PERFORMANCE ANALYSIS OF CHANNEL ESTIMATION METHODS IN OFDM SYSTEMS

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PERFORMANCE ESTIMATION OF CHANNEL ESTIMATION METHODS IN ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

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I certify that in my opinion the thesis submitted by Khawla Mohsan Guma GAMILA titled "CHANNEL MODELING AND ESTIMATION FOR WIRELESS COMMUNICATION SYSTEMS USING A TIME-FREQUENCY APPROACH" is fully adequate in scope and in quality as a thesis for degree of Master of Science.

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This thesis is accepted by the examining committee with a unanimous vote in the Department of Electrical-Electronics Engineering as master thesis. December 18, 2017

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The degree of Master of Science by the thesis submitted is approved by the Administrative Board of the Graduate School of Natural and Applied Sciences, Karabuk University.

Prof. Dr. Filiz ERSÖZ ....
Head of Graduate School of Natural and Applied Sciences

"I declare that all the information within this thesis has been gathered and presented in accordance with academic regulations and ethical principles and I have according to the requirements of these regulations and principles cited all those which do not originate in this work as well."

Khawla Mohsan Guma GAMILA

ABSTRACT

M. Sc. Thesis

PERFORMANCE ESTIMATION OF CHANNEL ESTIMATION METHODS IN ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

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Graduate School of Natural and Applied Sciences
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Orthogonal frequency Division Multiplexing (OFDM) technique is a promising technology due to its attractive advantages, including; efficient bandwidth utilization, high data rates and lower multi-path distortion. However, radio frequency (RF) channel introduces distortion to the signal causing inter-symbol interference and hence there is a need for channel estimation methods that allows determining that distortion.

This thesis evaluates the performance for several channel estimation methods, such as "Least squares (LS)", "Minimum Mean Square Error (MMSE)", "Time-Domain Linear Minimum Mean Square Error (TD-LMMSE)", "Time Division Duplex Linear Minimum Mean Square Error (TDD-LMMSE)", "Time Domain absolute value of the Quadrature signal LMMSE (TD Q_{abs} LMMSE)", theory-LS and theory-LMSSE.

The evaluation is performed on MATLAB environment in terms of channel MSE. The evaluation is performed by varying different parameters, including, modulation order, FFT size, beta, cyclic prefix length. The performance of the considered methods varies differently according to these parameters. Larger modulation order results in worse performance because more symbols are sent, which results in higher probability of error. On the other hand, better MSE performance is achieved with larger FFt size. Using larger guard bands reduces the probability of interference between symbols and hence lower MSE is obtained.

Generally, MMSE is the best channel estimation method since it achieved the minimum MMSE in most of the considered cases, while theory LS achieved the worst MSE performance.

Key Words : Orthogonal frequency division multiplexing, channel estimation, least squares, minimum mean square error, time-domain linear minimum mean square error.

Science Code : 905.1.053

ÖZET

Yüksek Lisans Tezi

ZAMAN FREKANS YAKLAŞIMI KULLANARAK KABLOSUZ İLETİŞİM SİSTEMLERİ İÇİN KANAL MODELLEMESİ VE TAHMİNİ

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Dikey frekans bölmeli çokluma (DFBÇ) tekniği, cazip avantajları sayesinde umut verici bir teknolojidir. Bununla birlikte, radyo frekans (RF) kanalı sinyalin bükülmesine yol açarak semboller arası parazit yaratır ve bu bükülmeyi belirlemeye izin veren kanal tahmin yöntemlerine ihtiyaç duyulmaktadır.

Bu tez, "En Küçük Kareler" (KK), "Minimum ortalama karesel hata" (MOKH), "Zaman bölmesi doğrusal minimum ortalama karesel hata" (ZB-DMOKH), "Çift yönlü zaman bölmesi minimum ortalama karesel hata" (ÇYZB-DMOKH), "Zaman bölmesi dördün DMOKH sinyalin mutlak değeri", KK-teori ve DMOKH-teori gibi birçok kanal tahmin yönteminin performansını değerlendirmektir.

Değerlendirme, OKH kanalında MATLAB ortamında yapılmıştır. Değerlendirme, modülasyon sırası, FFT boyutu, beta, çevrim önek uzunluğu ve kanal da dahil olmak üzere farklı parametrelerin değiştirilmesi ile gerçekleştirildi. Bu yöntemlerin performansı bu parametrelere göre farklılık gösterir ancak MOKH, kabul edilen vakaların çoğunda minimum OKH 'ye elde ettiği için en iyi kanal tahmin yöntemidir.

Anahtar Kelimeler : Dikey frekans bölmeli çokluma, kanal tahmini, küçük kareler, minimum ortalama karesel hata, zaman bölmesi doğrusal minimum ortalama karesel hata.

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I would like to thank my great mother, my lovely family and friends, for their encouragement, support, and unwavering love, which makes my dream come true. I appreciate support and patience of my wife and children.

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SYMBOLS AND ABBREVITIONS INDEX

SYMBOLS

n(t) : Noise

T_s : Sampling time

Q : Channel estimator

T_G : Guard interval

α_m : Channel fading parameter

ABBREVITIONS

AWGN : Additive White Gaussian Noise

OFDM : Orthogonal Frequency Division Multiplexing

SNR : Signal to-Noise Ratio

IFFT : Inverse Fast Fourier Transform

FFT : Fast Fourier Transform

DFT : Discrete Fourier Transform

IDFT : Inverse Discrete Fourier Transform

SISO : Single Input Single Output communication

MIMO : Multiple Inputs Multiple Outputs

SIMO : Single Input Multiple Output

MISO : Multiple Input Single Output

LS : Least squares

MMSE : Minimum Mean Square Error

TD-LMMSE : Time-Domain Linear Minimum Mean Square Error

TD Q_{abs} LMMSE : Time Domain absolute value of the Quadrature signal LMMSE

MSE : Mean Square Error

QoS : Quality of Service

CFR : Channel Frequency Response

CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

With the continuous development and improvements in the communication technology field, there is an increasing demand for services that provide higher values of data rate, including voice, data and multimedia over wireless and wired links. This in turn increases the need for developing new schemes for transferring large data amount oppositely from existing techniques. In practice, higher data rate, minimum delay and allowable "Bit Error Rate (BER)" should be provided by these techniques. As example of these technique is the Orthogonal Frequency Division Multiplexing (OFDM) [1, 2].

Generally, OFDM is a promising choice technique for future wireless communication systems due to its attractive advantages, including high-data-rate transmission capability, lower multi-path distortion and efficient bandwidth utilization. Within OFDM technology, the whole bandwidth of the channel is partitioned into many sub-channels with narrow bandwidth, hence, this allows the conversion of a frequency-selective channel into groups of frequency at the channels. Furthermore, "Inter-Symbol Interference (ISI)" is being avoided by the applying cyclic prefix (CP) that is achieved by the extension of OFDM symbol frames with some portion of their tail or head [3, 4].

In practice, "Digital Audio Broadcasting (DAB)" has adopted the technology of OFDM and many other applications such as "Wireless Local Area Network (WLAN)" technology that is referred to IEEE 802.11a/b/g/n. As well, the OFDM has been used as a core technique for the fourth-generation (4G) of mobile communication networks [5].

“Signal-to-Noise Ratio (SNR)” is a measurement used to describe how much desired sound is presented in an audio recording, as opposed to unwanted sound (noise). The need for channel tracking, estimation and “Differential Phase Shift Keying (DPSK)” is employed by OFDM systems. Hence, this result appears as a 3 dB loss in SNR if when it compared to that in coherent demodulation like phase-shift keying (PSK). The performance of OFDM systems can be well improved by permitting coherent demodulation when the accurate channel estimation technique is being utilized [6].

1.2. PROPAGATION OF SIGNALS OVER WIRELESS CHANNEL

Wireless communication networks perform efficiently by means of controlling and managing the channel environments. Practically, the wireless channel case is a dynamic and cannot be predicted, which makes the exact analysis of that wireless communication system a difficult task. Recently, wireless communication systems optimization becomes critical due to rapid growth in mobile communication applications and services where it becomes possible to access the broadband internet by the mobile [7].

In fact, well-understanding of wireless channels will put the strong foundation to develop the performance in high level and efficient bandwidth of wireless transmission techniques. In wireless communication, the radio propagation is referring to the behavior of radio waves at the time they are propagating from a transmitter towards a receiver. During the propagation, radio waves are basically affected by three different physical phenomena; diffraction, scattering and reflection [8].

Reflection is a physical phenomenon that exists when an electromagnetic wave is propagated. It impinges upon an object at very large dimensions as compared to the wavelength, where the earth surface and constructions are examples of such phenomenon. It is forcing the transmitted signal power to be reflected back towards its origin instead of getting to the receiver [9].

The diffraction represents various phenomena, which occur when the radio path between the receiver and transmitter is obstructed by sharp irregularities surfaces or small openings. It looks as though bending of waveforms around the small obstacles and then spreading out the small openings of waves past. The secondary waves that are generated by diffraction could be useful for creating a path between the receiver and transmitter, even when the line-of-sight type of path is not presented [10].

Scattering is also a physical phenomenon that forces the electromagnetic wave radiation to deviate from the straight path by one or more local obstacles of small dimensions as compared to the wavelength. These obstacles that induce scattering, as lamp posts, street signs and foliage are treated as scatters. On the other hand, the radio wave propagation is uneasy and less predicted process, where it is managed and affected by scattering, diffraction, reflection, and their intensity is varying with different environments at different cases [10, 11].

Fading phenomenon is a unique characteristic in a wireless channel regardless of the variation of signals amplitude over frequency and time. In contrast with the additive type of noise that is considered as a common source of signals degradation, another source of signal degradation is fading. It is characterized as a non-additive signal disturbance in the wireless channels. Fading can be generated due to the multipath propagation, which known as multi-path fading, or due to the shadowing from physical obstacles that affect the radio wave propagation, which known as shadow fading [12].

The fading phenomenon in wireless communication channel was initially modeled for HF (High Frequency, 3_30MHz), UHF (Ultra HF, 300_3000 GHz), and SHF (Super HF,3_30 GHz) bands in themid-1900s. At that time, the most popular channel in wireless networks was established for 800MHz to 2.5 GHz band by extensive channel measurements in the field. These involve the ITU-R standard channel models specialized for a single-antenna model communication network, which typically known as a Single Input Single Output communication (SISO) over some frequency set of bands [13].

Previously, spatial channel models for a multi-antenna communication system, which known as MIMO (Multiple Input Multiple Output) systems, have been recently developed using various research and standardization activities, such as IEEE 802, METRA Project, 3GPP/3GPP2, and WINNER Projects, with a purpose to get high-speed wireless transmission and diversity gain. The fading phenomenon can be generally arranged into two different kinds; small-scale fading and large-scale fading [14].

In general, the large-scale fading happens as the mobile equipment moves through a large distance in coverage area, such as a distance of cell's size order. It happens due to signal path loss as a function of the distance and shadowing by large physical objects such as constructions, vegetation and intervening terrains.

Shadowing is a slow fading procedure, which observed by frequent change in the median path loss among the channel, receiver and transmitter in a specific area. Moreover, the large-scale fading is characterized based on considering the shadowing and the mean of path loss. Furthermore, small-scale fading refers to the very quick changing in the levels of the signal because of the destructive and constructive interference of multi-path channel [15].

Depending on the relative extent of the multipath, the selectivity in the frequency of a channel is being characterized (e.g., by frequency flat or frequency-selective) for the small-scale fading.

Meantime, depending upon the variation in time within the channel due to the speed of mobile unit (characterized by the mean Doppler spread), the short-term fading can be distributed as either slow fading or fast fading [16]. In Figure 1.1 is illustrated Fading types on wireless channel.

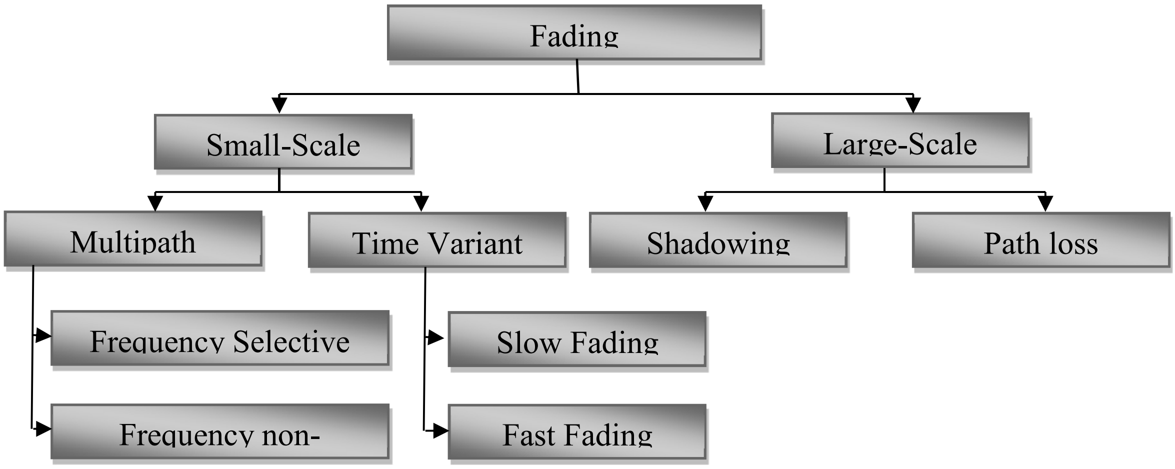

Figure 1.1. Fading types on wireless channel [12].

1.3. PROBLEM STATEMENT

During the signal propagation between the transmitter and the receiver, the transmitted signal is often subjected to several phenomena related to the propagation environment that results during the reception. Practically, a signal is composed of multiple elementary signals; where these signals take different paths and therefore have different propagation times and amplitudes. It exhibits phase shifts that can lead to a recombination of constructive and destructive ways, where this in turn causes a complete disappearance of the signal. The latter phenomenon commonly known as "fading" and it may affect the performance of mobile cellular networks.

In fading, the amplitude of a signal received can follow several statistical distributions such as Rayleigh, Nakagami. In this context, the evaluation of the performance of these systems is essential to develop highly efficient systems to deliver data in an efficient way from the transmitter to the receiver with considering different effects of the noisy channel. The transmission in any wireless network aims to be error less with considering large revolution in data applications. Thus, enormous amount of user's data is supposed to be exchanged throughout the network.

