Performance of DVB-T System under Multipath Fading with LS Channel Estimation and Equalization

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Submitted to the
Institute of Graduate Studies and Research
in partial fulfilment of the requirements for the Degree of

Master of Science
in
Electrical and Electronic Engineering

Eastern Mediterranean University
August 2015
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

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ABSTRACT

Digital Video Broadcast-Terrestrial (DVB-T) is a broadly used digital television standard in use around the globe for terrestrial television transmission. It offers many services and enables efficient use of the available radio frequency spectrum than the previous multiplexing modulation techniques to provide high data rates along with robustness against multipath. However, due to the frequency selectivity of the channel, DVB-T systems show poor performance and high probability of errors.

In this research, DVB-T system has been implemented in accordance with European Telecommunications Standards Institute (ETSI), EN 300 744 standard. Simulations and analysis based on performance evaluation of DVB-T system in Portable Indoor (PI), Portable Outdoor (PO), Rural Area (RA6), Rayleigh and Typical Urban (TU6) channel models has been conducted. In order to overcome the distortions caused by the multipath channel, Least Square (LS) channel estimation method has been proposed. BER performance of the system has been analysis for 4, 16 and 64 QAM constellations in all five channels. In order to clarify the results image transmission has been done for all three constellations in mentioned channels. As a result in received image distortion has been appeared as a salt and pepper noise, so that we proposed Median filter to overcome with channel noise. However in 4-QAM and 16-QAM the result was acceptable, in 64-QAM constellation result could not be clarify completely, although in RA6 channel with 24dB SNR and with usage of Median filter good improvement can be observed.

Keywords: DVB-T, OFDM, LS estimation, multipath fading channels, median filter

ÖZ

Sayısal Karasal Yayıncılık (SKY), karasal televizyon yayını için dünya çapında yaygın olarak kullanılan dijital televizyon standardıdır. Bu standart, çokyollu kanala karşı sağlamlığının yanında yüksek veri hızlarına ulaşmak için mevcut radyo frekans spektrumunun daha önceki modülasyon tekniklerinden daha etkili kullanımını sağlayan birçok hizmetleri sunmaktadır. Ancak, kanalın frekans seçici olduğu ortamlarda SKY sistemleri zayıf performans ve yüksek hata oranları vermektedir.

Bu araştırmadaki benzetimler ETSI EN 300 744 standardına uygun olarak gerçekleştirilmiştir. SKY sisteminin performans değerlendirmesi için gerekli benzetim çalışmaları ve analizler Bina içi Taşınabilir (BT), Açık hava Taşınabilir (AT), Kırsal Alan (KA), Rayleigh ve Tipik Kentsel (TK) kanal ortamlarında gerçekleştirilmiştir. Çokyollu kanaldan kaynaklanan bozulmaların üstesinden gelebilmek için, En Küçük Kareler (EKK) kanal kestirim yöntemi önerilmiştir. Sistemin Bit Hata Oranı (BHO) 4, 16 ve 64 QAM kullanılarak beş farklı kanal durumunda analiz edilmiştir. Görüntü aktarımının söz konusu kanallar altında nasıl olacağını gösteren çalışmalar her üç işaret kümesi için gerçekleştirilmiştir. Alına görüntülerde tuz ve biber gürültü olarak bilinen bozulmalar ortaya çıkmış ve bu bozulmaların üstesinden gelebilmek için ortanca süzgeci önerilmiştir. 4 ve 16-QAM ortamlarında kabul edilebilir sonuçlar alınabilmesine rağmen 64-QAM kullanılması durumunda tatmin edici sonuçlar alınamamıştır ancak RA6 ortamında 24dB'de ortanca süzgeci kullanımıyla 64-QAM ortamında da iyileşme gözlemlenmiştir.

Anahtar Kelimeler: SKY, DFBÇ, EKK, çokyollu sönümleme, ortanca süzgeç

To my family, my parents and my brother for their love, support and encouragement which got me through.

ACKNOWLEDGMENT

I would especially like to thank to Prof. Dr. Hasan Amca for his support and academic assistance without which this research could not be done. I would also like to express my sincere thanks to Assoc. Prof. Dr. Ahmet Rizaner for his consistent support and academic assistance without which my journey would have been impossible. My thanks also go to my family and friends for their love and support. Finally I would like to thank my love whose friendship have been the pillar to my success.

