrier to become a bandpass signal and transmitted to the receiver. In the frequency domain, this corresponds to translating all the subcarriers from baseband to the carrier frequency simultaneously.

2.5 INTERSYMBOL AND INTERCARRIER 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 intersymbol interference (ISI) [7]. In OFDM, ISI usually refers to interference of an OFDM symbol by previous OFDM symbols.

In OFDM, the spectra of subcarriers overlap but remain orthogonal to each other. This means that at the maximum of each sub-carrier spectrum, all the spectra of other subcarriers are zero [23]. The receiver samples data symbols on individual sub-carriers at the maximum points and demodulates them free from any interference from the other subcarriers. Interference caused by data symbols on adjacent sub-carriers is referred to intercarrier interference (ICI).

The orthogonality of subcarriers can be viewed in either the time domain or in frequency domain. From the time domain perspective, each subcarrier is a sinusoid with an integer number of cycles within one FFT interval. From the frequency domain perspective, this corresponds to each subcarrier having the maximum value at its own center frequency and zero at the center frequency of each of the other subcarriers. Figure 2.5 shows the spectra of four subcarriers in the frequency domain for the orthogonality case. The orthogonality of a subcarrier with respect to other subcarriers is lost if the subcarrier has nonzero spectral value at other subcarrier frequencies. From the time domain perspective, the corresponding sinusoid no longer has an integer number of cycles within the FFT interval. Figure 2.6 shows the spectra of four subcarriers in the frequency domain when orthogonality is lost. ICI occurs when the multipath channel varies over one OFDM symbol time. When this happens, the Doppler shift on each multipath component causes a frequency offset on the subcarriers, resulting in the loss of orthogonality among them. This situation can be viewed from the time domain perspective, in which the integer number of cycles for each subcarrier within the FFT interval of the current symbol is no longer maintained due to the phase transition introduced by the previous symbol. Finally, any offset between the subcarrier frequencies of the transmitter and receiver also introduces ICI to an OFDM symbol

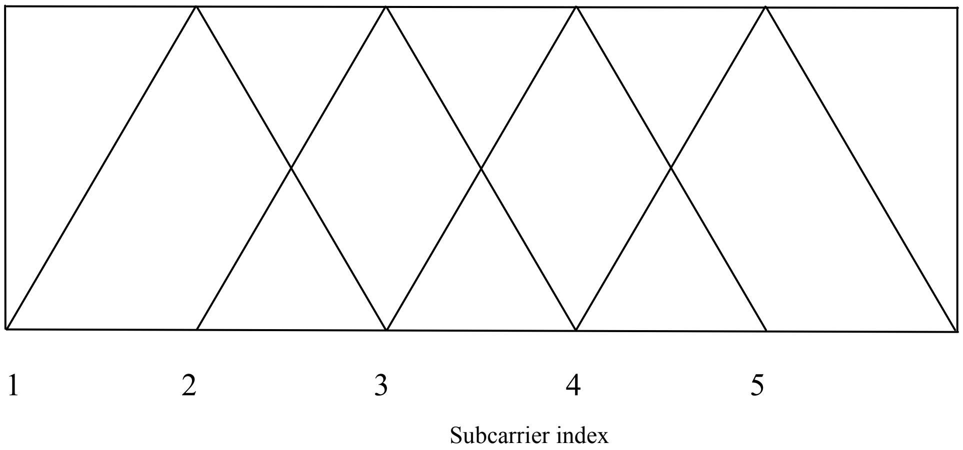

Fig 2.5: Spectra of four orthogonal subcarriers

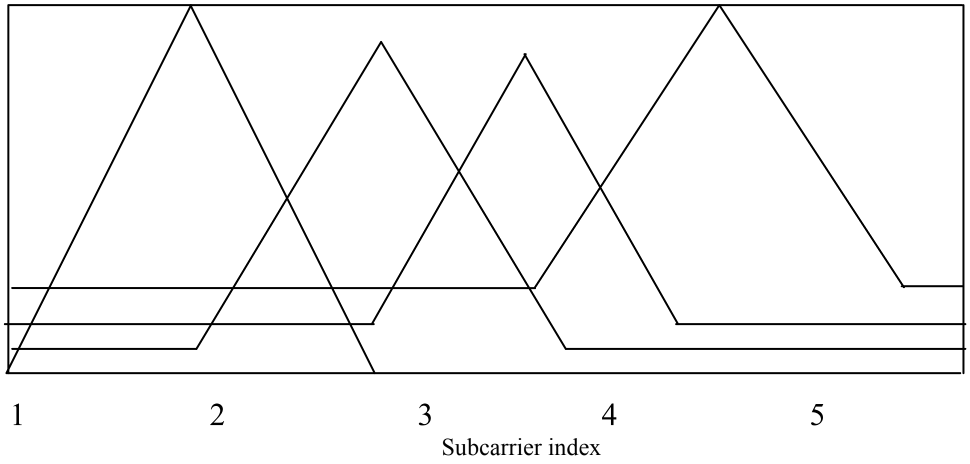

Fig 2.6: Spectra of four non-orthogonal subcarrier

2.6 GUARD TIME INSERTION

One of the most important properties of OFDM transmissions is its high level of robustness against multipath delay spread. This is a result of the long symbol period used, which minimizes the inter-symbol interference. The level of multipath robustness can be further increased by the addition of a guard period between transmitted symbols. The guard period allows time for multipath signals from the pervious symbol to die away before the information from the current symbol is gathered. 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 multipath immunity as well as symbol time synchronization tolerance. As long as the multipath delay echoes stay within the guard period duration, there is strictly no limitation regarding the signal level of the echoes: they may even exceed the signal level of the shorter path! The signal energy from all paths just add at the input to the receiver, and since the FFT is energy conservative, the whole available power feeds the decoder. If the delay spread is longer then the guard interval then they begin to cause inter-symbol interference. However, provided the echoes are sufficiently small they do not cause significant problems. This is true most of the time as multipath echoes delayed longer than the guard period will have been reflected of very distant objects.

CHAPTER 3

SYSTEM DESCRIPTION

In this chapter fully description of OFDM system is given. The whole description of the system is based on discrete domain.

DESCRIPTION OF BASE BAND OFDM SYSTEM

The OFDM system based on pilot channel estimation is given in Figure 3.1.

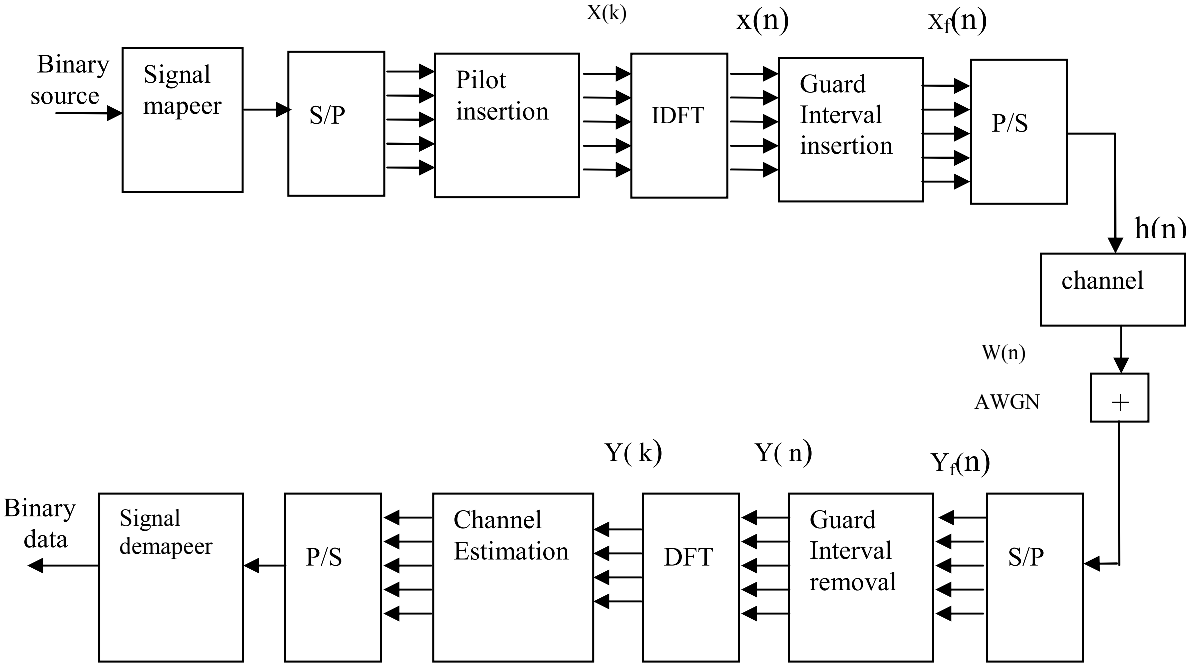

Fig. 3.1: Baseband OFDM system

The binary information is first grouped and mapped ac-cording to the modulation in "signal mapeer". After inserting pilots either to all sub-carriers with a specific period or uniformly between the information data sequence, IDFT block is used to transform the data sequence of length into time domain signal with the following equation

$$x(n) = IDFT\{X(k)\} \qquad n = 0,1,2.....N-1$$

$$= \sum_{k=0}^{N-1} X(k)e^{j(2\pi kn/N)} \qquad 3.1$$

Where N is the DFT length. Following IDFT block, guard time, which is chosen to be larger than the expected delay spread, is inserted to prevent inter-symbol interference.