Recently, the need for using additional technologies to reduce those performance impacts in communication systems is increasing over time. OFDM is one of the promising techniques that is used in current and future communication systems due to different benefits achieved by this technique, such as; resilience to multipath distortion, lower multi-path distortion and high spectral efficiency.

Practically, there are several estimation methods for the wireless channel that are used with OFDM technique, such as; Least squares (LS), Minimum Mean Square Error (MMSE), Time-Domain Linear Minimum Mean Square Error (TD-LMMSE), Time Division Duplex Linear Minimum Mean Square Error (TDD-LMMSE), Time Domain absolute value of the Quadrature signal LMMSE (TD Q_{abs} LMMSE), theory-LS and theory-LMSSE. Evaluating the performance of the communication system under these methods is essential and critical in order to determine which one of these methods is effective to be used.

1.4. PURPOSE OF THE STUDY

This thesis aims to implement an OFDM system in MATLAB and evaluate its BER performance using different estimation methods; LS, MMSE, TD-LMMSE, (TDD-LMMSE), (TD Q_{abs} LMMSE), theory-LS and theory-LMSSE. Several objectives are expected to be achieved throughout this thesis, which are:

- Investigate and demonstrate the concepts of OFDM system and its benefits.
- Investigate different channel estimation methods that were mentioned previously.
- Develop the OFDM system on MATLAB and evaluate its MSE performance.
- Implement different channel estimation methods in MATLAB.
- Evaluate the BER performance for the seven estimation methods.

1.5. PROPOSED WORK

The concept of OFDM has always been the most popular technology for wireless networks with high data rate of transmission. This is due to the good achieved results of this technology over the schemes of single carrier modulation in the vicinity of frequency selective, multi-path fading channels. However, Inter-Carrier Interference

(ICI), which resulted from frequency shifts (Doppler effects) and multipath fading is severely degrading the OFDM systems performance, then accurate channel parameters estimation is strongly required at the receiver end. Hence, after the receiver getting the proper imagination about the channel impact on the transferred signals, the decoding, demodulating and other receiver's functions can be designed to reduce these impacts on the channel. In this work, the received signal is analyzed by the representation of time – frequency, in which the estimation was performed through the channel and then the channel modulation was taking place.

The resultant performance of the proposed system is examined under different levels of noisy channel. This method allows obtaining the transfer function of the time-dependent channel representation from the noisy channel output. Moreover, the estimated channel parameters can be employed to get best detection of data input at the receiver end. The work is performed in the MATLAB environment, where the same process is involved to test the received signal in many scenarios of the channel.

1.6. ORGANIZATION OF THE THESIS

This thesis is organized as follow:

Chapter 1: Introduction

This chapter presents an introduction to the OFDM systems, fading over wireless channel and estimation techniques that are related to the thesis topic. The chapter also presents the problem statement, purpose of the study and the proposed work throughout this research work.

Chapter 2: Literature Review

This chapter introduces a comprehensive theoretical background about estimation methods for OFDM system over wireless channel. The chapter also reviews some of previous studies and researches that are related to the thesis topic.

Chapter 3: Research Methodology

This chapter represents a detailed description for the setup model using MATLAB program.

Chapter 4: Results and Discussion

This chapter evaluates the performance of the simulated model in terms of different performance criteria. The results are explained in detail and compared to other models.

Chapter 5: Conclusion and Future Works

This chapter summarizes the whole work introduced in the thesis in addition to some headlines for future in order to improve our model performance.

CHAPTER 2

WIRELESS CHANNELS ALLOCATION

2.1. ANTENNA CONFIGURATIONS

In practice, “Multiple Inputs Multiple Outputs (MIMO)” communication is considered as one of the efficient signal processing methods that are employed to improve the wireless system performance using several antennas at the receiver, transmitter or both. In MIMO, the performance is improved via either exploiting or combating multipath scattering over communication channel between the receiver and transmitter [25]. MIMO comes with different formats or configurations as shown below.

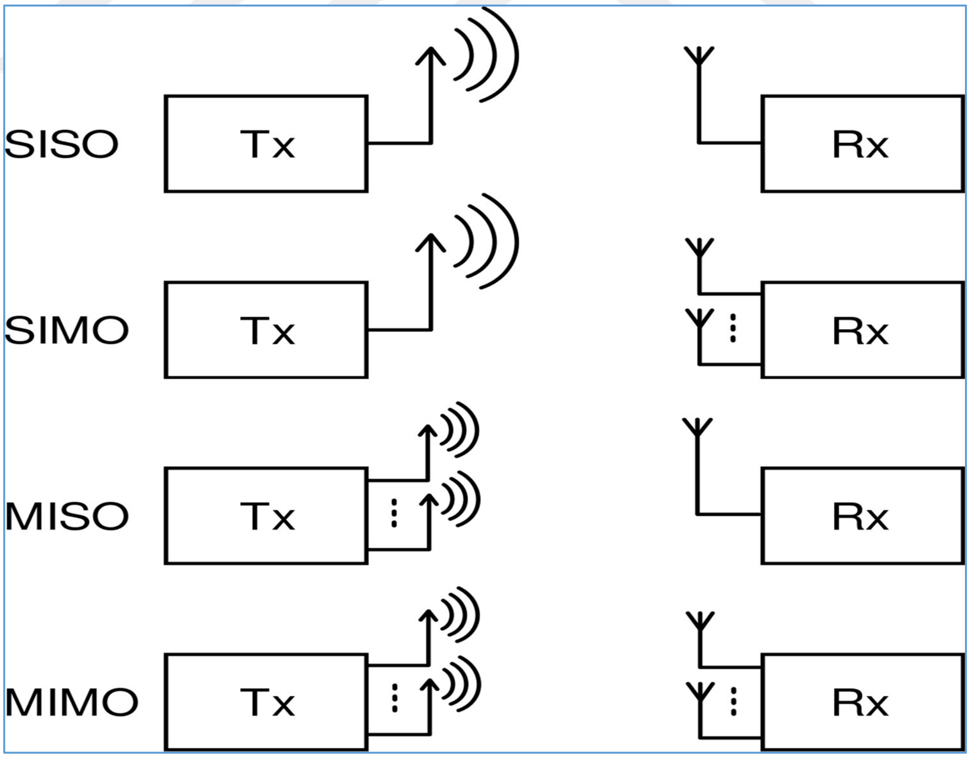

Figure 2.1. SISO, SIMO, MISO and MIMO formats [25].

As shown in Figure 2.3, there are four basic configurations [25]:

- Single Input Single Output (SISO)
- Single Input Multiple Output (SIMO)
- Multiple Input Single Output (MISO)
- Multiple Input Multiple Output (MIMO)

2.1.1. SISO

Practically, SISO is the simplest radio link form in which only single antenna is used at both the transmitter and receiver. This format has the simplicity benefit compared to other MIMO configurations since it does not need any additional processing or diversity. On the other hand, the performance of such configuration is limited and it is affected by both fading and interference more than other MIMO forms. Furthermore, there is a limit on the bandwidth according to Shannon limit, where the throughput is related to SNR and the channel bandwidth [25].

2.1.2. SIMO

SIMO is configured by using a single antenna at the transmitter side and several antennas at the receiver side.This form is usually employed in combating the fading effect within systems that receive signals from different independent sources. This format can be easily setup despite that some level of processing must be performed at the receiver side. However, the processing level is limited by battery drain, cost and receiver size [25].

2.1.3. MISO

This form is also called also the transmit diversity, where different antennas are used at the transmitter and only one single antenna in used at the receiver side. In MISO, same data are redundantly transmitted two times from two different antennas. The receiver in turn receives the optimum signal that can be used in extracting the required data. This format has benefits for the receiver since the process is changed to the transmitter side. Consequently, this positively affects the battery life, size and cost for the receiver [25].

2.1.4. MIMO

In MIMO, multiple antennas are used at both the receiver and the transmitter. It is employed mainly to improve the channel throughput and robustness but more processing must be performed at both side of radio channel [25].

2.2. LITERATURE REVIEW

Several works have been introduced during the last years concerning channel estimation on OFDM systems and other communication systems. Some of the recent conducted investigations are reviewed in this section.

In [26, 27, 28], researchers proposed various algorithms that depend on the subspace based on using both redundant linear pre-coding and non-redundant linear pre-coding. In such methods, the pre-coder of linear block is added at the transmitter side, while the channel information is gathered using the covariance matrix of the signals that received from the transmission.

In [29], researchers estimated the non-blind channel by inserting the pilot tones into a selected number of subcarriers for each symbol of OFDM or by inserting them into the all of subcarriers for symbols of OFDM within a particular period. In the worst scenario, a symbol of OFDM with the inserted pilot tones into all of subcarriers is very often known as training sequence and such sort of pilot arrangement may refer to as arrangement of block-type pilot.

In general, channel estimation methods can be divided into four categories; traditional channel estimation based on the Channel Frequency Response (CFR), parametric model (PM) based channel estimation, Iterative channel estimation (ICE), and channel estimation for MIMO-OFDM systems [30, 31]. Traditional channel estimation in

OFDM systems is based on estimating the CFR as stated in [32, 33]. CFRs of pilot symbols or training symbols are estimated first, then the CFRs of data symbols can be obtained through decision-based tracking or interpolation. For PM-based approaches proposed in [34], the channel is modeled using a set of parameters which are estimated to reconstruct the channel response in the receiver. Iterative processing has been extended to the overall design of the receiver. In MIMO-OFDM where signals from multiple antennas arrive at the receive antenna simultaneously, different channel estimation should be considered.

In [34], researchers presented a block-type of channel estimation that developed under the supposition of slow fading channel, where constant channel is assumed over one or more symbol periods of an OFDM symbol. The estimation of the channel for block-type pilot arrangement is based on “Least Square (LS)” or “Minimum Mean-Square Error” (MMSE). It is commonly known that MMSE estimators have a moderated performance but they suffer from a highly computational complexity. On the other hand, the Least Square estimators have low complexity, but their performance is not as well as that performance of Minimum Mean-Square Error estimators. The MMSEs estimation has been proposed to provide gain up-to 4 dB in SNR over the Least Square estimate for the same MSE of the estimation in the channel.

To decrease the complexity of the Minimum Mean-Square Error estimator, researchers in [35] presented a method of optimal rank-reduction to the linear Minimum Mean-Square Error estimators by exploiting the singular value decomposition (SVD) and the channel frequency correlation. Linear minimum mean square error (LMMSE) in turn uses additional information like the operating SNR and the other channel statistics. LMMSE is smoother, interpolator and extrapolator, and hence it is very attractive for the channel estimation of OFDM based systems with pilot subcarriers. Practically, “Time-Domain Linear Minimum Mean Square Error (TD-LMMSE)”, “Time Division Duplexing Linear Minimum Mean Square Error (TDD-LMMSE)” and “Time Domain absolute value of the Quadrature signal LMMSE (TD Qabs LMMSE)”, are subsets of LMMSE.

Researchers in [36] introduced that frequency domain techniques of channel estimation employ known symbols, called pilots at known positions in the OFDM symbol grid. These pilots were regularly arranged as a card type or block type. In a card type arrangement, pilots are found in several sub-carriers of all OFDM symbols, while pilots in block-type arrangement are found in several OFDM symbols in all sub-carriers. Reliability is better in terms of system BER for comb-type regulation in fast fading channel environments.

CHAPTER 3

RESEARCH METHODOLOGY

3.1. OVERVIEW

As stated early, this thesis aims to evaluate the performance of OFDM system under seven channel estimation methods. This chapter gives detailed description for the methodology that was followed during the work on the thesis. All needed flow charts and mathematical equations and expressions are introduced in this chapter.

3.2. GENERAL METHODOLOGY FLOW CHART

Several stages were considered during evaluating the performance of the seven estimation methods on OFDM system, the following flow chart summarizes these steps.

The first step of this research is preliminary and deep study for OFDM based communication system as shown in Figure. 3.1. The basic concepts of OFDM system are covered with al needed flow chart and equations related to this system. The second step is identifying the metric that will be used in evaluating the OFDM system performance.

In our work, channel "Mean Squared Error (MSE)" is considered as performance criterion. The next step is to model the steps that will be theoretically followed in evaluating the OFDM performance. This will be performed via extensive study for each step OFDM system, with its inputs and outputs. The considered channel estimation methods will be then investigated in order to be understood before being simulated. MATLAB program is then used in simulating the OFDM system involving the seven estimation methods. The performance is finally evaluated in terms of channel MSE as stated early.

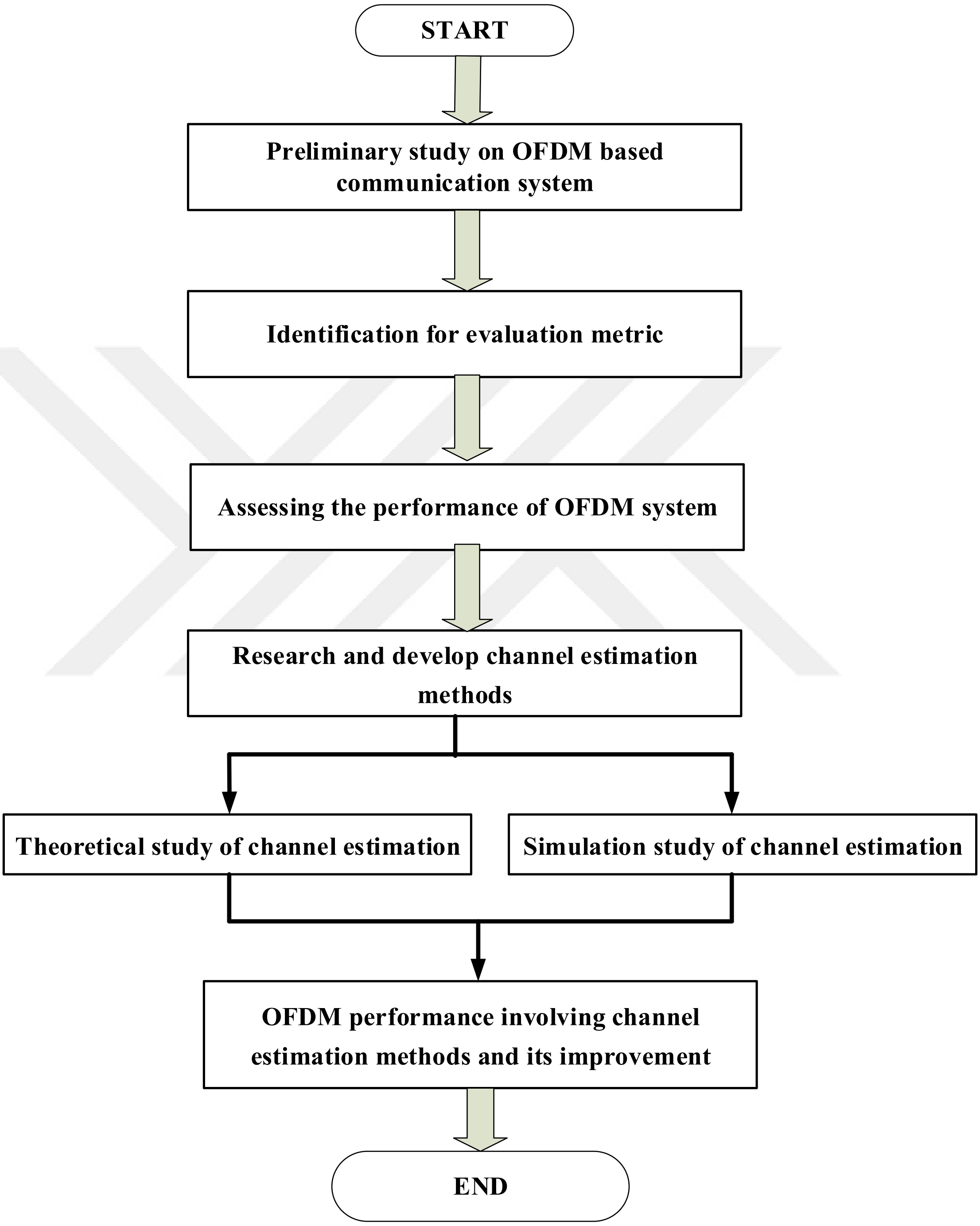

Figure 3.1. Flow chart of the work.