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$f_{Doppler}$	Doppler Frequency
f_k	Subcarrier Frequency
N	Number of Symbols
S_f	Period of Pilot Tones in Frequency Domain
S_t	Period of Pilot Tones in Time Domain
T	Elementary Period
T_G	Length of CP
T_F	Frame Transmission Duration
T_s	Frequency Domain Symbol Duration
T_{sym}	Duration of Transmission
T_{sub}	Effective Symbol Duration
$\Psi_{l,k}$	The *l*th OFDM Signal at the *k*th Subcarrier
σ_{max}	Maximum Delay Spread
ADTB-T	Advanced Digital Television Broadcasting Terrestrial
AM	Amplitude Modulation
ASK	Amplitude Shift Keying
ATSC	Advanced Television Systems Committee
AWGN	Additive White Gaussian Noise
BCH	Bose Chaudhuri Hocquengham
BPSK	Binary Phase Shift Keying
COST 2	European projects for Digital Land Mobile Radio Communications
CP	Cyclic Prefix
C/N	Carrier to Noise

CS	Cyclic Suffix
DAB	Digital Audio Broadcasting
DFT	Discrete Fourier Transform
DMB-T	Digital Multimedia Broadcast Terrestrial
DSL	Digital Subcarrier Line
DTMB	Digital Terrestrial Multimedia Broadcast
DVB	Digital Video Broadcasting
DVB-C	Digital Video Broadcasting Cable
DVB-H	Digital Video Broadcasting for Handheld
DVB-S	Digital Video Broadcasting Satellite
DVB-T	Digital Video Broadcasting-Terrestrial
ETSI	European Telecommunications Standards Institute
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FM	Frequency Modulation
FS	Frequency Selective
FSK	Frequency Shift Keying
HDTV	High Definition Television
HP	High Priority
ICI	Inter-Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
IFT	Inverse Fourier Transform
ISDB-T	Integrated Services Digital Broadcasting Terrestrial
ISI	Inter Symbol Interference

LAN	Local Area Wireless
LDPC	Low Density Parity Check
LMS	Least Mean Square
LOS	Line of Sight
LP	Low Priority
LS	Least Square
MCM	Multi Carrier Modulation
MHz	Megahertz
MMSE	Minimum Mean Squared Error
MUX	Multiplexer
NFS	Non Frequency Selective
OFDM	Orthogonal Frequency Division Multiplexing
PI	Portable Indoor
PO	Portable Outdoor
PM	Phase Modulation
PSD	Power Spectral Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QEF	Quasi Error Free
QPSK	Quadrature Phase Shift Keying
RA6	Rural Area Reception
RF	Radio Frequency
SNR	Signal to Noise Ratio
S/P	Serial to Parallel
TPS	Transmission Parameters Signaling

TU6	Typical Urban Reception
UHF	Ultra High Frequency
VHF	Very High Frequency
ZF	Zero Forcing
ZP	Zero Padding

Chapter 1

INTRODUCTION

Our life has been surrounded by intelligent communication devices and lately the demand for such devices as smartphones has grown rapidly. The important role of these smartphones in nowadays life is undeniable. In addition to saying also, which is the very reason mobile phones were invented, giving directions, saving your information which you don't want to memories, social activities, writing, reading and organizing your daily life is also done with the click of several buttons. Furthermore, watching your favorite TV shows while you are in traffic is one of the important demands. Digital Video Broadcasting for Handheld (DVB-H) devices is a technical specification for bringing broadcast services to handheld receivers. The Digital Video Broadcasting-Terrestrial (DVB-T) is the basic standard for this development [1]. As The Digital Video Broadcasting (DVB) standards develop the importance of Orthogonal Frequency Division Multiplexing (OFDM) shine brighter, especially when we consider the usage of smartphones as receivers. Due to its high data rate transmission capability with high bandwidth efficiency and robustness to multipath delay, OFDM is being used as a standard scheme in DVB-T [2]. DVB-T allows the usage of radio frequency spectrum efficiently, resulting in better sound and picture quality and the possibility of adding new services such as high definition pictures.

Communications of wireless devices in terrestrial environments rely on multiple copies of the transmitted signals arriving at the receiver through multiple paths.

These paths with different arrival times and phases can add constructively to yield a high quality signal or destructively, to yield a low quality signal. The situation gets worse when the channel becomes frequency selective and causes Inter Symbol Interference (ISI) [3]. Channel coding and adaptive equalization are some of the techniques which have been widely used as a solution. However, due to the natural delay in the coding and equalization process and precious hardwires, it is quite difficult to use these techniques in systems operating at high bit rates.