This guard time includes the cyclically extended part of OFDM symbol in order to eliminate inter-carrier interference (ICI). The resultant OFDM symbol is given as follows:

$$\begin{aligned} x_f(n) &= x(N+n), \qquad && n = -N_g, -N_g+1, \ldots\ldots, -1 \\ &= x(n) && n = 0, 1, \ldots\ldots N-1 \end{aligned} \qquad 3.2$$

where N_g is the length of the guard interval

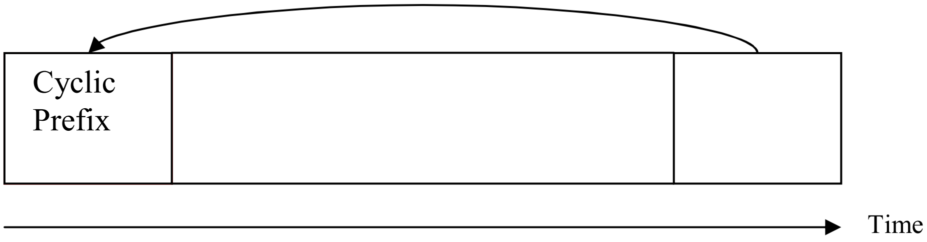

Fig 3.2 OFDM symbols with cyclic

The transmitted signal $x_f(n)$ will pass through the frequency selective time varying fading channel with additive noise. The received signal is given by:

$$y_f(n) = x_f(n) \otimes h(n) + w(n) \qquad 3.3$$

where $w(n)$ is Additive White Gaussian Noise (AWGN) and $h(n)$ is the channel impulse response. The channel response can be represented by [32]:

$$h(n) = \sum_{i=0}^{r-1} h_i e^{j(2\pi/N) f_{di} T n} \delta(\lambda - \tau_i) \qquad 0 \leq n \leq N-1 \qquad 3.4$$

where r is the total number of propagation paths, h_i is the complex impulse response of the ith path, f_{di} is the ith path Doppler frequency shift, λ is delay spread index, T is the sample period and τ_i is the ith path delay normalized by the sampling time. At the receiver, after passing to discrete domain through A/D and low pass filter, guard time is removed:

$$\begin{aligned} & y_f(n) && \text{for } (-N_g \le n \le N-1) \\ y(n) &= y_f(n+N_g) && n = 0,1,......N-1 \end{aligned} \qquad 3.5$$

Then $y(n)$ is sent to DFT block for the following operation:

$$\begin{aligned} Y(k) &= DFT\{y(n)\} \quad k = 0,1,2....N-1 \\ &= \frac{1}{N}\sum_{n=0}^{N-1} y(n)e^{-j(2\pi kn/N)} \end{aligned} \qquad 3.6$$

Assuming there is no ISI, [33] shows the relation of the resulting $Y(k)$ to $H(k) = DFT\{h(n)\}$, and $W(k) = DFT\{w(n)\}$, with the following equation:

$$Y(k) = X(k)H(k) + W(k) \qquad 3.7$$

Following DFT block, the pilot signals are extracted and the estimated channel $\hat{H}(k)$ for the data sub-channels is obtained in channel estimation block. Then the transmitted data is estimated by:

$$\hat{X} = \frac{Y(k)}{\hat{H}(k)} \qquad k = 0,1.....N-1 \qquad 3.8$$

Then the binary information data is obtained back in “signal demapeer” block. Based on principle of OFDM transmission scheme, it is easy to assign the pilot both in time domain and in frequency domain.

CHAPTER 4

CHANNEL ESTIMATION IN OFDM SYSTEMS

INTRODUCTION

A wideband radio channel is normally frequency selective and time variant. For an OFDM mobile communication system, the channel transfer function at different subcarriers appears unequal in both frequency and time domains. Therefore, a dynamic estimation of the channel is necessary. Pilot-based approaches are widely used to estimate the channel properties and correct the received signal. In this chapter we have investigated two types of pilot arrangements.

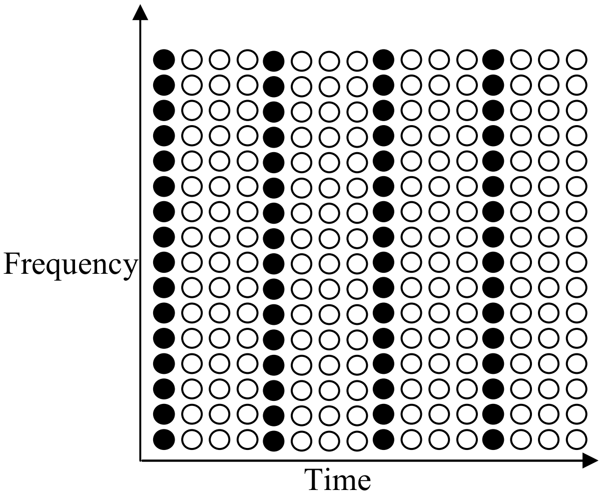

Fig. 4.1: Block type pilot arrangement

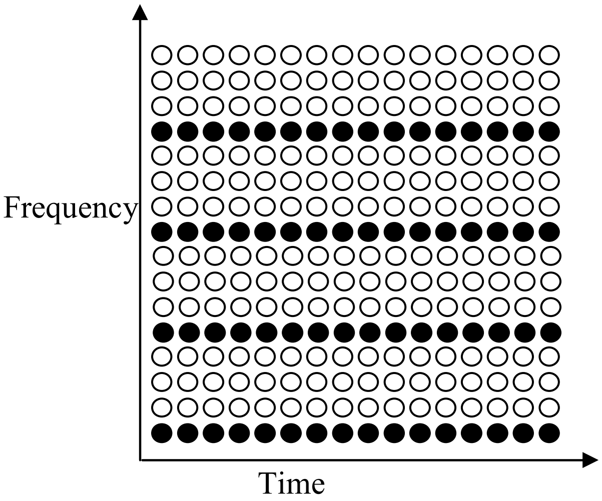

Fig. 4.2 : Comb type pilot arrangement

The first kind of pilot arrangement shown in Figure 4.1 is denoted as block-type pilot arrangement. The pilot signal assigned to a particular OFDM block, which is sent periodically in time-domain. This type of pilot arrangement is especially suitable for slow-fading radio channels. Because the training block contains all pilots, channel interpolation in frequency domain is not required. Therefore, this type of pilot arrangement is relatively insensitive to frequency selectivity. The second kind of pilot arrangement shown in Figure 4.2 is denoted as comb-type pilot arrangement. The pilot arrangements are uniformly distributed within each OFDM block. Assuming that the payloads of pilot arrangements are the same, the comb-type pilot arrangement has a higher re-transmission rate. Thus the comb-type pilot arrangement system is provides better resistance to fast-fading channels. Since only some sub-carriers contain the pilot signal, the channel response of non-pilot sub-carriers will be estimated by interpolating neighboring pilot sub-channels. Thus the comb-type pilot arrangement is sensitive to frequency selectivity when comparing to the block-type pilot arrangement system.

4.1 CHANNEL ESTIMATION BASED ON BLOCK-TYPE PILOT ARRANGEMENT

In block-type pilot based channel estimation, OFDM channel estimation symbols are transmitted periodically, in which all sub-carriers are used as pilots. If the channel is constant during the block, there will be no channel estimation error since the pilots are sent at all carriers. The estimation can be performed by using either LSE or MMSE [23], [34].