3.3. OFDM BASICS

OFDM is one of digital modulation schemes by which the single subcarrier modulation concept is extended via employing several subcarriers in a single channel. Instead of the high rate data stream using single subcarrier, OFDM employs different orthogonal closely spaced subcarriers for parallel transmission. A traditional modulation scheme, like; “Quadrature Phase Shift Keying (QPSK)”, 16-Quadrature Amplitude Modulation (QAM), is used to modulate each subcarrier. However, similar data rate like this achieved using single subcarrier is also achieved with OFDM subcarriers within equivalent bandwidth.

The idea of OFDM comes from FDM technique, in which different information streams are mapped to seprated frequency channels. A guard band is used to separate the adjacent FDM channels from each other. The following points are distiguished charachterstics for OFDM technique:

- The information stream is carried by multiple carriers.
- Orthogonal subcarriers are used.
- ISI and channel delay spread are minimized by adding a guard interval to each symbol.

OFDM signal concept is illustrated below in Figure. 3.2, where the relationship between time and frequency domains is illustrated. In frequency domain, multiple subcarriers are modulated independently with complex data.

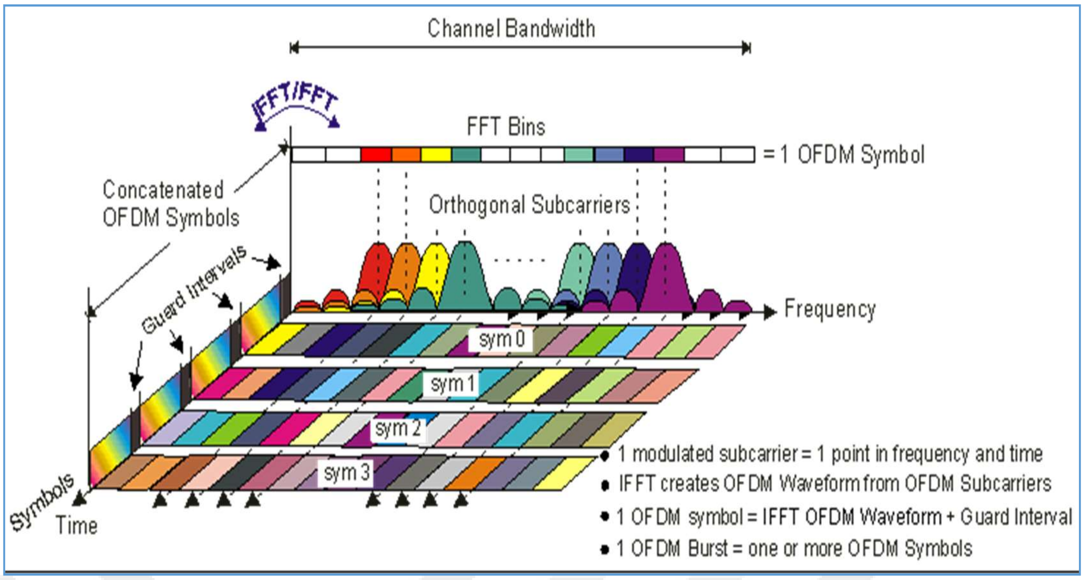

Figure 3.2. Frequency-time representative of OFDM signal.

OFDM symbols are produced in time domain via applying “Inverse Fast Fourier Transform (IFFT)” on subcarriers in frequency domain. Guard bands are then added in time domain between adjacent symbols in order to avoid ISI that results from multipath delay spread within radio channel. The overall OFDM burst signal is obtained by concatenating multiple symbols. The original data is recovered at the receiver side via applying FFT on OFDM symbols. OFDM generation is illustrated in Figure 3.3 [36, 37].

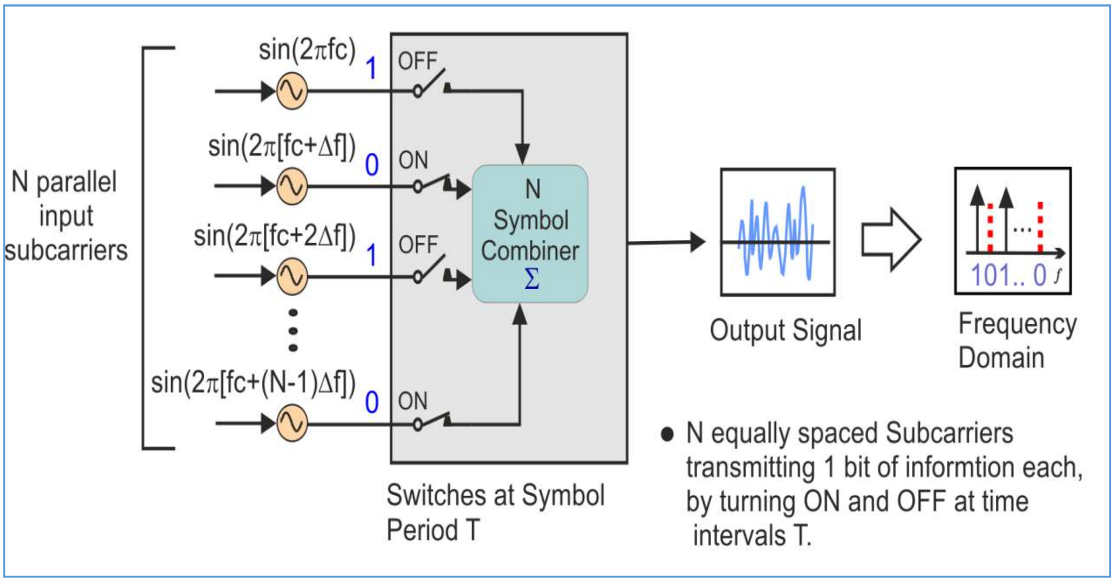

Figure 3.3. OFDM generation.

As shown in Figure 3.3 N parallel subcarriers are used as input signals. One information bit is transmitted by each subcarrier. These bits are combined using combiner to produce N-bits symbol. Each subcarrier frequency is chosen from orthogonal signals group. The receiver uses these frequencies for recovering the signal. T represents the symbol period and the output is updated every T. Period T should be the reciprocal of the spacing between subcarriers in order to preserve orthogonality.

OFDM signal is usually described as a group of closely spaced FDM subcarriers. Each one of the transmitted subcarriers produces *sinc* function in frequency domain. An overlapping is produced between the side lobes of different *sinc* functions. Figure 3.4 illustrates the frequency spectra for OFDM signal.

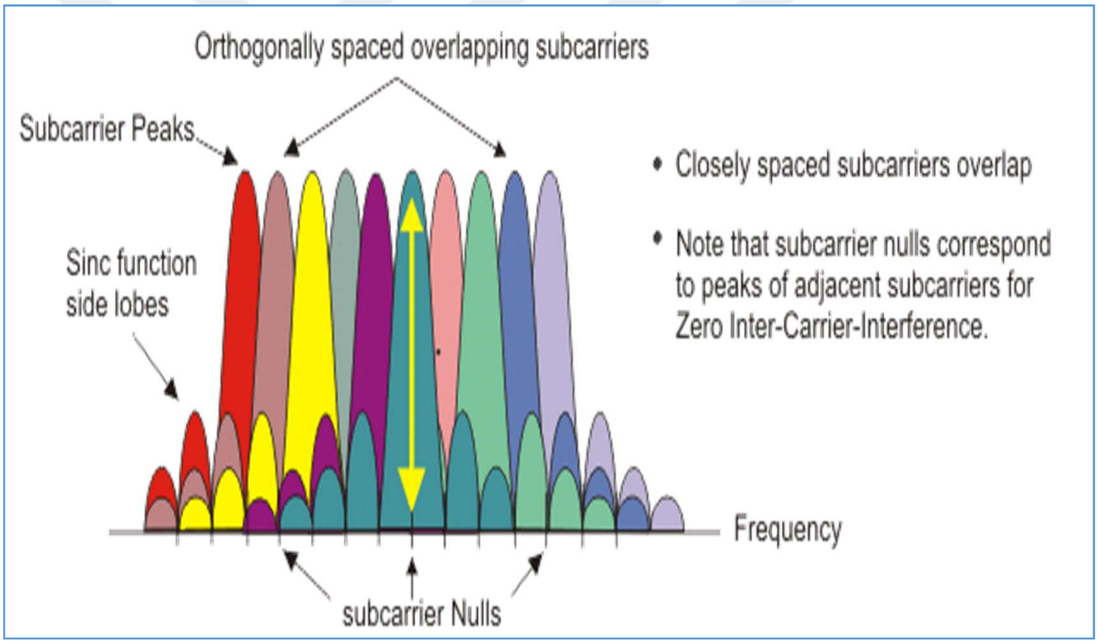

Figure 3.4. Frequency spectra for OFDM signal.

As shown in Figure 3.4, the overlap in turns produces subcarrier interference except at the frequencies that are orthogonally spaced. At these frequencies, subcarriers individual peaks line up with other subcarriers nulls. The ability of the system to restore the original signal does not affected by this overlapping. The original sent bits are recovered by the receiver via correlating incoming signal with known sinusoids set. Employing orthogonal subcarriers improves the system SE since that more subcarriers per same bandwidth are used. The interference between overlapped carriers is prevented by orthogonality in perfect OFDM systems. Once the orthogonality is loosed, interference between subcarriers occurs.

3.4. OFDM BLOCK DIAGRAM

There are several steps that are included and should be performed while generating OFDM symbol. The following block diagram illustrates the transmitter, channel and receiver for OFDM-based communication systems.

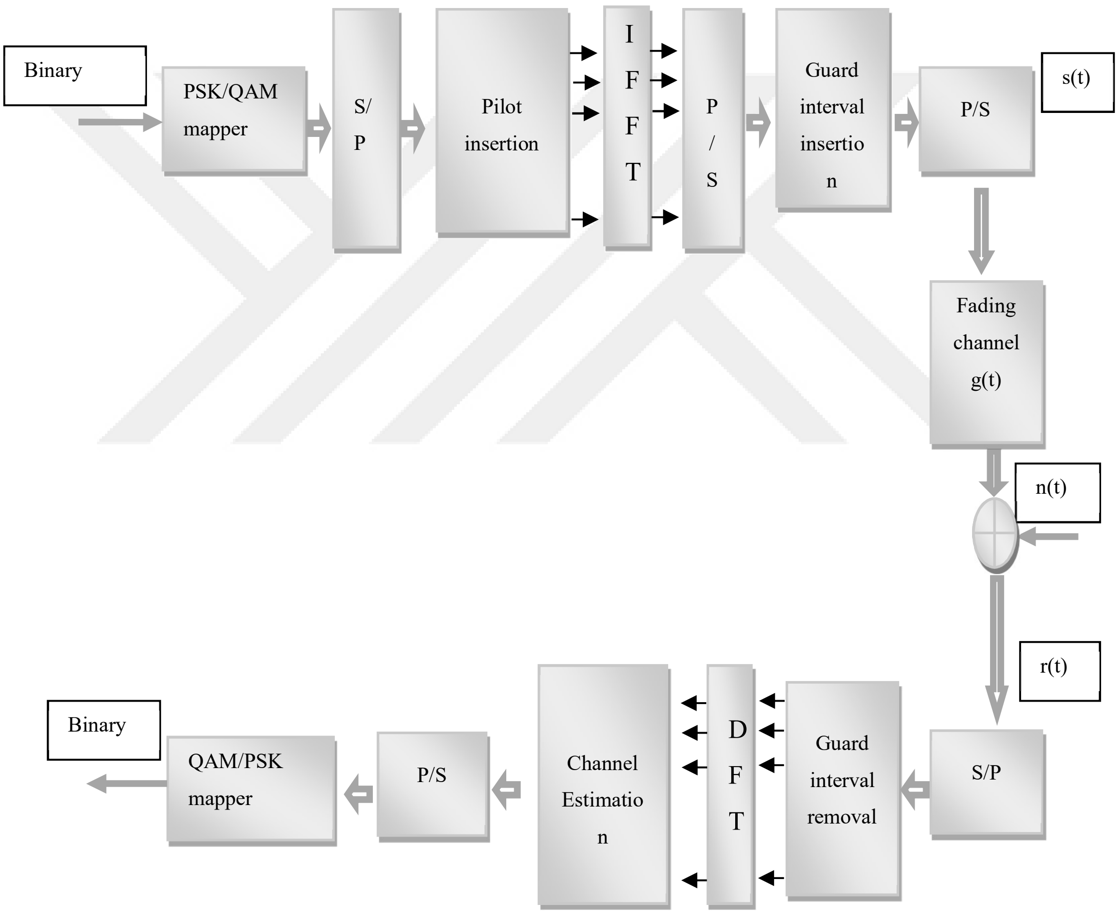

Figure 3.5. OFDM block diagram.