DVB-T is more sensitive to channel fluctuations than single-carrier schemes such as Frequency Division Multiple Access (FDMA) due to the hierarchical modulation techniques (such as 64 Quadrature Amplitude Modulation (QAM)) employed [4,5]. Early DVB systems were therefore designed to operate solely in Line-of-Sight (LOS) scenarios employing a high tower transmitter and roof-top receiver antenna [6]. However, losing the LOS between transmitter and receiver, the resulting signal at the receiver will consist of echoes only and causes a significant loss in Signal-to-Noise-Ratio (SNR). In the case of No-LOS, for the system to operate successfully, the channel has to be sensed precisely using a reliable estimation method such as Zero Forcing (ZF) or Minimum Mean Squared Error (MMSE). The channel sensing is relatively easier when the channel is Non-Frequency-Selective (NFS) but becomes a trivial problem when the channel becomes Frequency Selective (FS) [4].

In general, the channel can be estimated by using a preamble or pilot symbols known to both transmitter and receiver. Choice of the best estimation method for a particular system depends on the aimed performance, tolerable computational complexity and speed of variation of the channel [7]. The block-type pilot is suitable for slow fading channel by estimating the channel along the time axis while the comb-type pilot would be chosen for equalizing fast fading channels [7, 8]. The arrangement of comb-type pilots suits well to the Least Square (LS), MMSE and Least Mean Square (LMS) methods. Although, Discrete Fourier Transform (DFT) estimation method, has been provided to improve the performance of MMSE or LS estimation method, where the noise effects on maximum channel delay, DFT will take action by taking the Inverse Discrete Fourier Transform (IDFT) of the channel estimate either by LS or MMSE [7].

1.1 DVB Organization and Worldwide Coverage

Since the introduction of TV in human life in 1928 by Philo Farnsworth [9], inventors have been searching for ways of increasing their revenue obtained from TV manufacturing. People like to share their thoughts, opinions and observations in their everyday communication. By using this kind of electronic communications devices such as TV and radio, this dream became true, even in long distances. This always increased the potential of exchanging ideas. As the days went by, developments in the TV industry and technology become evident. The broadcasting were done through signals transmitted over relays. The amplitudes and phases of these signals are varied to transform data, voice, video or an image over these channels; this was called Analog Transmission [10].

The increasing need for higher volumes of data communication per unit time demanded that the capacities of electronic communication systems increased significantly. This development brought digital transportation of data among the electronic devices which made continues signals to discrete type in order to satisfy the requirement of huge data transmission in modern life. A simple digital communication has been shown in Figure 1.1 [11].

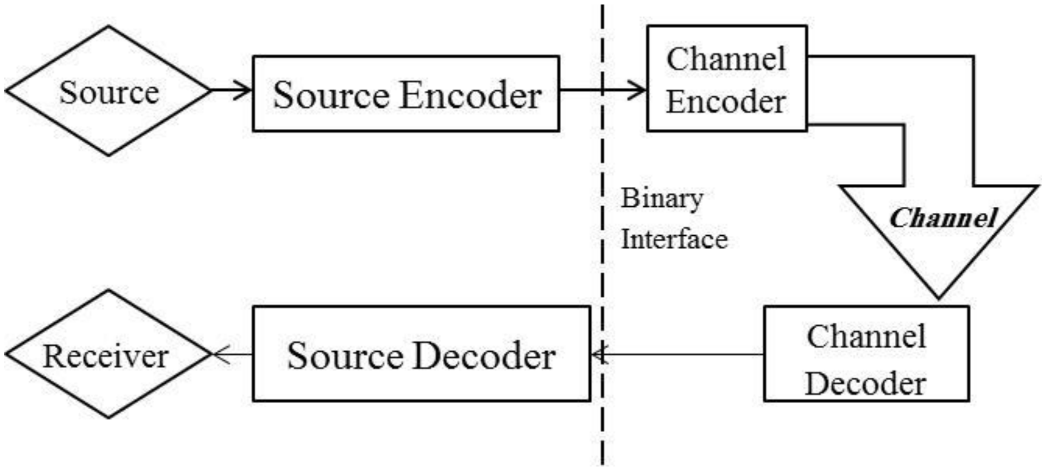


Figure 1.1: Simple Digital Communication [22]

In order to develop digital terrestrial TV, many broadcasters and consumer equipment manufacturers have been gathered to standardize the digital broadcasting systems in the interest of global sharing and development of communication systems. Since then, there are four different types of standards for digital broadcasting in all over the world. These are known as DVB, Advanced Television Systems Committee (ATSC), Integrated Services Digital Broadcasting Terrestrial (ISDB-T) and Digital Terrestrial Multimedia Broadcast (DTMB). Each standard has its own usage area. Since 2006, DTMB has been the national Chinese standard for digital terrestrial television broadcast. It is separated into two parts, ADTB-T and DMB-T, the earlier was a single-carrier standard while the later was a multicarrier technique based on OFDM and it is working on UHF and VHF bands with 8 MHz bandwidth for each RF channel [22]. In December 2003 Japan has launched its own standard called ISDB-T and there are a number of countries which have been adapted to this standard and it is concurrently used for HDTV and handheld receivers [13].