If inter symbol interference is eliminated by the guard interval, we write (3.7) in matrix notation:

$$\begin{aligned} Y &= XFh + W \\ &= XH + W \end{aligned} \qquad 4.1$$

Where

$$\begin{aligned}
X &= diag\ \{X(0), X(1), \ldots\ldots X(N-1)\} \\
Y &= [Y(0), Y(1), \ldots\ldots Y(N-1)]^T \\
W &= [W(0), W(1), \ldots\ldots W(N-1)]^T \\
H &= [H(0), H(1), \ldots\ldots H(N-1)]^T = DFT_N\{h\} \\
F &= \begin{bmatrix} W_N^{00} & \cdots & W_N^{0(N-1)} \\ \vdots & \ddots & \vdots \\ W_N^{(N-1)0} & \cdots & W_N^{(N-1)(N-1)} \end{bmatrix} \\
W_N^{nk} &= \frac{1}{N} e^{-j2\pi(n/N)k}
\end{aligned} \qquad 4.2$$

4.1.1 Minimum Mean Square Error (MMSE) Estimation:

MSE (mean square error) $J(e) = E[(H-\hat{H})^2]$

$$= E[(H-\hat{H})^{\mathcal{H}}(H-\hat{H})] \qquad 4.3$$

Here $\hat{H} = MY$ where M is a linear estimator.

Invoking the well-known orthogonality principle in order to minimize the mean square error vector $e = H - \hat{H}$ has to be set orthogonal by the MMSE equalizer to the estimators input vector Y.

That is $$E[(H-\hat{H})Y^{\mathcal{H}}] = 0 \qquad 4.4$$

$$\Rightarrow \; E[HY^{\mathcal{H}}] - ME\,[YY^{\mathcal{H}}] = 0$$

$$\Rightarrow \; E[FhY^{\mathcal{H}}] - ME\,[YY^{\mathcal{H}}] = 0$$

If the time domain channel vector h is Gaussian and uncorrelated with the channel noise W, then

$$FR_{hY} = MR_{YY} \tag*{4.5}$$

Where $R_{hY} = E[hY^{\mathcal{H}}]$ and $R_{YY} = E[YY^{\mathcal{H}}]$

$$R_{hY} = E[hY^{\mathcal{H}}] = E[h(XFh + w)^{\mathcal{H}}]$$

$$R_{hY} = R_{hh}F^{\mathcal{H}}X^{\mathcal{H}}$$

because of $E[hw^{\mathcal{H}}] = 0$ i.e. h is uncorrelated with w.

And
$$R_{YY} = E[YY^{\mathcal{H}}] = E[(XFh + w)(XFh + w)^{\mathcal{H}}]$$

$$R_{YY} = XFR_{hh}F^{\mathcal{H}}X^{\mathcal{H}} + \sigma^2 I_N \tag*{4.6}$$

where σ^2 is the variance of noise.

$$M = FR_{hY}R_{YY}^{-1} \tag*{4.7}$$

$$\hat{H} = FR_{hY}R_{YY}^{-1}Y \tag*{4.8}$$

The time domain MMSE estimate of h is given by

$$\hat{h}_{MMSE} = R_{hY}R_{YY}^{-1}Y \tag*{4.9}$$

4.1.2 Least Square Error (LSE) Estimation:

We have to minimize

$$J = (Y - XH)^{\mathcal{H}}(Y - XH) \tag*{4.10}$$

$$= (Y^T - H^{\mathcal{H}}X^{\mathcal{H}})(Y - XH)$$

$$= Y^{\mathcal{H}}Y - Y^{\mathcal{H}}XH - H^{\mathcal{H}}X^{\mathcal{H}}Y + H^{\mathcal{H}}X^{\mathcal{H}}XH \tag*{4.11}$$

For minimization of J we have to differentiate J with respect to H

$$\left.\frac{\partial J}{\partial H}\right|_{\hat{H}} = 0 \tag*{4.12}$$

That is

$$-2Y^{\mathcal{H}}X - 2\hat{H}^{\mathcal{H}}X^{\mathcal{H}}X = 0$$

$$\Rightarrow Y^{\mathcal{H}} X = \hat{H}^{\mathcal{H}} X^{\mathcal{H}} X$$

$$\Rightarrow (Y^{\mathcal{H}} X)(X^{\mathcal{H}} X)^{-1} = \hat{H}^{\mathcal{H}} (X^{\mathcal{H}} X)(X^{\mathcal{H}} X^{-1})$$

$$\Rightarrow Y^{\mathcal{H}} X X^{-1} (X^{\mathcal{H}})^{-1} = \hat{H}^{\mathcal{H}}$$

$$\Rightarrow Y^{\mathcal{H}} (X^{\mathcal{H}})^{-1} = \hat{H}^{\mathcal{H}}$$

$$\Rightarrow \hat{H} = [(X^{\mathcal{H}})^{-1}]^{\mathcal{H}} Y$$

$$\Rightarrow \hat{H} = [(X^{\mathcal{H}})^{-1}]^{\mathcal{H}} Y = X^{-1} Y$$

$$\Rightarrow \hat{H} = X^{-1} Y \qquad 4.13$$

The time domain LS estimate of h is given by

$$\hat{h} = F^{\mathcal{H}} X^{-1} Y \qquad 4.14$$

4.2 CHANNEL ESTIMATION BASED ON COMB-TYPE PILOT ARRANGEMENT:

In comb-type based channel estimation, the n_p pilot signal are uniformly inserted into X(k) according to following equation:

$$\begin{aligned} X(k) &= X(mL + l) \\ &= \{X_p(k), \qquad l = 0 \\ &= \{\inf .data \qquad l = 1, \ldots\ldots. L-1 \end{aligned} \qquad 4.15$$

Where $L =$ number of carriers $/ n_p$

Suppose that the frequency-selective channels remain invariant over an OFDM block, and length of the cyclic prefix exceeds the channel order. After demodulation the demodulation, the received signal on the nth subcarrier corresponding to pilot symbols can be written as

$$Y[k] = \sqrt{\varepsilon_p} H(k) X(n) + w(k) \quad , \quad k \in \Im_p \qquad 4.16$$

Where $\Im_p$ denotes the set of subcarriers on which the pilot symbols are transmitted, ε_p is the transmitted power per pilot symbol, $H(k)$ is the channel frequency response on kth carrier $X(k), k \in \Im_p$, is the pilot symbol, and $w(k)$ is the complex additive white Gaussian noise (AWGN) with zero-mean and variance $N_0 / 2$

The received samples corresponding to information symbols can be expressed as

$$\mathrm{Y[k]} = \sqrt{\varepsilon_s}\, H(k)X(k) + w(k),\ \mathrm{k} \in \Im_s \qquad 4.17$$

Where ε_s the transmitted power per information is symbol, and $\Im_s$ denotes the set of subcarriers on which the information symbols are transmitted. Suppose that the total number of subcarrier is N, and set of $\Im_p$ is $|\Im_p| = P$. For simplicity, we assume that the size of $\Im_s$ is $|\Im_s| = N - P$, although it is possible that $|\Im_s| < N - P$, when null subcarriers are inserted for spectrum shaping .Selecting information symbols from M-PSK constellation, we have also that $|X(k)| = 1, \forall k \in \Im_s$. The frequency-selective channel is assumed to be Rayleigh-fading, with channel impulse response $h := [h(0), \ldots\ldots\ldots, h(L-1)]^T$ where L denoting the number of taps; i.e. $h(l),\ \forall l \in [$ 0, L -1], are uncorrelated complex Gaussian random variables with zero-mean. Channels are normalized so that $\sum_{l=0}^{L-1} \sigma_h^2(l) = 1$.Define the $L \times N$ matrix $[F]_{l,n} := \exp(j2\pi(l-1)(k-1)/N$, and let f_n of F .Then $H(k) = f_k^{\mathcal{H}} h$, is a complex Gaussian variable with zero-mean and unit variance. The average signal-to-noise ratio (SNR) per pilot (information) symbol is ε_p / N_0 (ε_s / N_0). The AWGN variables $w(k)$ are assumed to be uncorrelated, $\forall k$.