The first step is to group binary information, coding and mapping them according to the signal within signal mapper. The data is then transferred into time domain using IDFT block. After that, the guard band is inserted in order to avoid ISI between symbols.

The resultant signal then goes through the fading channel that is modeled using "Channel impulse response" (CIR) denoted by g(t) followed by AWGN denoted by n(t). The impulse response of the channel represents the output of the channel when an impulse is used as an input, CIR is given by

$$g(t) = \sum_{m=1}^{M} \alpha_m \, \delta(t - \tau_m T_s) \ldots \tag{3.1}$$

Where; α_m is a complex value that represents the channel fading parameter and $0 \leq \tau_m T_s \leq T_G$, where T_G is the guard band interval.

A block diagram of estimation methods can be described as follows [37, 38]

$$x_n = IFFT_N\{X_k\} = \sum_{k=0}^{N-1} X_k e^{j2\pi nk/N}, 0 \leq n, k \leq N-1 \tag{3.2}$$

where: *n* – time domain sampling index,
X_k – data at kth subcarrier,
N – total number of subcarriers.

The guard interval id then removed, the data is then converted back to frequency domain using DFT block. Channel estimation is then applied using several methods. Channel decoding and demodulation is then performed using signal de-mapper to recover the binary data.

3.5. CHANNEL ESTIMATION

Channel estimation is essential method particularly within mobile wireless systems, where the channel varies through time. High data rates and reliability can be provided via accurate estimation for this channel. Channel estimation depends on unique bit training sequence for specific transmitter and it's repeated within each transmitted burst. Via channel estimator, the knowledge on CIR is given to the detector to be estimated separately for each burst. The general structure for estimation techniques is illustrated below in the following block diagram.

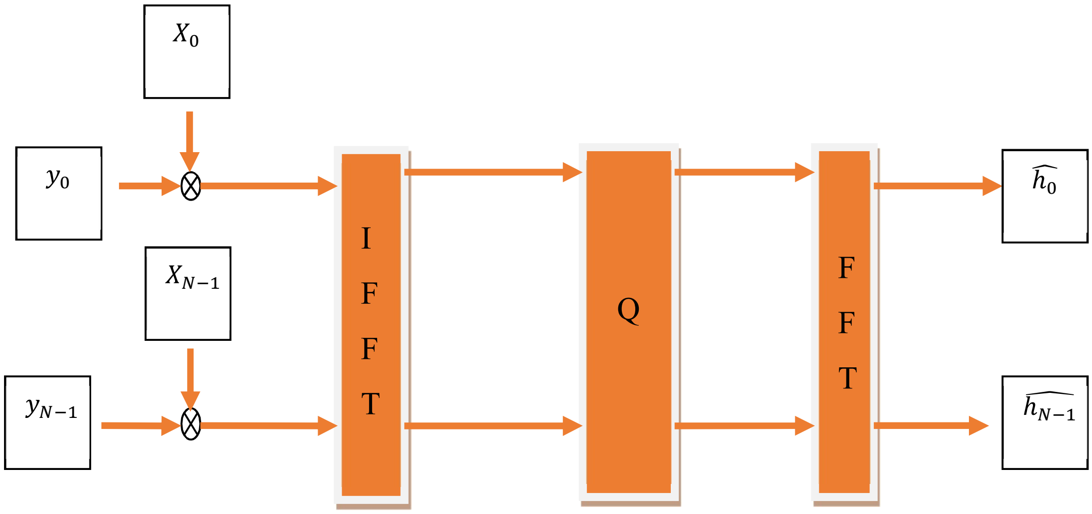

Figure 3.6. General structure for estimation techniques.

Seven major channel estimation methods are discussed and evaluated in this thesis. Figure 3.7 summarizes them.

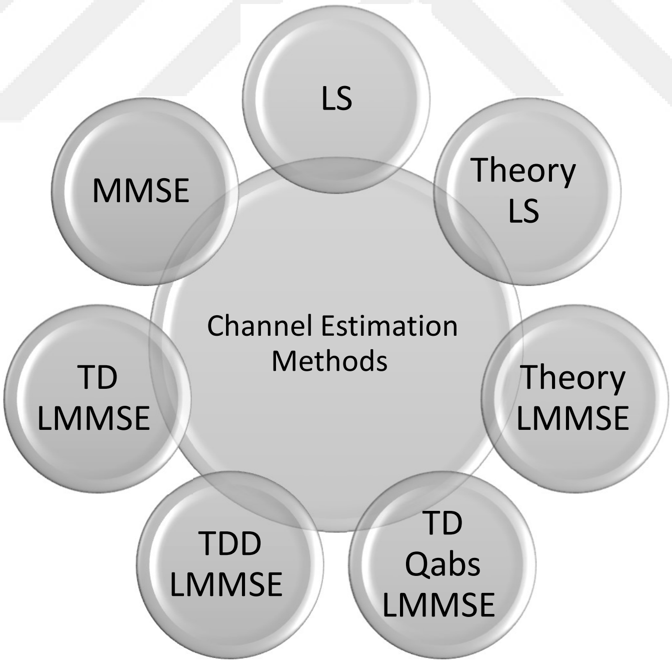

Figure 3.7. Channel estimation methods.

Channel estimator is part from the receiver and it is connected as feedback from the demodulator to the receiver filter as given below in the following block diagram.

For estimation methods described in Figure 3.8 we can write the received signals as

$$Y = FFT_N\{IFFT_N\{X\}\, g + \tilde{n}\} \tag{3.3}$$

where: $Y = [Y_0\, Y_1 \dots Y_{N-1}]^T$ – received vector;

$X = [X_0\, X_1 \dots X_{N-1}]^T$ – vector of transmitted signal;

$g = [g_0\, g_1 \dots g_{N-1}]^T$ – sampled frequency response of $g(\tau)$

$\tilde{n} = [\tilde{n}_0\, \tilde{n}_1 \dots \tilde{n}_{N-1}]^T$ – sampled frequency response of AWGN.

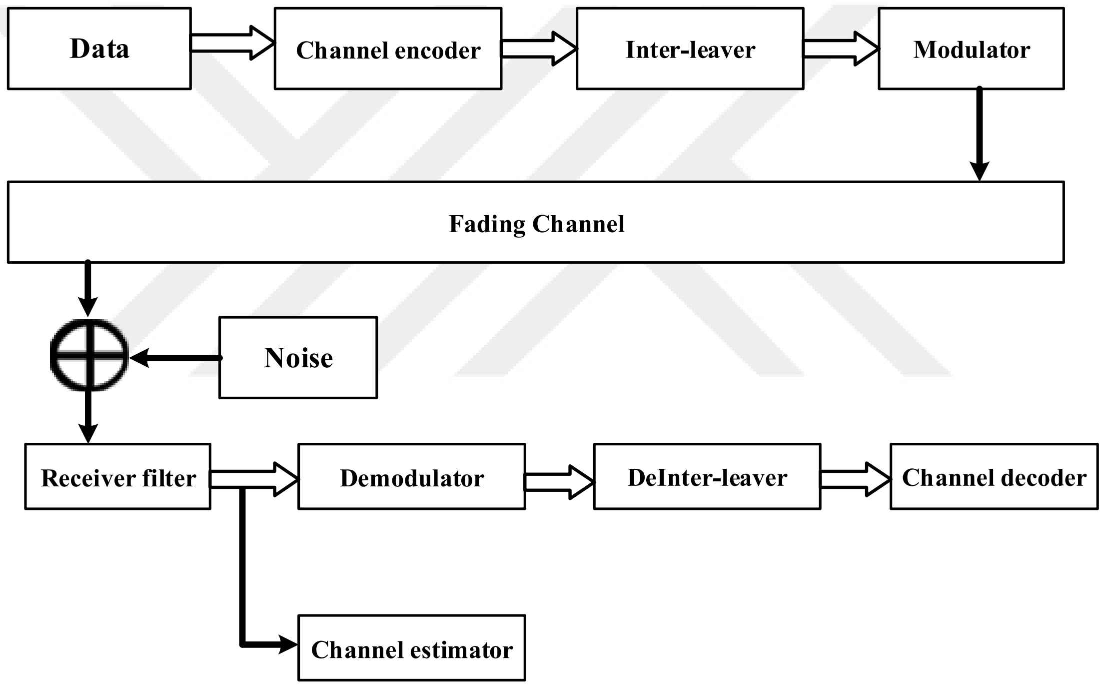

Figure 3.8. Block diagram for estimation methods.

There *Y* and *X* are frequency domain data. The equation (3.3) we rewrite as follows

$$Y = XF_g + F\tilde{n} \tag{3.4}$$

X is a diagonal matrix containing the elements of *X* in equation (3.3), so

$$F = \begin{bmatrix} W_N^{00} & \cdots & W_N^{0(N-1)} \\ \vdots & \ddots & \vdots \\ W_N^{(N-1)0} & \cdots & W_N^{(N-1)(N-1)} \end{bmatrix} \tag{3.5}$$

Equation (3.5) is FFT matrix, where: $W_N^{nk} = \frac{1}{\sqrt{N}} e^{-j2\pi\frac{nk}{N}}$. If $h = FFT_N(g) = Fg$ and $n = FFT_N(\tilde{n}) = F\tilde{n}$, equation (3.4) can be written

$$Y = Xh + n. \tag{3.6}$$

3.6. SYSTEM MODEL DESCRIPTION

The OFDM system involving the channel estimation methods was simulated in MATLAB environment in order to evaluate the performance of the estimation methods in terms of channel MSE via simulation results. The code is summarized below in the following flow chart.

The first step of the program is to define and select initial values for the system parameters including, SNR, beta, FFT size, modulation order, length of guard interval. The data is then randomly generated and grouped. The signal is then modulated using QAM scheme. Different estimation methods are then defined and initialized. Signal is then converted to time domain using IFFT followed by guard band insertion to avoid interference. AWGN is then added and the signal is received by the receiver. The guard interval is removed and the signal is converted back to frequency domain using FFT. The channel estimation is then calculated using seven different methods. Finally, the performance is evaluated and compared using MSE criterion. According to the equation (3.6) Least-Square (LS) estimator minimizes the cost function as follows

$$\min_{h} \left(Y - X\tilde{h}\right)^H \left(Y - X\tilde{h}\right) \tag{3.7}$$

where $[\cdot]^H$ is the Hermitian (conjugate) transpose operator, LS estimator of h is given by

$$\tilde{h}_{LS} = \frac{Y}{X} = \left[\frac{Y_k}{X_k}\right]^T \tag{3.8}$$

where $[\cdot]^T$ is transpose operator, $k = 0, 1, \dots, N-1$. LS estimator is equivalent to what is also referred to as the zero-forcing estimator since it can be obtained from t-domain LS estimator with no assumption on the number of CIR taps or length [36, 37].

Then we can write

$$\tilde{h}_{LS} = FQ_{LS}F^H X^H Y \tag{3.9}$$

where:

$$Q_{LS} = (F^H X^H XF)^{-1} \tag{3.10}$$

The minimum mean-square error is widely used in the OFDM channel. Assume, R_{gg}, R_{hh}, and R_{YY} as the auto covariance matrix of g, h, and Y, respectively. We define R_{gY} as the cross-covariance matrix between g and Y. We derive that

$$R_{hh} = E\{HH^H\} = E\left\{(F_g)(F_g)^H\right\} = FR_{gg}F^H , \tag{3.11}$$

$$R_{gY} = E\{gY^H\} = E\left\{g\left(XF_g + Fn\right)^H\right\} = R_{gg}F^H X^H \tag{3.12}$$

$$R_{gY} = E\{YY^H\} = XFR_{gg}F^H X^H + \sigma_n^2 I_N \tag{3.13}$$

where: σ_n^2 – is the noise variance,

$E\{|n|^2\}$ and I_N – N x N identity matrix.

We can write MMSE estimator equation by assuming that R_{hh}, operating SNR, channel correlation matrix and σ_n^2 are known at the receiver.

$$\hat{g}_{MMSE} = R_{gY}R_{YY}^{-1}Y \tag{3.14}$$

In last, frequency domain MMSE estimator can be calculated by

$$\begin{aligned}\hat{h}_{MMSE} &= F\hat{g}_{MMSE} = F\left[(F^H X^H)^{-1}R_{gg}^{-1}\sigma_n^2 + XF\right]^{-1}Y = \\ &= FR_{gg}\left[(F^H X^H XF)^{-1}\sigma_n^2 + R_{gg}\right]F^{-1}\hat{h}_{LS} \\ &= R_{hh}[R_{hh} + \sigma_n^2(XX^H)^{-1}]^{-1}\hat{h}_{LS} .\end{aligned} \tag{3.15}$$

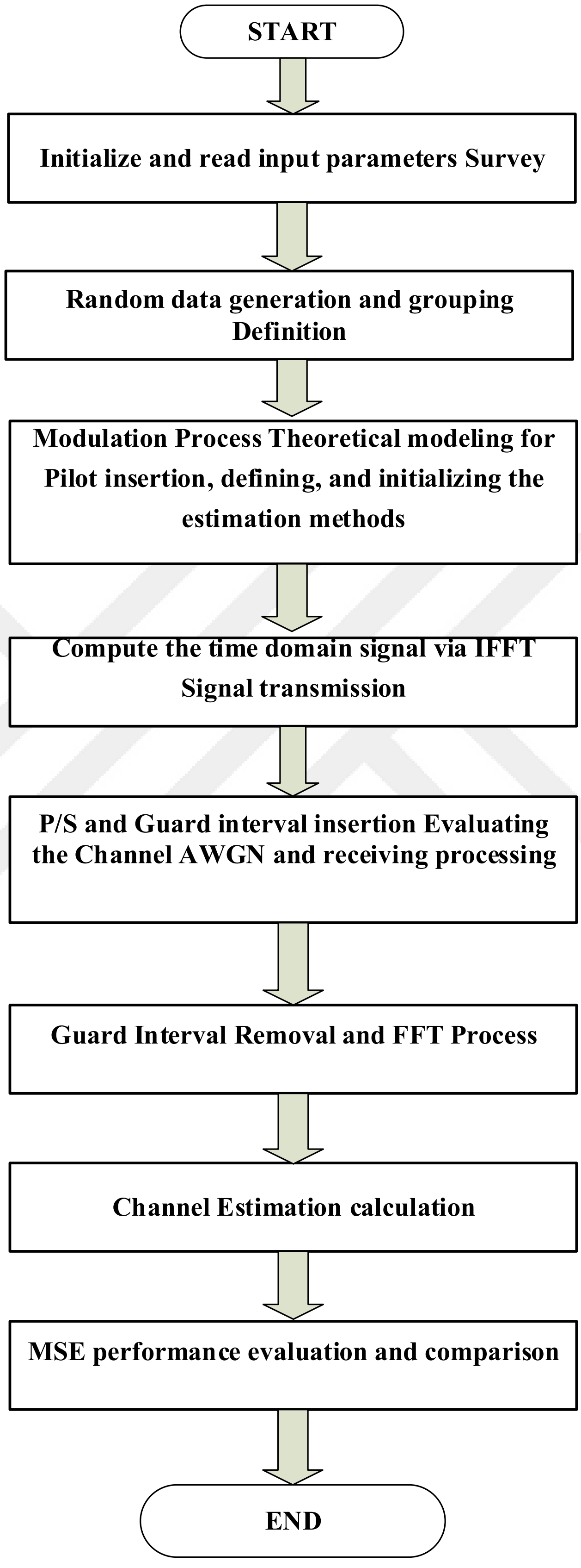

Figure 3.9. Flow chart of MATLAB Simulation.