Suppose that the set of pilot subcarrier is given by $\Im_p = \{k_i\}_{i=1}^{P}$. Letting $H_p := [H(k_1), \ldots\ldots, H(k_p)]^T$ contains frequency response on pilot subcarriers, and defining $F_p := [f_{k_1}, \ldots\ldots, f_{k_p}]$, we can relate the fast Fourier transform (FFT) pair via: $H_p = F_p^{\mathcal{H}} h$. Let the $P \times 1$ vector $Y = [Y(k_1), \ldots\ldots Y(k_p)]^T$ consist of the received pilot samples per block, and define $X_p := [X(k_1), \ldots\ldots, X(k_p)]^T$, and $w := [w(k_1), \ldots\ldots\ldots, w(k_p)]^T$.From (4.16) we have

$$Y = \sqrt{\varepsilon_p} D(X_p) H_p + w = \sqrt{\varepsilon_p} D(X_p) F_p^{\mathcal{H}} h + w \qquad 4.18$$

Given X_p and Y, we wish to estimate h based on (4.18). While it may be possible to use pilot samples from different OFDM blocks to estimate the channel. We will rely on pilots from only one block to estimate the channel on a per block basis. This is particularly suitable for packet data transmission, where the receiver may receive different blocks with unknown delays.

4.2.1 Minimum Mean Square Error (MMSE) Estimation:

With knowledge of channel statistics channel estimation in MMSE [35] way can be written as

$$\hat{h} = R_{yh}^{\mathcal{H}} R_{yy}^{-1} y \tag*{4.19}$$

Where $R_{yy} := E[yy^{\mathcal{H}}] = \varepsilon_p D(X_p) F_p^{\mathcal{H}} R_{hh} F_p D^{\mathcal{H}}(X_p) + N_0 I_p$

$R_{yh} := E[yh^{\mathcal{H}}] = \sqrt{\varepsilon_p} D(X_p) F_p^{\mathcal{H}} R_{hh}$

And $R_{hh} := E[hh^{\mathcal{H}}] = diag(\sigma_h^2(0),.....,\sigma_h^2(L-1))$

The channel estimator is given by $\in = h - \hat{h}$, which is Gaussian distributed with zero-mean, and covariance $R_{\in} := E[\in\in^{\mathcal{H}}] = (R_{hh}^{-1} + \varepsilon_p F_p F_p^{\mathcal{H}} / N_0)^{-1}$ where $\sigma_h^2(l) \neq 0, \forall l$, so that R_{hh} is invertible. The estimated channel frequency response on nth carrier can be obtained as:- $\hat{H}(k) = f_k^{\mathcal{H}} \hat{h} = H(k) - \in(k)$, where $\in(k) := f_k^{\mathcal{H}} \in$ with $\in(k) \sim CN(0, \sigma_{\in(k)}^2)$, and $\sigma_{\in(k)}^2 := f_k^{\mathcal{H}} R_{\in} f_k$.

The estimator $\hat{H}(k)$ is Gaussian distributed with zero mean .Since the ortogonality principle renders $\in$ uncorrelated with h, $\in(k)$ and $\hat{H}(k)$ are uncorrelated.

4.2.2 Least Square Error (LSE) Estimation:

If we define $G := (\varepsilon_p F_p D^{\mathcal{H}}(X_p) D(X_p) F_p^{\mathcal{H}})^{-1} (\sqrt{\varepsilon_p} D(X_p) F_p^{\mathcal{H}})^{\mathcal{H}}$, then the least-square error (LSE) estimate of channel impulse response is given by[35]

$$\hat{h} = Gy = h + \eta \tag*{4.20}$$

Where $\eta = Gw$.

Using the fact that $D^{\mathcal{H}}(X_p) D(X_p) = I_p$, it follows readily that $\eta \sim CN(0, (F_p F_p^{\mathcal{H}})^{-1} N_0 / \varepsilon_p)$

The estimated channel frequency response on the kth subcarrier can be obtained as

$$\hat{H}(k) = f_k^{\mathcal{H}} \hat{h} = H(k) + v(k) \tag*{4.21}$$

Where $v(n) \sim CN(0, \sigma_{v(k)}^2)$ with $\sigma_{v(k)}^2 := f_k^{\mathcal{H}} (F_p F_p^{\mathcal{H}})^{-1} f_k N_0 / \varepsilon_p$

4.2.3 Channel Estimation Based On Interpolation Techniques:

Without going back to time domain channel frequency response for each subcarrier can be found by using interpolation techniques. In comb-type pilot based channel estimation, an efficient interpolation technique is necessary in order to estimate channel at data sub-carriers by using channel information at pilot sub-carriers.

Channel transfer function at pilot sub-carriers estimated from (4.16) in LSE sense. The estimated transfer function at pilot frequencies will be

$$\hat{H}_p(k) = \frac{Y(k)}{\sqrt{\varepsilon_p} X_p(k)} \quad \text{for} \quad k \in \Im_p \qquad 4.22$$

4.2.3.1 Linear Interpolation:

In the linear interpolation algorithm, two successive pilot sub-carriers are used to determine the channel response for data sub-carriers that are located in between the pilots. The channel estimation at data-carriers k, $mL < k < (m+1)L,$ is given by:

$$\begin{aligned} H(n) &= H_d(n) \\ &= H_d(mL+l) \qquad 0 \le l \le L \\ &= (H_p(m+1) - H_p(m))\frac{l}{L} + H_p(m) \qquad 4.23 \end{aligned}$$

4.2.3.2 Spline and Cubic Interpolation:

Spline and Cubic interpolations are done by using “interp1” function of *MATLAB*. Spline and Cubic interpolations produce a smooth and continuous polynomial fitted to given data points. Spline interpolations works better than linear interpolation for comb pilot arrangement.

CHAPTER 5

RESULTS
AND
DISCUSSION

An OFDM system is modeled using Matlab to allow various parameters of the system to be varied and tested. The aim of doing the simulations is to measure the performance of OFDM system under different channel conditions, and to allow for different OFDM configurations to be tested.

5.1 OFDM MODEL USED IN SIMULATIONS

An OFDM system model used is shown in Figure 5.1.

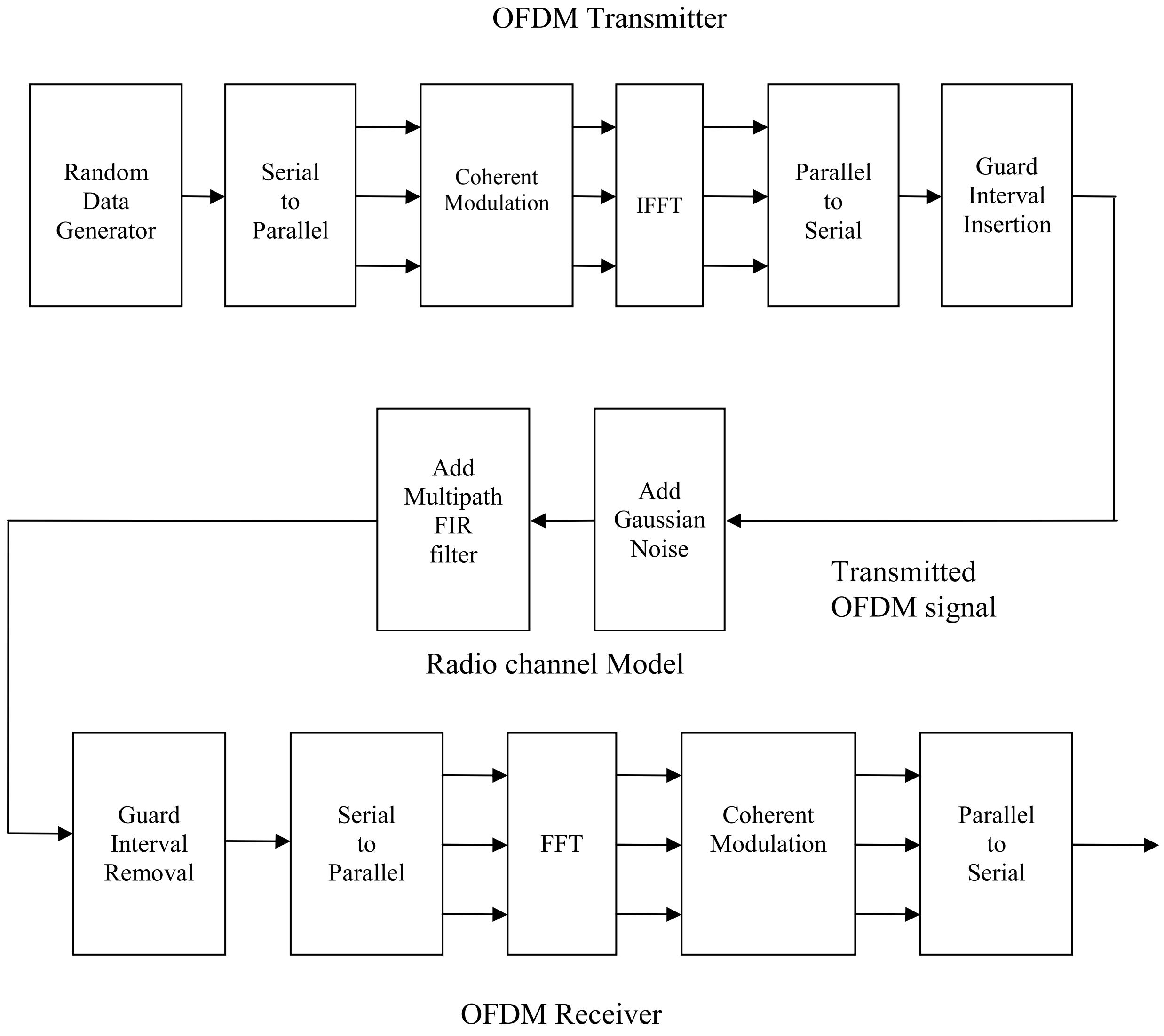

Fig. 5.1: OFDM model used for Simulations

The input signal which we used is the random data generated by *randn*() function of the matlab, and limit the data to its maximum value e.g. 16 (for 16QAM).