CHAPTER 4

RESULTS AND ANALYSIS

4.1. OVERVIEW

As stated early, seven channel estimation methods are evaluated throughout this thesis. The seven methods are; LS, MMSE, TD-LMMSE, (TDD-LMMSE), (TD Q_{abs} LMMSE), theory-LS and theory-LMSSE. OFDM system was programmed on MATLAB environment and the seven techniques are then used for channel estimation in order to compare their performance in terms of channel MSE. This chapter introduces and discusses the performance for these methods under different cases by varying several parameters as will be given later.

4.2. EFFECT OF MODULATION ORDER

The first parameter that is considered in this thesis is he modulation order, which is defined as the number of symbols that are able to be transmitted using the digital communication scheme. The channel MSE has been evaluated for different QAM modulation orders, which are; 16 QAM, 32 QAM, 64 QAM,128 QAM, 256 QAM, and 512 QAM. Figure 4.1 illustrates the seven methods performances for 16 QAM modulation order.

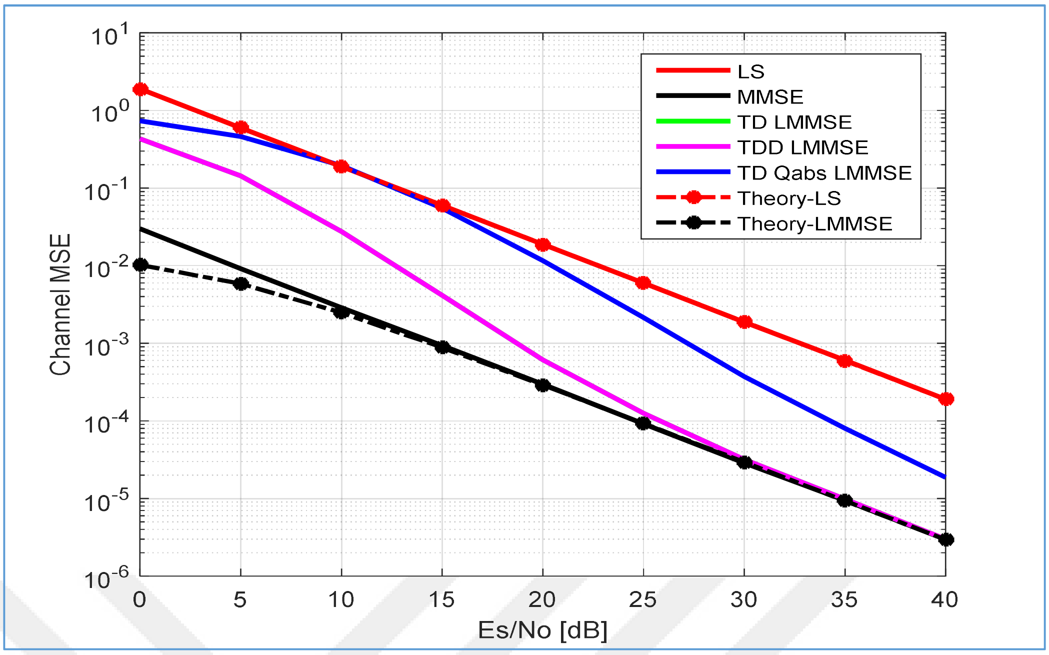

Figure 4.1. MSE versus Es/No for FFT-size =64 and 16 QAM order method.

As shown in Figure 4.1, the best performance is achieved by using theory LMMSE method with best value less than 10^{-6} achieved at 40 dB. This method works good for also low SNR value differently from other estimation methods. The worst one is theory-LS method value greater than 10^{-6} achieved at 40 dB. For all methods, increasing SNR results in less channel MSE and hence better performance. As illustrates in the same Figure, there are points of intersection between the curves, which means that the two methods achieve the same channel MSE performance at this point. It can be also noticed that the performance of the methods differs according to the range of SNR, for example; LS method is better than TDD LMMSE method for $SNR < 7\ dB$ but it is worse for $SNR > 7\ dB$. The second value for modulation order is 32 QAM and its corresponding figure is illustrated in Figure 4.2.

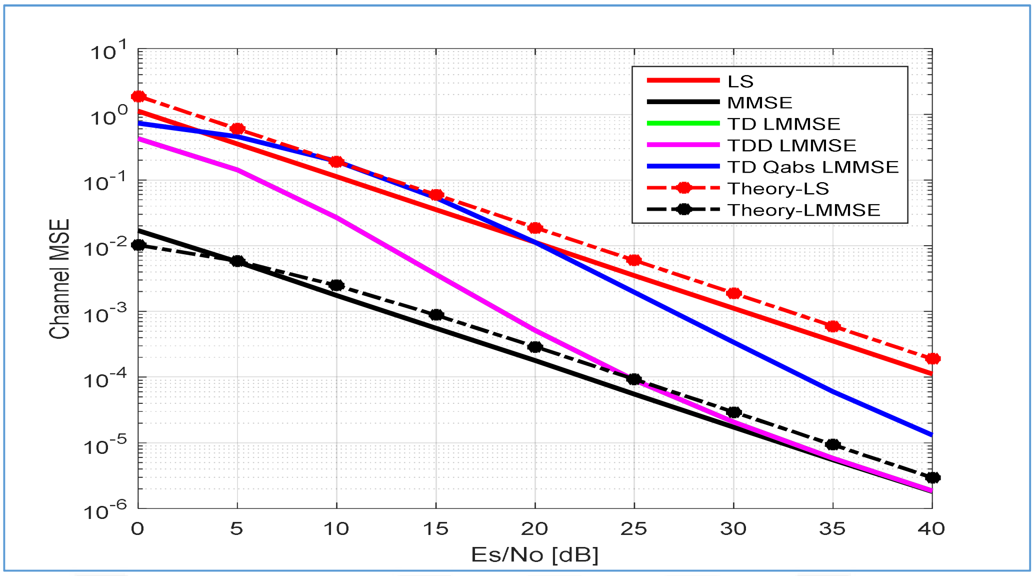

Figure 4.2. MSE versus Es/No for FFT-size =64 and 32 QAM order method.

As shown in Figure. 4.2, duplicating the modulation order from 16 to 32 results in worse performance; since all curves of the methods are shifted above, which means larger channel MSE. Actually, this occurs because more symbols are sent with 32QAM, which results in higher probability of error. The best achievable performance was obtained using MMSE method with value between 10^{-6} and 10^{-5} achieved at 40 dB. Differently, the worst performance is achieved using Theory-LS; it achieves a channel MSE between 10^{-4} and 10^{-3} at 40 dB. The next modulation order is 64 and is illustrated in Figure 4.3.

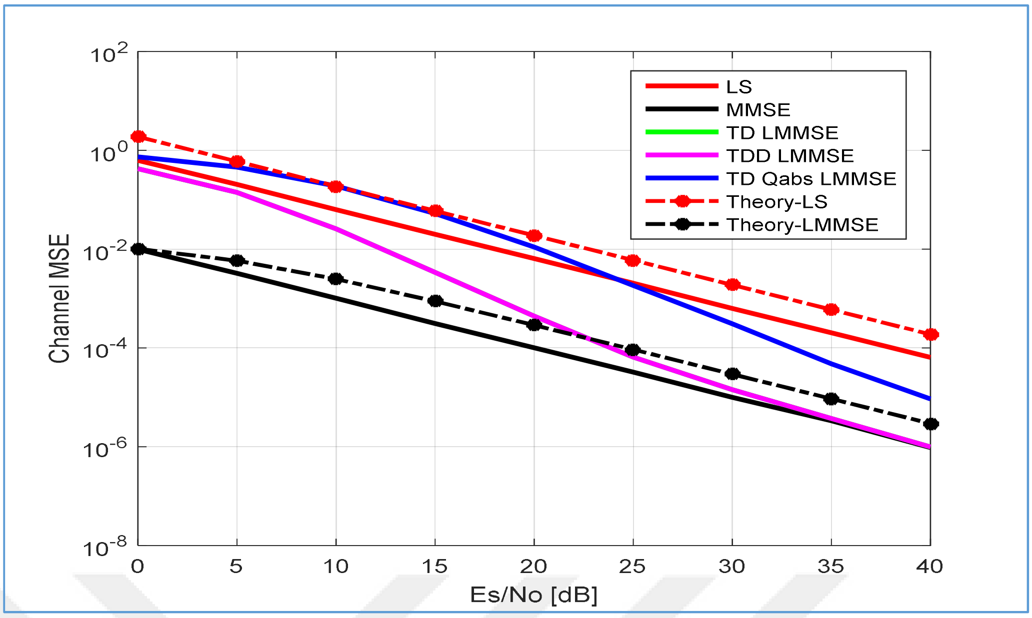

Figure 4.3. MSE versus Es/No for FFT-size =64 and 64 QAM order method.

As shown in Figure 4.3, increasing the modulation order form 32 QAM to 64 QAM results in shifting the curves of the methods down or above the curves of Figure. 4.2. It also results in shifting the intersection points between the algorithms to right. For example, the TDD LMMSE and theory LMMSE intersects at 23 dB with channel MSE greater than 10^{-4} . This means that TDD LMMSE is better to be used for SNR greater than 23 dB. The next value for modulation order is 512 QAM and its related figure is given in Figure 4.4.

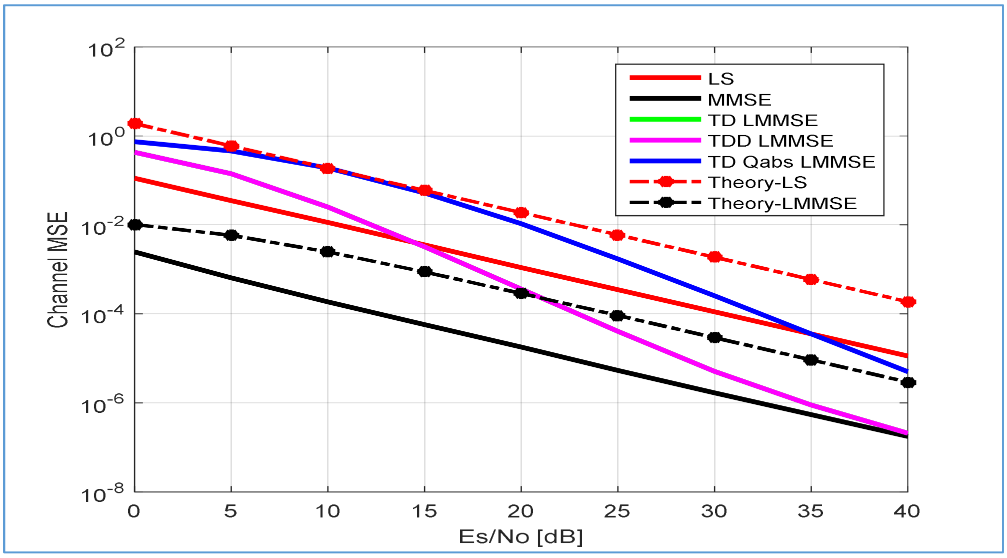

Figure 4.4. MSE versus Es/No for FFT-size =64 and 512 QAM order method.

In comparison with LMMSE method is the most affected one by changing the modulation order from 16QAM to 512QAM (Figure 4.4). LMMSE method achieves a channel MSE value between 10^{7-} and 10^{-6} at 40 dB. The worst performance obtained using theory LS method with value between 10^{-4} and 10^{-3} at 40 dB.

4.3. EFFECT OF FFT SIZE

The second factor that is studied in this thesis is the FFT size. The selected FFT size values are 32, 64, 128 and 256. The Figure 4.5 illustrates the MSE performance for the seven methods when FFT size= 32 bins.

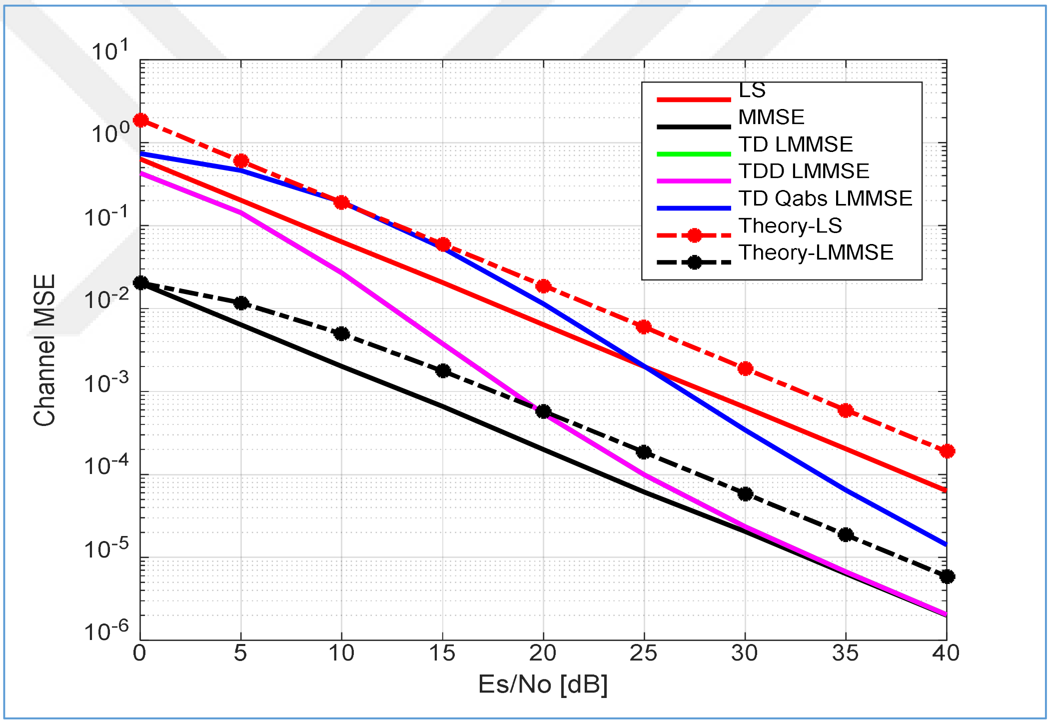

Figure 4.5. MSE versus Es/No for FFT size =32 and 64 QAM order method.