SERIAL TO PARALLEL CONVERSION:

The input serial data stream is formatted into the word size required for transmission, e.g. 2bit/word for QPSK, and shifted into a parallel format. The data is then transmitted in parallel by assigning each data word to one carrier in the transmission.

MODULATION OF DATA

The data to be transmitted on each carrier is modulated into a QAM and M-ary PSK format. The data on each symbol is mapped. In the simulations we used 16-QAM BPSK,QPSK,8PSK modulation.

INVERSE FOURIER TRANSFORM

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

CHANNEL MODEL USED

A Channel model is then applied to the transmitted signal. Standard channel models used in mobile radio environment have been referred from [29],[35]. The model allows for the signal to noise ratio and multipath to be controlled. The signal to noise ratio is set by adding a known amount of white noise to the transmitted signal.

(1) In the block type pilot arrangement 16-QAM modulation scheme is used for a 64-subcarrier OFDM system with a two ray multipath channel. The channel impulse response $h(t)$ is a time limited pulse train in the form of [29]

$$h(t) = \sum_m \alpha_m \delta(t - \tau_m T_s)$$

Where the amplitudes α_m are complex valued, τ_m is m th path delay and T_s is sampling time. Guard time T_G is taken such that $0 \le \tau_m T_s \le T_G$ .The above continuous time relationship can be represented as a discrete time version having discrete channel impulse response $h(n)$ as:

$$h(n) = \sum_m \alpha_m e^{-j\frac{\pi}{N}(n+(N-1)\tau_m)} \frac{\sin(\pi\tau_m)}{\sin(\frac{\pi}{N}(\tau_m - n))}$$

In the simulation for block type pilot arrangement we have taken two ray multipath channels.

$$h(t) = \delta(t - 0.5T_s) + \delta(t - 3.5T_s)$$

(2) In comb type pilot arrangement we have considered Rayleigh-fading channel. The frequency selective channel is assumed to be Rayleigh-fading, with channel impulse response $h(l) = [h(0),........h(L-1)]^T$, where L=40 is the number of taps are uncorrelated complex Gaussian random variables with zero mean[35]. We adopt an exponential power profile delay for taps.

RECEIVER

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

5.2 SIMULATION RESULT FOR BLOCK TYPE PILOT ARRANGEMENT

In the simulation we consider a system operating with a bandwidth of 500 kHz, divided into 64 tones with total symbol period of 138 µs, of which 10 µs is a cyclic prefix. Sampling is performed with a 500 kHz rate. A symbol thus consists of 69 samples, five of which are contained in the cyclic prefix. 10,000 channels are randomized per average SNR. We consider the two ray channel as $h(t) = \delta(t - 0.5T_s) + \delta(t - 3.5T_s)$ [29]. Figure 5.2 demonstrates discrete time impulse response |h(n)| at different taps. Figure 5.3 demonstrates Mean square error of channel estimation at different SNRs in dB. As SNR increases mean square error decreases for both LSE and MMSE. Figure 5.4 shows Average SNR versus Symbol Error Rate (SER). As SNR increases Symbol Error Rate decreases for both cases. For a given SNR, MMSE estimator shows better performance than LSE estimator. The complexity of MMSE estimators will be lager than LSE estimators but give better performance in comparison to LSE. It should be noticed that MMSE estimators have been derived under assumption of known channel correlation and noise variance. In practice these quantities R_{hh} and σ_n^2, are either taken as fixed or estimated, possibly in an adaptive way. This will increase the estimator complexity but improve performance over LSE estimators.

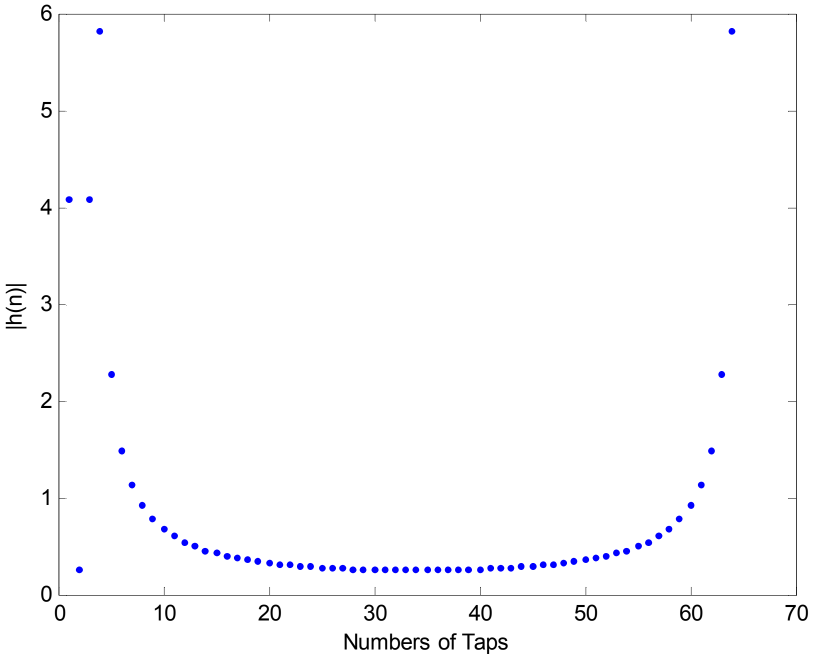

Fig 5.2: Channel impulse response |h(n)|

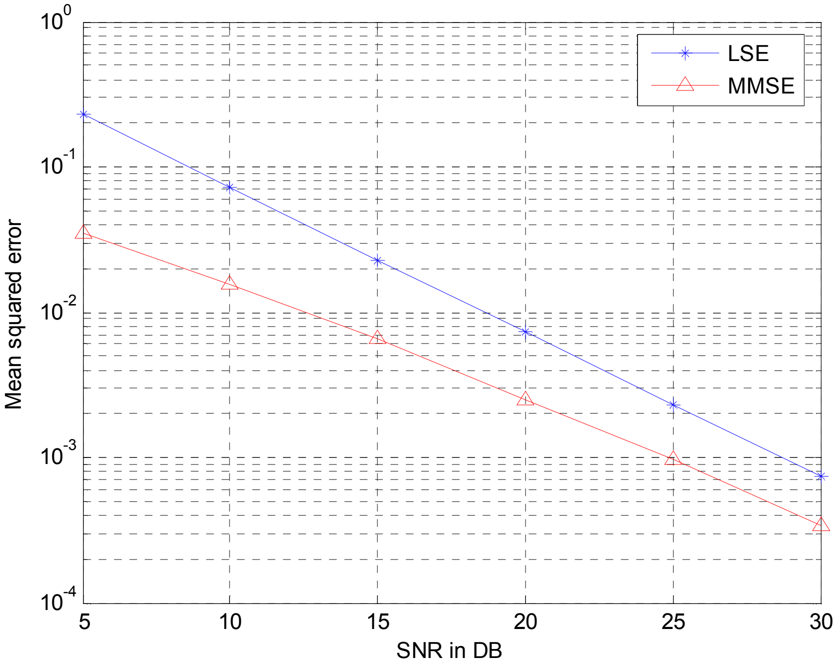

Fig. 5.3: Mean-Square Error for LSE and MMSE estimators at different SNRs.

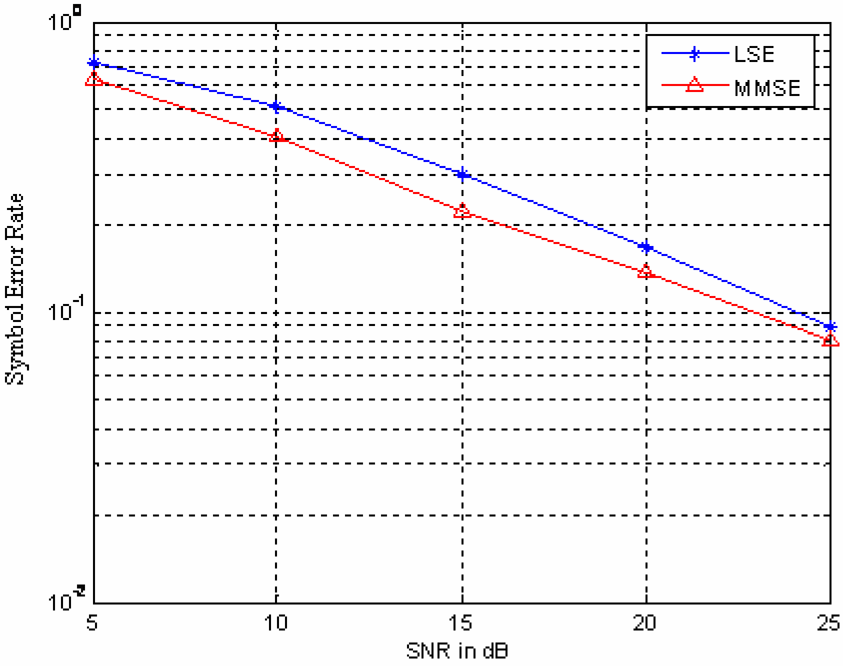

Fig. 5.4: SER for LSE and MMSE estimators at different SNRs

5.3 SIMULATION RESULT FOR COMB-TYPE PILOT ARRANGEMENT:

For comb type pilot arrangement we consider an OFDM system with N=1024 subcarriers. The frequency selective Rayleigh channel has L= 40 zero-mean uncorrelated complex Gaussian random taps.

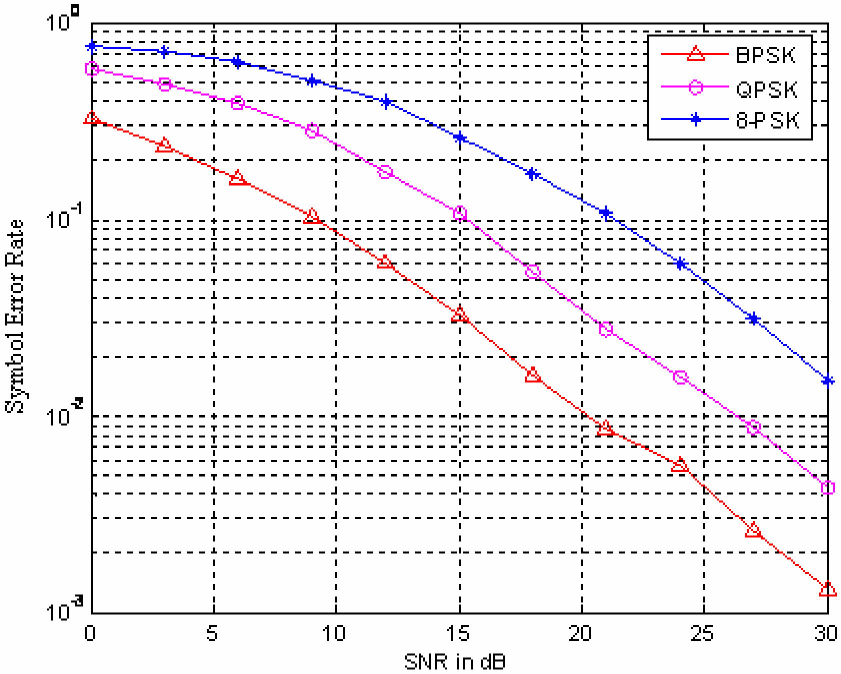

Fig. 5.5: SER (MMSE channel Estimation) for M-PSK modulation for different SNRs

The spacing between pilots are taken as 4. So the number of pilots are 256 and number of information symbols are 768. In the simulation we consider BPSK, QPSK and 8-PSK modulations. Figure 5.5 and Figure 5.6 demonstrate Symbol Error Rate (SER) performance (SNR versus SER) for different modulations in MMSE and LSE estimators respectively. It shows that as SNR increases the Symbol error rate decreases and also by going higher order modulation Symbol Error Rate increases which is coming true as we expected.

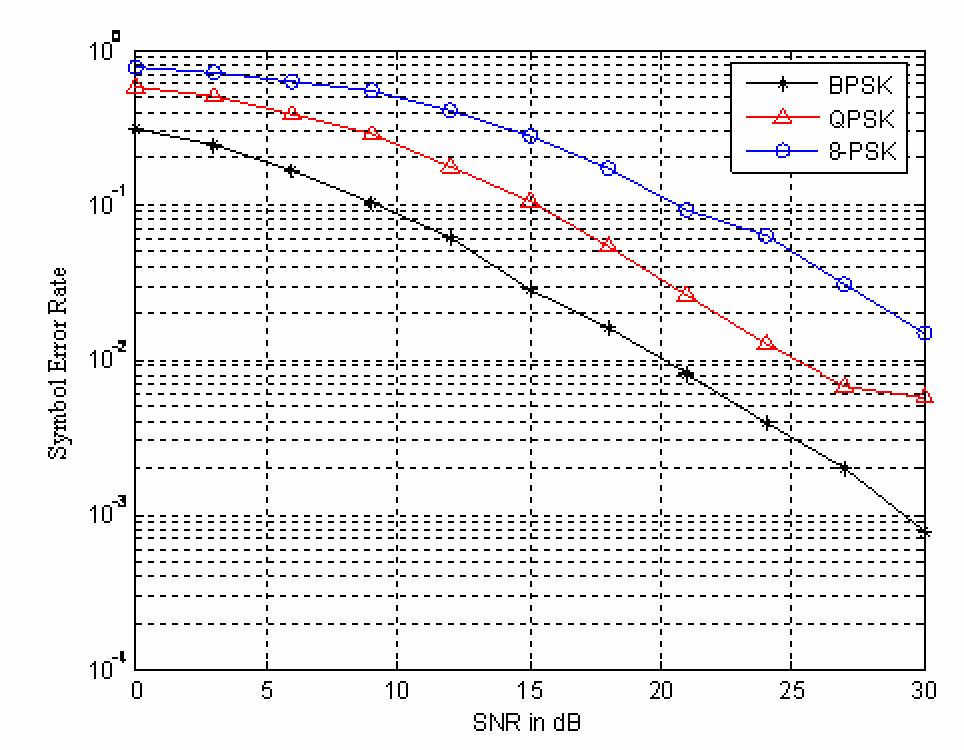

Fig. 5.6: Bit Error rate versus SNR (LSE channel Estimation) for M-PSK modulation

In Figure 5.7 we compared the performance between MMSE and LSE estimators. MMSE estimators have less Symbol Error Rate than LSE estimators in low SNRs. But at higher SNRs both will have equal performance. At lower SNRs noise is the prominent factor. In this case MMSE estimator works better. But at higher SNRs, it is better to go for LSE estimator because of its simplicity where noise is less effective. Figure 5.8 shows result for interpolation techniques used in the simulation. The interpolation techniques are applied to LSE estimation. It is found that spline interpolation having better performance than linear interpolation.