As shown in Figure 4.5, the best achievable performance occurred using MMSE method since it has the lowest MSE values compared to the remaining six estimation methods. Both MMSE and TDD LMMSE work good for large SNR values. TDD LMMSE is better than LS, TD Qabs LMMSE and theory LS methods. Theory LMMSE is better to be used for $SNR < 20\ dB$ compared to TDD LMMSE method. The next considered FFT size is 64 and its related figure is given in Figure 4.6.

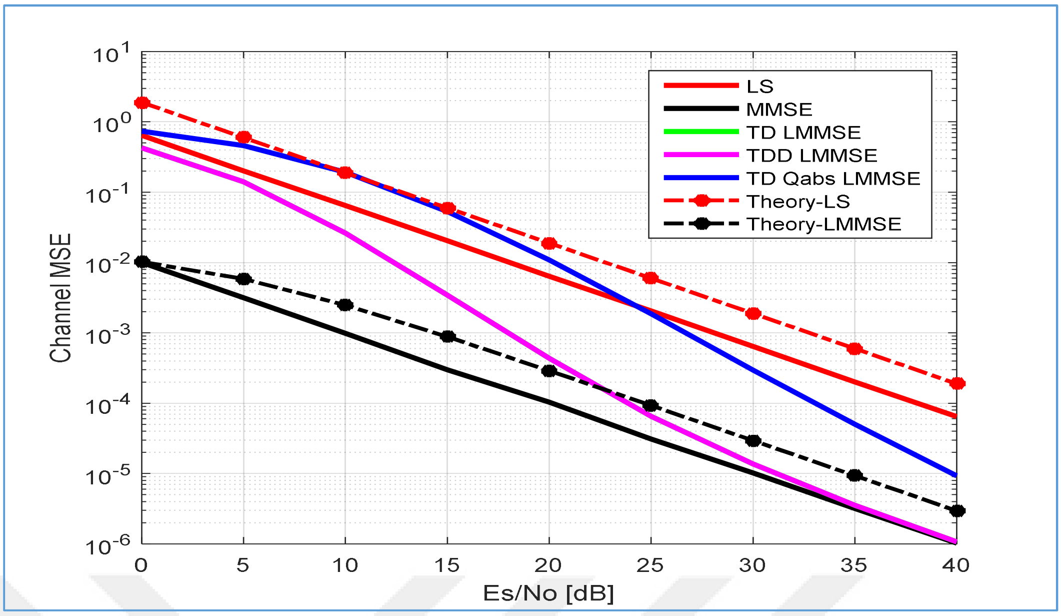

Figure 4.6. MSE versus Es/No for FFT size =64 and 64 QAM order method.

As shown in Figure 4.6, less MSE is obtained when the FFT size is increased from 32 to 64 bins. The curves are shifted below, which means better performance. MMSE stills the best method and theory LS is the worst one. The intersection points between the curves are also shifted, which gives larger range of SNR to some methods to be used. The next FFT size value is 128 and its related figure is given below.

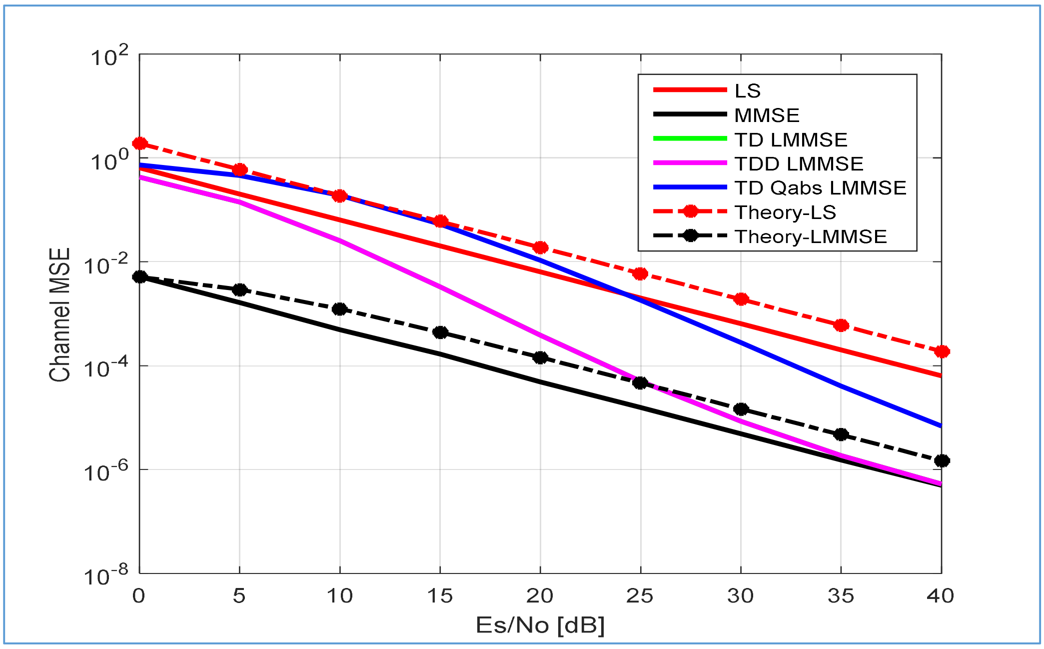

Figure 4.7. MSE versus Es/No for FFT size =128 and 64 QAM order method.

As shown in Figure 4.7, theory LMMSE and TDD LMMSE achieves the same MSE value at SNR = 25 dB. TD Qabs LMMSE and LS achieve the same MSE at SNR = 24 dB. The best and worst performance are achieved by MMSE and theory LS respectively. The last value for FFT size is 256 and its related figure is shown below.

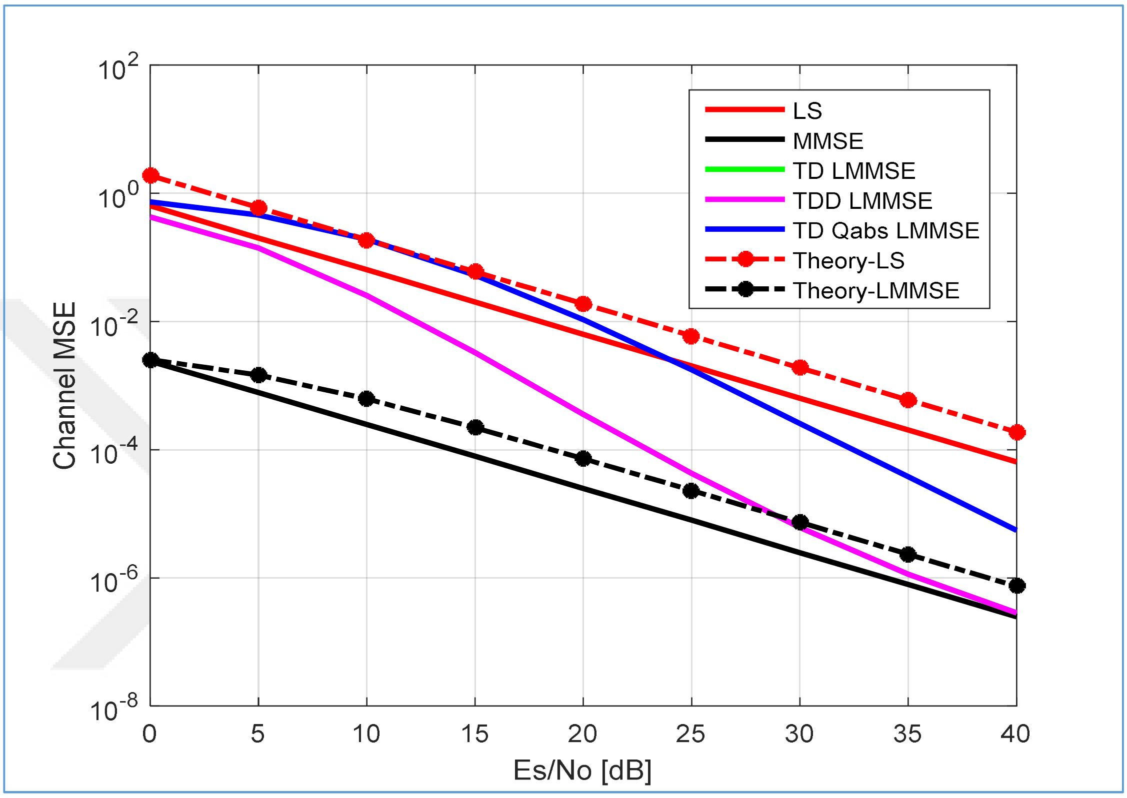

Figure 4.8. MSE versus Es/No for FFT size =256 and 64 QAM order method.

According to Figure 4.8, the intersection points between TDD LMMSE and Theory LMMSE is shifted to 30 dB, which means that Theory LMMSE is better to be used for $SNR < 30\ dB$, but TDD LMMSE is better to be used for $SNR \geq 30\ dB$. The best and worst performance is achieved by same methods as Figure. 4.7.

4.4. EFFECT OF GUARD INTERVAL LENGTH

The third factor that is evaluated in this thesis is the length of Cyclic Prefix (GUARD INTERVAL). Guard interval is used between two symbols to prevent Inter-Symbol-Interference (ISI). The selected values for guard interval are 4 and 12; the Figure 4.9 is obtained when guard interval=4.

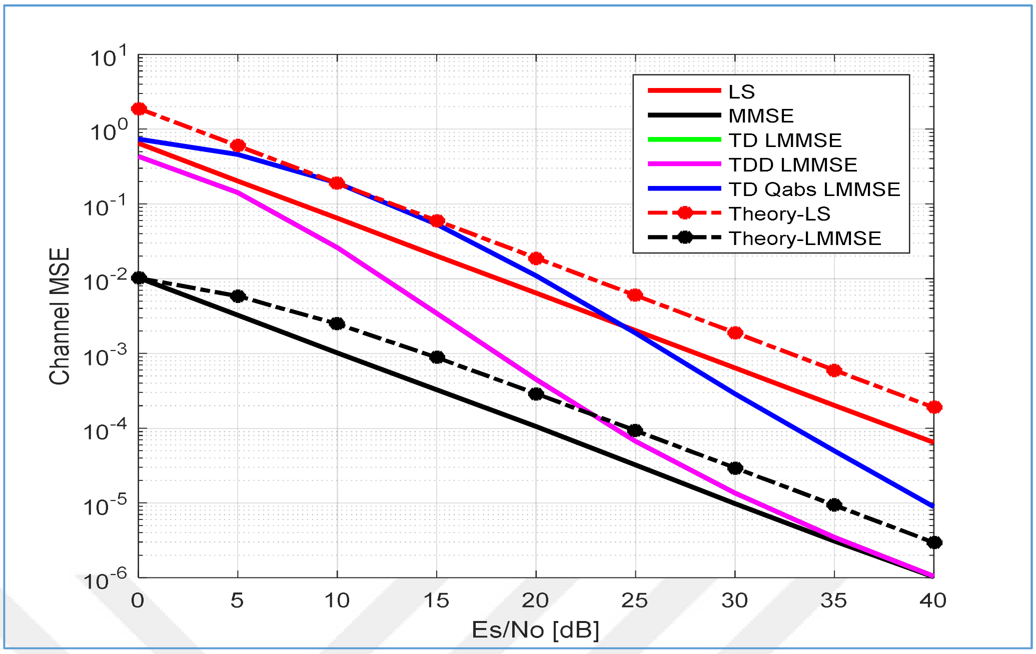

Figure 4.9. MSE versus Es/No for FFT size =64 and 64 QAM order method with guard interval=4.

As shown in Figure 4.9, the best performance is still achieved by MMSE method and the worst one is theory LS method. The remaining five methods perform differently for the considered SNR range. TDD LMMSE and theory LMMSE perform similarly at SNR = 23 dB. LS and TD Qabs LMMSE perform similarly at SNR = 24.5 dB. The next considered guard interval length is 12 and its related figure is given below (Figure 4.10).

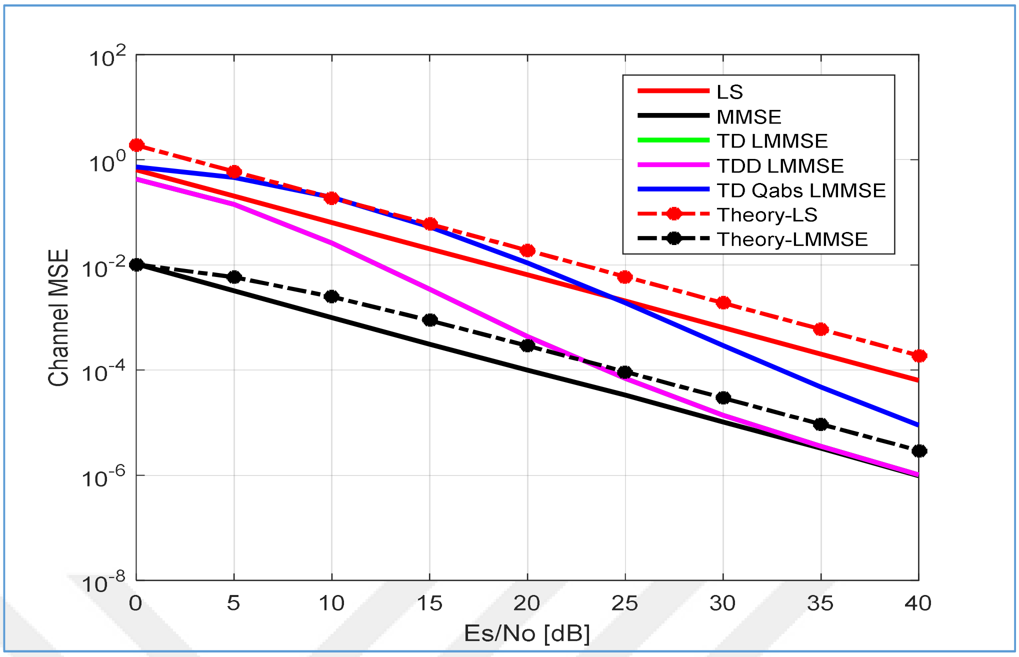

Figure 4.10. MSE versus Es/No for FFT size = 64 and 64 QAM order with guard interval=12.

As shown in Figure 4.10, no one of the methods affected by changing the value of guard interval. So, all curves in Figure 4.10 are the same as those in Figure 4.9. The achieved channel MSE value is the same for both guard interval values.

4.5. EFFECT OF CHANNEL

The fourth factor that is studied in this thesis the effect of the channel on the MSE for the seven methods. The channel effect was evaluated at three different values, which are; 500, 1000 and 1500. The following figure illustrates the obtained MSE performance for MC=500.

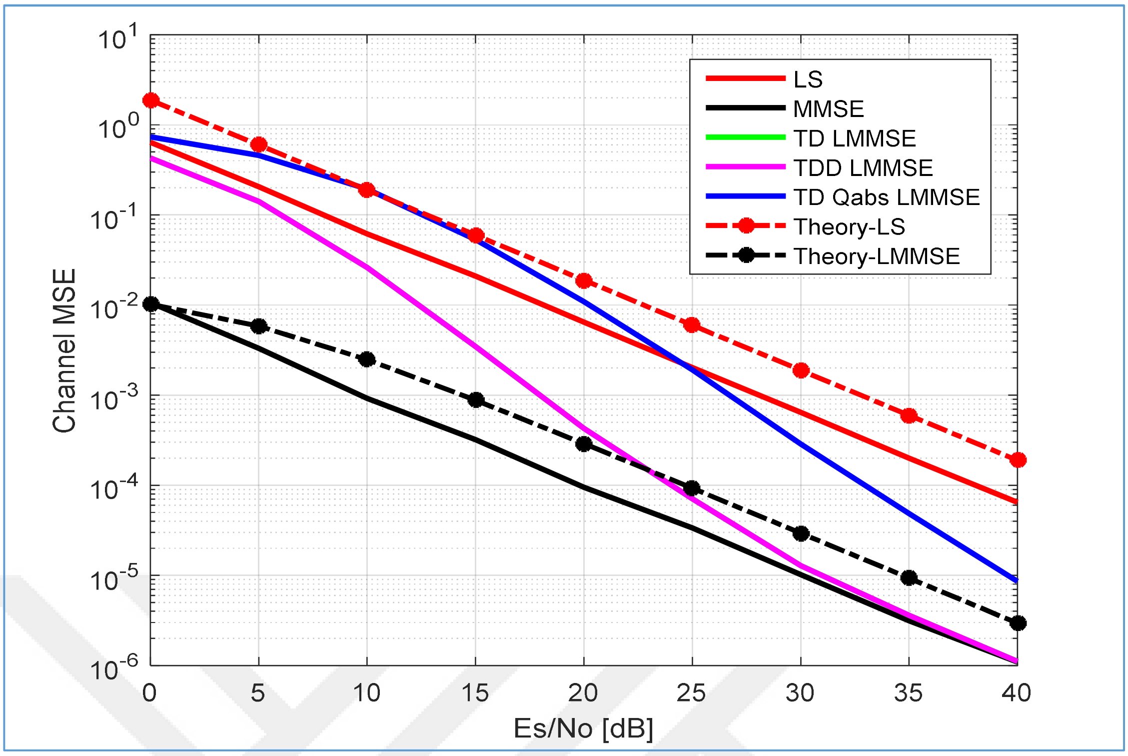

Figure 4.11. MSE versus Es/No for FFT size =64 and 64 QAM order method with MC=500

As shown in Figure 4.11, the worst performance is achieved by theory LS method and the best performance is achieved by MMSE method and the. The remaining five methods perform differently between the best and the worst performance. TDD LMMSE and theory LMMSE perform similarly at SNR = 23 dB. LS and TD Qabs LMMSE perform similarly at SNR=24.5dB. the best MSE performance is obtained using MMSE and TDD LMMSE with value equal to 10^{-6} achieved at SNR=40 dB. The next considered MC is 1000 and its related figure is given below.

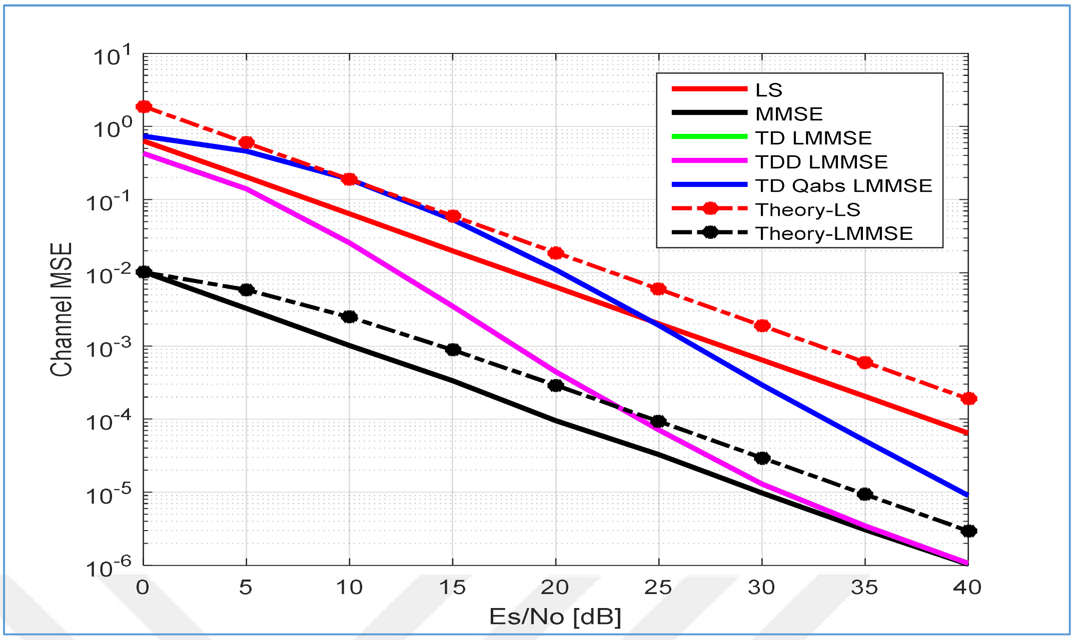

Figure 4.12. MSE versus Es/No for FFT size =64 and 64 QAM order method with MC=1000

Figure 4.12 is almost similar to Figure 4.11 and hence the MSE performance is the same. This means that varying MC from 500 to 100 has no effect on the channel MSE for the seven estimation methods. The last selected value for MC is 1500 and its related figure is illustrated below.

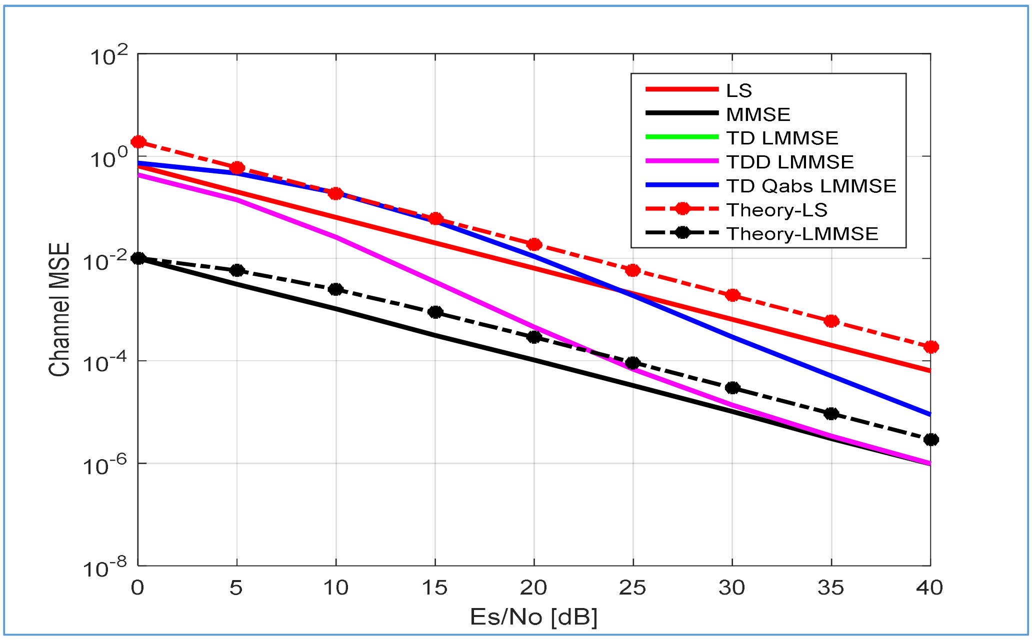

Figure 4.13. MSE versus Es/No for FFT size = 64 and 64 QAM order method with MC=1500

According to Figure 4.13, changing the MC value from 1000 to 1500 has an effect on the MSE performance of the seven estimation methods. The curves get closer to each other and the distance between them get shorter. Theory LS and MMSE have the worst and best achievable MSE performance, respectively. There is also points of intersections between different methods, which means that it has the same MSE value at these points.

4.6. EFFECT OF BETA

The last factor that is studied in this thesis is Beta. Beta is an adjust factor of MMSE. Several values are selected to this variable in order to estimate its effect on the MSE performance for the considered estimation methods. Figure 4.14 illustrates the MSE performance for beta=0.001.

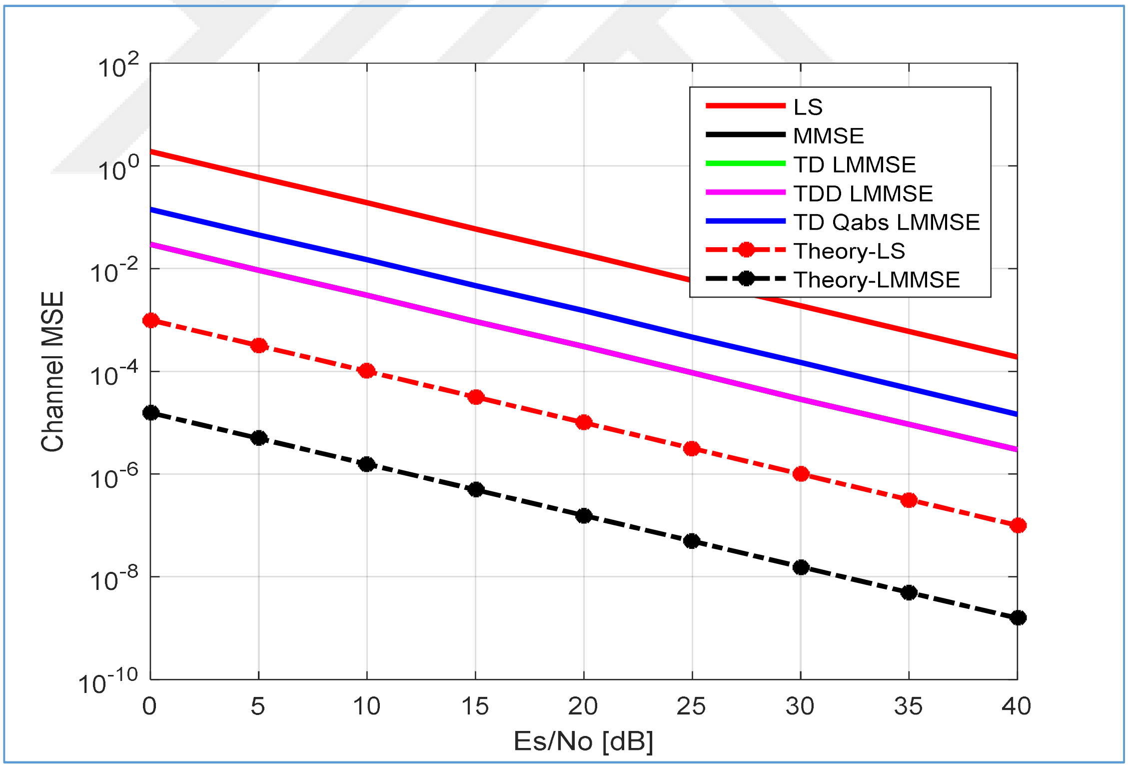

Figure 4.14. MSE versus Es/No for FFT size =64 and 64 QAM order method with Beta=0.001

According to Figure 4.14, selecting beta=0.001 results in totally parallel curves for the methods. This means that their MSE performance will never be equal at any point. However, some curves are don't occur in the figure, which means that they are identical to one of the other curves. The best achievable performance is obtained using theory LMMSE method with minimum MSE equal to 10^{-9} obtained at SNR=40 dB. The worst achievable performance is obtained using theory LS method with minimum MSE less than to 10^{-4} obtained at SNR=40 dB. The second value for beta is 2 and its related figure is given in Figure 4.15.