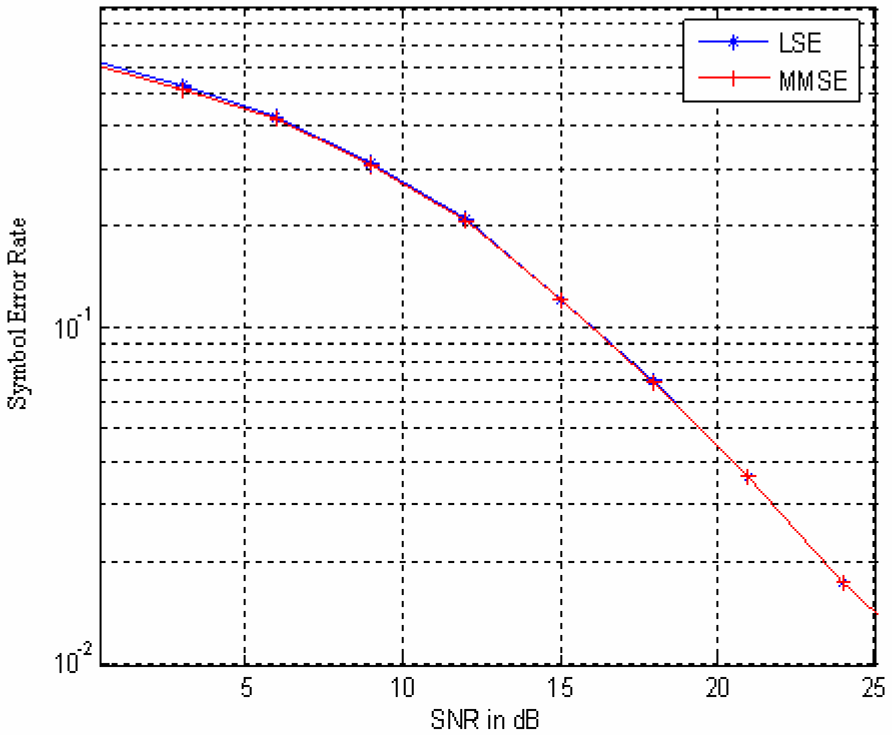

Fig. 5.7: SER comparison between LSE and MMSE channel estimation

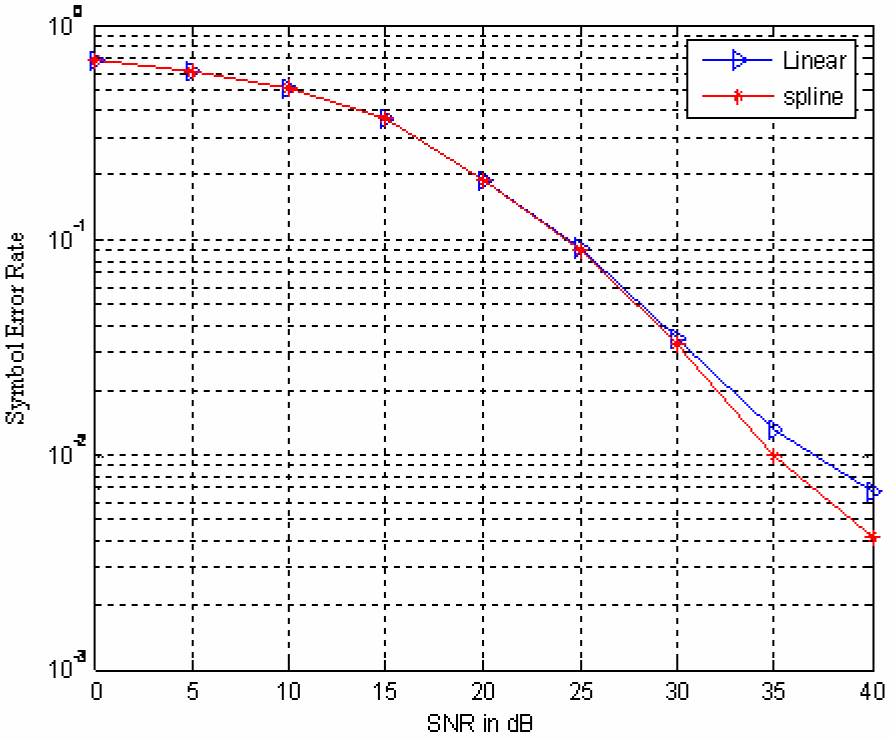

Fig. 5.8: BER comparison between Linear and Spline interpolations

Figure 5.9 and Figure5.10 demonstrate the Mean square error versus Number of pilots for MMSE and LSE estimators respectively. As number of pilots increases mean square error decreases. With the increase in number of pilots, MSE reduces and achieves the lower limit. So increasing the number of pilots beyond certain limit becomes unnecessary. Further sending more number of pilots results decrease in number of information symbols and redundant pilots can be eliminated.

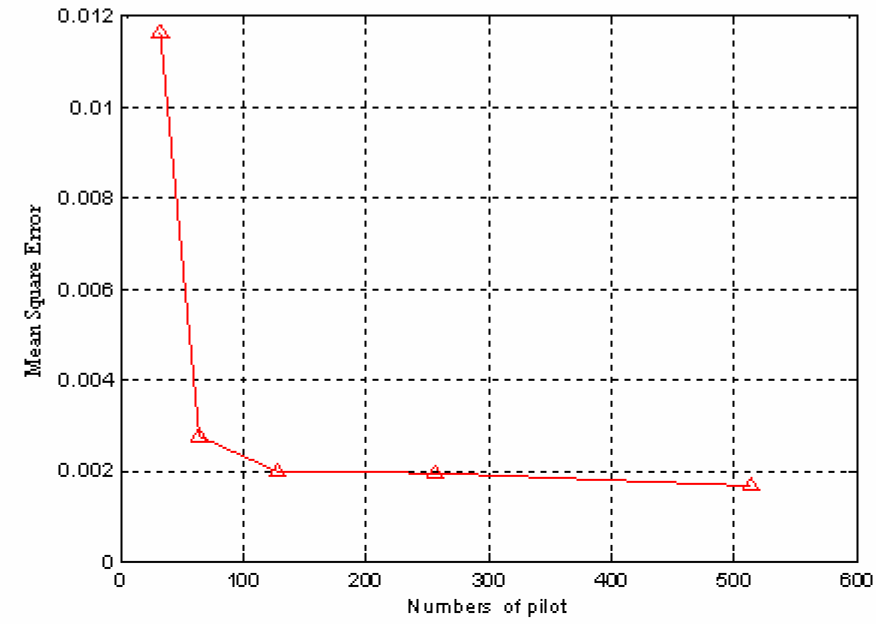

Fig. 5.9: Mean Square Error versus Number of pilots (MMSE estimation)

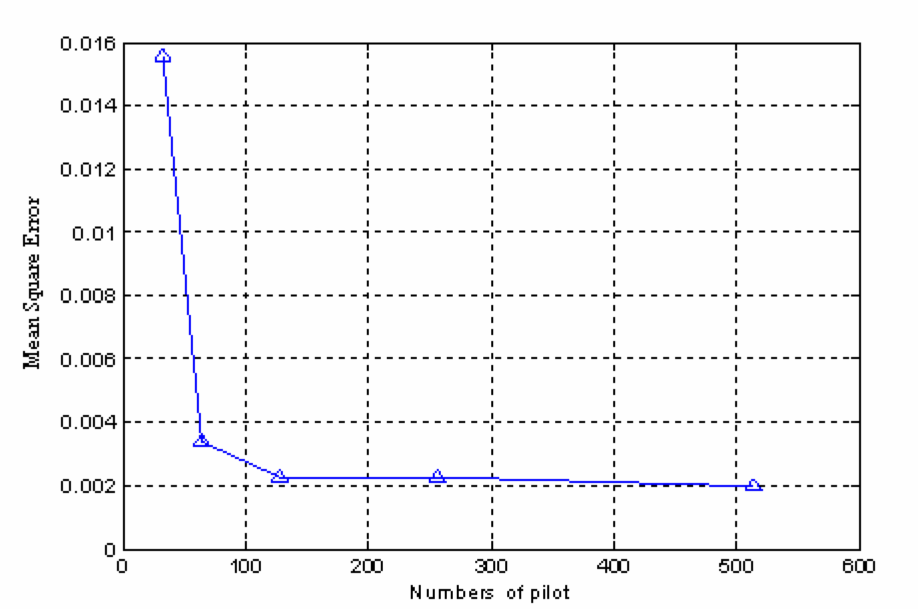

Fig. 5.10: Mean Square Error versus Number of pilots (LSE estimation)

CHAPTER 6

CONCLUSION
AND
FUTURE WORK

6.1 CONCLUSION

In this work, we have studied LSE and MMSE estimators for both block type and comb type pilot arrangement. The estimators in this study can be used to efficiently estimate the channel in an OFDM system given a certain knowledge about channel statistics. The MMSE estimators assume a priori knowledge of noise variance and channel covariance. Moreover, its complexity is large compare to the LSE estimator. For high SNRs the LSE estimator is both simple and adequate. The MMSE estimator has good performance but high complexity. The LSE estimator has low complexity, but its performance is not as good as that MMSE estimator basically at low SNRs.

In comparison between block and comb type pilot arrangement, block type of pilot arrangement is suitable to use for slow fading channel where channel impulse response is not changing very fast. So that the channel estimated, in one block of OFDM symbols through pilot carriers can be used in next block for recovery the data which are degraded by the channel. In our simulation of block type pilot arrangement we used two ray static channel for 16-QAM modulation. Here 64 numbers of carriers are used in one OFDM block. We calculated BER and MSE in channel estimation for different SNRs in simulation.

Comb type pilot arrangement is suitable to use for fast fading channel where the channel impulse response is changing very fast even if one OFDM block. So comb type of pilot arrangement can not be used in this case. We used both data and pilot carriers in one block of OFDM symbols. Pilot carriers are used to estimate the channel impulse response. The estimated channel can be used to get back the data sent by transmitter certainly with some error. In the simulation we used 1024 number of carriers in one OFDM block. In which one fourth are used for pilot carriers and rest are of data carriers. We calculated BER for different SNR conditions for M-PSK signaling. We also have compared performance of LSE with MMSE estimator. MMSE estimation is better that LSE estimator in low SNRs where at high SNRs performance of LSE estimator approaches to MMSE estimator. We also used interpolation techniques for channel estimation. It is found that higher order interpolation technique (spline) is giving better performance than lower order interpolation technique (linear). In simulation we have also calculated MSE for estimation of channel with number of pilot arrangement. MSE decreases when number of pilots increase. But we have to limit the number pilots when mean square error comes constant.

6.2 FUTURE WORK

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

1. Implementation of other interpolation techniques for channel estimation:
   In this work we have considered only two type interpolation techniques. We can extend this work for other interpolation techniques such as second order, low-pass etc.
2. Feasibility study of Multiple Input Multiple Output (MIMO) OFDM systems:
   In this study we have discussed about Single Input Single Output (SISO) OFDM systems. MIMO OFDM can be implemented using multiple transmitting and receiving antennas which is an interesting work of future.

REFERENCES

[1] Rappaport, T., Wireless Communication: Principles and Practice. New Jersey: Prentice Hall, 1996.

[2] Chang, R., "Synthesis of band limited Orthogonal Signals for multichannel data transmission." Bell System Technical Journal. vol. 46, (December 1996): pp. 1775-1796.

[3] Proakis, J., Digital Communications. New York: McGraw-Hill, 1998.

[4] Torrance, J., and Hanzo, L., "Comparative study of pilot symbol assisted modem systems." Proceedings of IEEE conference on Radio Receivers and Associated Systems, Bath UK, (September 1995): pp. 36-41.

[5] Weinstein, S. and Ebert, P., "Data Transmission by Frequency Division Multiplexing using the Discrete Fourier Transform." IEEE Transaction Communication Technology. vol. COM-19, (October 1971): pp. 628-634.

[6] Bello, P. A., "Selective Fading limitations of the KATHRYN modem and some system design considerations." IEEE Transaction Communication Technology. vol.COM-13, (1965): pp. 320-333.

[7] Zimmerman, M. and Krisch, A., "The AN/GSC-10/KATHRYN/ variable rate data modem for HF radio." IEEE Transaction Communication Technology. vol.CCM-15,(April 1967): pp.197-205.

[8] Hirosaki, B., "An analysis of automatic equalizers for orthogonally multiplexed QAM systems," IEEE Transaction Communication Technology. vol. COM-28, (January 1980): pp. 73-83.

[9] Peled, A. and Ruiz, A., "Frequency Domain Data Transmission using Reduced Computational Complexity Algorithms." Proceedings of International Conference on Acoustics. vol. 3, (April 1980): pp. 964-967.

[10] Ketel, I., "The Multitone Channel." IEEE Transaction on Communication. vol. 37, (February 1989): pp. 119-124.

[11] Fazel, K. and Fettis, G., "Performance of an Efficient Parallel Data Transmission System." IEEE Transaction Communication Technology. (December 1967): pp. 805-813.

[12] Meyr, H., Moeneclaey, M. and Fechtel, S. A., Digital Communicatio Receivers. John Wiley and Sons, 1998.

[13] Li, Y., Seshadri, N. and Ariyavisitakul, S., "Channel Estimation for OFDM systems with transmitter diversity in mobile wireless channels." IEEE J. Select. Areas Communication (March 1999): pp. 461-470.

[14] Moher, M. L. and Lodge, J. H., "TCMP- a modulation and coding strategy for Rician fading channels," IEEE Trans. Communication Technology. (December 1967): pp.805-813.

[15] Aghamohammadi, A., Meyr, H., and Asheid, G., "A new method for phase synchronization and automatic gain control of linearly modulated signals on frequency flat fading channels," IEEE Trans. Communication Technology. (January 1991): pp.25-29.

[16] Cavers, J. K., "An analysis of Pilot symbol assisted modulation for Rayeigh fading channels." IEEE Transaction on Vehicular Technology. vol. 40(4), (November 1991):pp. 686-693.

[17] Moon, JAe Kyoung and Choi, Song In., "Performance of channel estimation methods for OFDM systems in multipath fading channels." IEEE Transaction on Communication Electronics. vol.46, (February 2000): pp. 161-170.

[18] Tufvesson, F., Faulkner, M., Hoeher, P. and Edfors, O., "OFDM Time and Frequency Synchronization by spread spectrum pilot technique." 8th IEEE Communication Theory Mini Conference in conjunction to ICC'99, Vancouver, Canada, (June 1999): pp. 115-119.

[19] Tufvesson, F. and Hoeher, P., "Channel Estimation using Superimposed pilot Sequences," IEEE Trans. Communication (March 2000).

[20] Moon, T. K., "The Expectation Maximixzation Algorithm." IEEE Signal Processing Magazine. vol. 13, (November 1996): pp. 47-60.

[21] Xiaoqiand, Ma., Kobayashi, H. and Schwartz, Stuart C., "An EM Based Estimation of OFDM Signals." IEEE Transaction Communication. (2002).

[22] Edfors, O., Sandell, M.,Van de Beek, J. J., Wilson, S. K. and Boriesson, P. O., "Analysis of DFT-based channel estimators for OFDM." Vehicular Technology Conference. (July 1995).

[23] Coleri, S., Ergen, M., Puri, A. and Bahai, A., "Channel Estimation Techniques based on Pilot Arrangement in OFDM systems," IEEE Transaction on Broadcasting. (September 2002).

[24] Edfors, O., Sandell, M., Van de Beek, J. J., Wilson, S. K. and Boriesson, P. O., "OFDM Channel Estimation by Singular Value Decomposition." IEEE Transaction on Communication. vol. 46(7), (July 1998): pp. 931-939.

[25] Wang, X., Ray Liu, K. J., "OFDM Channel Estimation based on time frequency polynomial model of fading multipath channels." IEEE Transaction on Communication. (June 2001).

[26] Julia Fernadez-Getino Garcia, M., Edfors, O. and Paez-Borrallo, Jose M., "Frequency offset correction for coherent OFDM in mobile cellular systems." Proceedings of IEEE. (2001).

[27] Tufvesson, F. and Maseng, T., "Pilot Assisted Channel Estimation for OFDM in Mobile Cellular Systems," Proceedings of IEEE Vehicular Technology Conference, Phoenix USA, (May 1997):pp. 1639-1643.

[28] Hieh, MEng-Han and Wei, Che-Ho, "Channel Estimation for OFDM Systems based on COMB-Type Pilot arrangement in frequency selective fading channels." IEEE Transaction Communication. (1998).

[29] Van de Beek, J. J., Edfors, O., Sandell, M., Wilson, S.K., and Borjesson, P. O., "On Channel Estimation in OFDM Systems." Proceedings IEEE 45th Vehicular Technology Conference. Chicago, IL., (July 1995): pp. 815-819.

[30] Fazel, K. and Fettwis, G., "Performance of an efficient parallel Data Transmission System." IEEE Transaction Communication Technology. (December 1967): pp. 805-813.

[31] Warner, W. and C. L. Leung C. L., "OFDM/FM frame synchronization for mobile radio data communication." IEEE Transaction on Vehicular Technology. vol. 42, (August 1993): pp. 302-313.

[32] Cimini, L. J., "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing." IEEE Transaction Communication. vol. 33, no. 7, (July 1985): pp. 665–675.

[33] Li, Y., “Pilot-symbol-aided channel estimation for OFDM in wireless systems.” IEEE Transaction Vehicular Technology. vol. 49, no. 4,(Jul. 2000).

[34] Bahai, A. R. S. and Saltzberg, B. R., Multi-Carrier Digital Communications: Theory and Applications of OFDM. Kluwer Academic/Plenum, 1999.

[35] Cai, Xiaodong and Giannakis, Georgious B., “Error Probability Minimizing Pilots for OFDM with M-PSK Modulation Over Rayleigh-Fading Channels.” IEEE Transaction. Vehicular Technology. vol. 53, no.1, (January 2004): pp. 146-145.