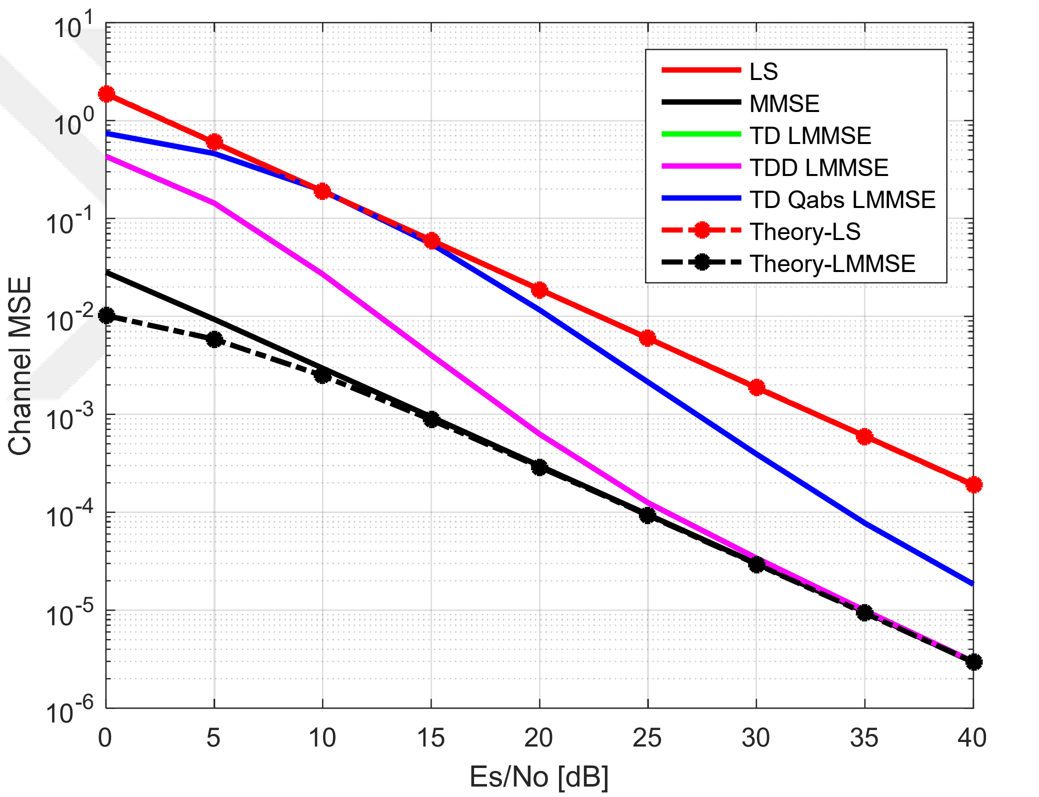

Figure 4.15. MSE versus Es/No for FFT size =64 and 64 QAM order method with Beta=2

As shown in Figure 4.15, increasing beta from 0.001 to 2 results in worse performance since that larger MSE values are obtained. The curves also become intersected at different points, which means similar performance at the intersection points. The curves in general are shifted above. The best and worst performances are obtained using theory LMMSE and LS methods, respectively. The next value for beta is six and its related figure is given in Figure 4.16.

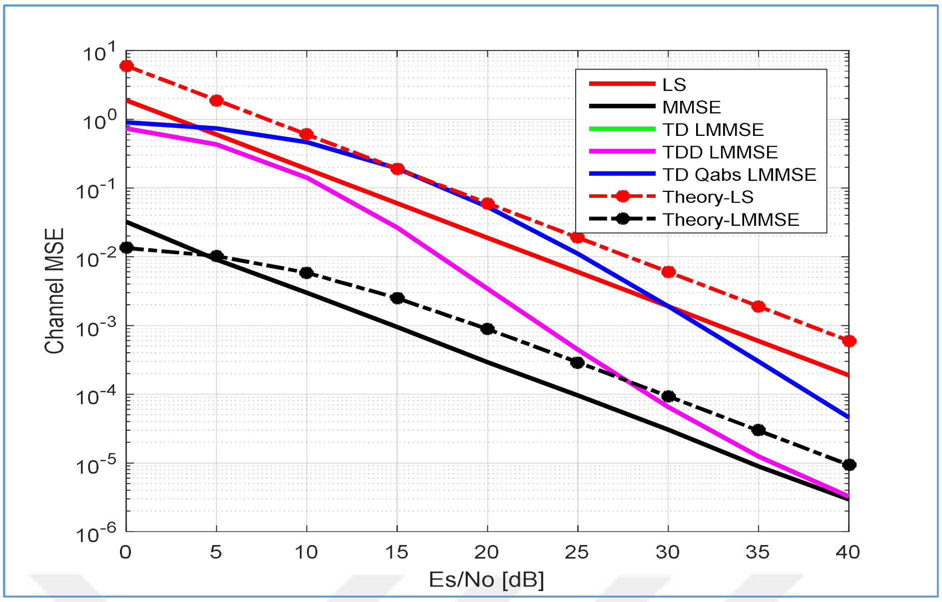

Figure 4.16. MSE versus Es/No for FFT size =64 and 64 QAM order method with Beta=6

According to Figure. 4.16, increasing beta from 2 to 6 changes the performance of the methods clearly. MMSE becomes the best method since the minimum MSE is obtained using it. Theory LS has the worst MSE performance. MMSE and theory LMMSE performs similarly at SNR = 5 dB with $MSE = 10^{-2}$. TDD Qabs LMMSE is better to be used than LS method within the range 5 dB – 30 dB. The last beat value is 10 (Figure 4.17).

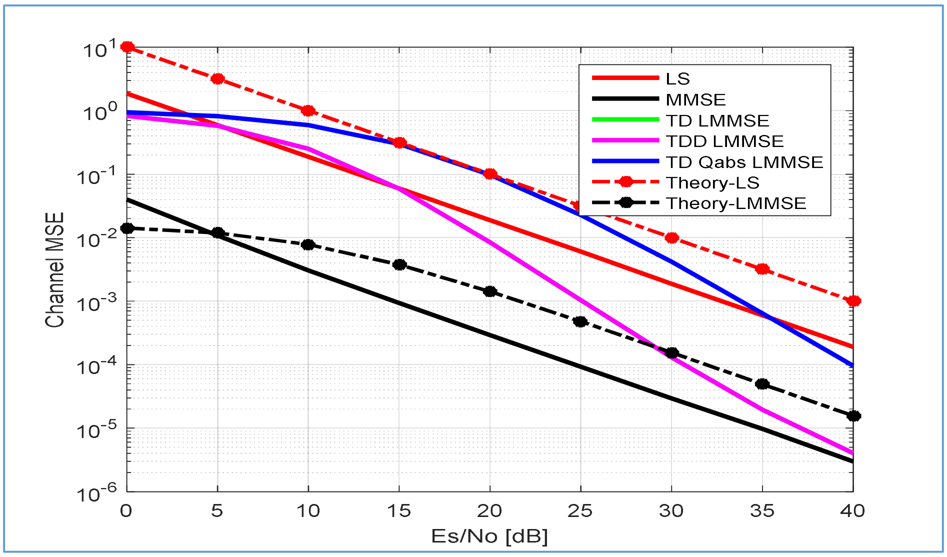

Figure 4.17. MSE versus Es/No for FFT size =64 and 64 QAM order method with Beta=10

As shown in Figure. 4.17, increasing beta to 10 results in shifting the curves away from each other. The intersection points between curves are also shifted which gives larger SNR range for some methods to be instead of other methods because they have less MSE. The best and worst MSE performances are achieved using MMSE and theory LS methods, respectively.

4.7. SUMMARY

This chapter covers a detailed analysis for the obtained simulation results using MATLAB program. The results were obtained by varying the values of different factors in order to evaluate their effect on the MSE performance of the seven estimation methods. No one of the methods performs perfectly in all cases and the performance for each algorithm varies according to the selected parameters values. MMSE is the best channel estimation method since it achieved the minimum MMSE in most of the considered cases.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1. CONCLUSION

To conclude all, OFDM technique is considered one of the most effective methods to be use as an effective choice within wireless communication systems; because it has several advantages, such as; lower multi-path distortion, high-data-rate transmission capability and efficient bandwidth utilization. The idea of OFDM techniques lies in dividing the overall available bandwidth into narrower bandwidth sub-channels. A guard interval is used between the symbols so that ISI is avoided.

There are different estimation methods for the wireless channel that are used with OFDM technique, such as; "Least squares" (LS), "Minimum Mean Square Error" (MMSE), "Time-Domain Linear Minimum Mean Square Error" (TD-LMMSE), "Time Division Duplex Linear Minimum Mean Square Error" (TDD-LMMSE), "Time Domain absolute value of the Quadrature signal LMMSE" (TD Q_{abs} LMMSE), theory-LMSSE and theory-LS.

In this thesis, the performance for these methods is estimated and discussed in order to determine which one of these methods is effective to be used. OFDM system is programmed on MATLAB environment and the seven techniques are then used for channel estimation in order to compare their performance in terms of channel MSE.

Larger modulation order results in worse performance because more symbols are sent, which results in higher probability of error. On the other hand, better MSE performance is achieved with larger FFT size. Using larger guard bands reduces the probability of interference between symbols and hence lower MSE is obtained. Actually, and according to the obtained results, the performance of these methods varies differently according to these parameters, but MMSE is the best channel estimation method since it achieved the minimum MMSE in most of the considered cases, while theory LS achieved the worst MSE performance.

5.2. FUTURE WORKS

There are some plans to be performed in the future in order to improve the performance obtained in this thesis, which are:

- Include more estimation methods in the comparison, such as; ML, PCMB, etc.
- Develop a new estimation method to achieve better performance than the considered methods.

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APPENDIX A.

MATLAB CODE

```
clc
clearall
closeall
sigma=4;% choose sigma=4 means(16-QAM); sigma=5 means(32-QAM);  sigma=6
means(64-QAM); and so on
nGUARD INTERVAL = 8;%Cyclic Prefix Length round(TGUARD
INTERVAL/Ts)
nFFT = 64; % you can change the FFT size from here options are 128, 256, 512 and
1024 and so on
NT = nFFT + nGUARD INTERVAL;
F = dftmtx(nFFT)/sqrt(nFFT);

MC = 1500;

EsNodB = 0:5:40;% you can change this for different SNR as well
snr = 10.^(EsNodB/10);
beta = 17/9;
M = 2^sigma; %modulation order
modObj = modem.qammod(M);
demodObj = modem.qamdemod(M);
L = 5;
ChEstLS = zeros(1,length(EsNodB));
ChEstMMSE = zeros(1,length(EsNodB));
TD_ChEstMMSE = zeros(1,length(EsNodB));
TDD_ChEstMMSE = zeros(1,length(EsNodB));
TDQabs_ChEstMMSE = zeros(1,length(EsNodB));

for ii = 1:length(EsNodB)
disp('EsN0dB is :'); disp(EsNodB(ii));tic;
ChMSE_LS = 0;
ChMSE_LMMSE=0;
   TDMSE_LMMSE =0;
   TDDMSE_LMMSE=0;
TDQabsMSE_LMMSE =0;
for mc = 1:MC
% Random channel taps
        g = randn(L,1)+1i*randn(L,1);
        g = g/norm(g);
        H = fft(g,nFFT);

        X = randi([0 M-1],nFFT,1);  %BPSK symbols
        XD = modulate(modObj,X)/sqrt(10); % normalizing symbol power
        x = F'*XD;
xout = [x(nFFT-nGUARD INTERVAL+1:nFFT);x];
        y = conv(xout,g);
nt =randn(nFFT+nGUARD INTERVAL+L-1,1) + 1i*randn(nFFT+nGUARD
INTERVAL+L-1,1);
        No = 10^(-EsNodB(ii)/10);
        y =  y + sqrt(No/2)*nt;
```

```
        y = y(nGUARD INTERVAL+1:NT);
        Y = F*y;
% frequency doimain LS channel estimation
HhatLS = Y./XD;
ChMSE_LS = ChMSE_LS + ((H -HhatLS)'*(H-HhatLS))/nFFT;
% Frequency domain LMMSE estimation
Rhh = H*H';
        W = Rhh/(Rhh+(beta/snr(ii))*eye(nFFT));
HhatLMMSE = W*HhatLS;
ChMSE_LMMSE = ChMSE_LMMSE + ((H -HhatLMMSE)'*(H-
HhatLMMSE))/nFFT;
% Time domain LMMSE estimation
ghatLS = ifft(HhatLS,nFFT);
Rgg = g*g';
        WW = Rgg/(Rgg+(beta/snr(ii))*eye(L));
ghat = WW*ghatLS(1:L);
TD_HhatLMMSE = fft(ghat,nFFT);%
        TDMSE_LMMSE = TDMSE_LMMSE + ((H -TD_HhatLMMSE)'*(H-
TD_HhatLMMSE))/nFFT;

% Time domain LMMSE estimation - ignoring channel covariance
ghatLS = ifft(HhatLS,nFFT);
Rgg = diag(g.*conj(g));
        WW = Rgg/(Rgg+(beta/snr(ii))*eye(L));
ghat = WW*ghatLS(1:L);
TDD_HhatLMMSE = fft(ghat,nFFT);%
        TDDMSE_LMMSE = TDDMSE_LMMSE + ((H -TDD_HhatLMMSE)'*(H-
TDD_HhatLMMSE))/nFFT;

% Time domain LMMSE estimation - ignoring smoothing matrix
ghatLS = ifft(HhatLS,nFFT);
TDQabs_HhatLMMSE = fft(ghat,nFFT);%
TDQabsMSE_LMMSE = TDQabsMSE_LMMSE + ((H -
TDQabs_HhatLMMSE)'*(H-TDQabs_HhatLMMSE))/nFFT;

end
ChEstLS(ii) = ChMSE_LS/MC;
ChEstMMSE(ii)=ChMSE_LMMSE/MC;
TD_ChEstMMSE(ii)=TDMSE_LMMSE/MC;
TDD_ChEstMMSE(ii)=TDMSE_LMMSE/MC;
TDQabs_ChEstMMSE(ii)=TDQabsMSE_LMMSE/MC;
toc;
end

% Channel estimation
semilogy(EsNodB,ChEstLS,'r','LineWidth',2);
holdon;gridon;xlabel('Es/No [dB]'); ylabel('Channel MSE');
semilogy(EsNodB,ChEstMMSE,'k','LineWidth',2);
semilogy(EsNodB,TD_ChEstMMSE,'g','LineWidth',2);
```

```
semilogy(EsNodB,TDD_ChEstMMSE,'m','LineWidth',2);
semilogy(EsNodB,TDQabs_ChEstMMSE,'b','LineWidth',2);

% Theoratical bound calculation
semilogy(EsNodB,beta./snr,'-.r*','LineWidth',2);
ThLMMSE = (1/nFFT)*(beta./snr).*(1./(1+(beta./snr)));
semilogy(EsNodB,ThLMMSE,'-.k*','LineWidth',2);
legend('LS','MMSE', 'TD LMMSE','TDD LMMSE','TD QabsLMMSE','Theory-LS',
'Theory-LMMSE');
```

RESUME

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