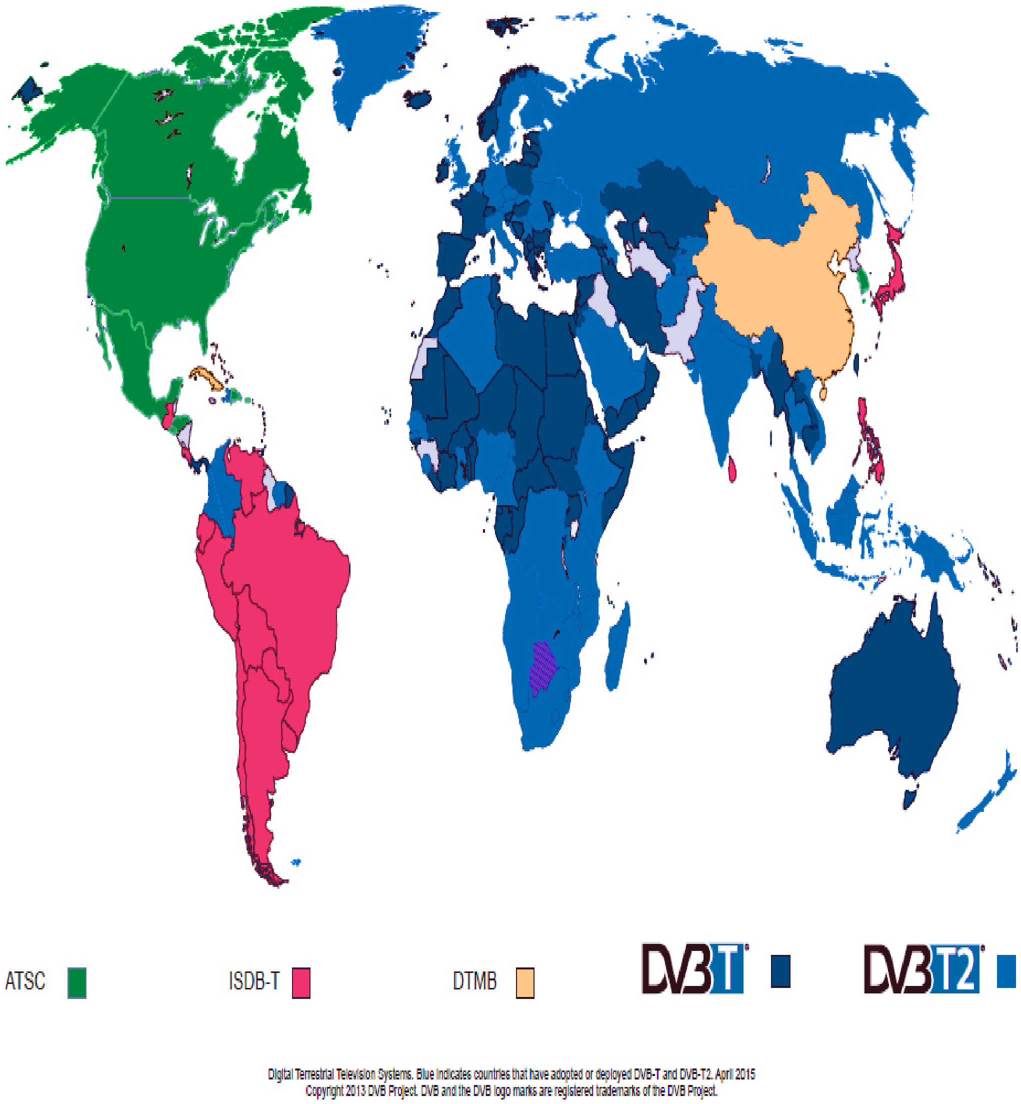


Figure 1.2: Users Zone of Different Types Standards [15]

ATSC was introduced in 1982 and it has been providing the service for Canada, Dominican Republic, El Salvador, Guatemala, Honduras, Mexico, and South Korea [14]. Confederation of about 200 companies, most of which are from Europe, has made the DVB project in 1993. They have provided a set of international standards for digital TV and there are more than 100 DVB standards all over the adopted countries. Source coding, subtitling, interfacing and transformation are just some few examples of DVB standards that are using in all electronic devices. Figure 1.2 represents the user's zone for different standards [15].

1.2 Contribution of Thesis

In this research, the performance of DVB-T system with 4, 16 and 64-QAM modulations in 2K mode of OFDM has been evaluated for the signals transmitted over the AWGN, Rician (LOS-case) and Rayleigh (Non-LOS case) channels. Some channel estimation approaches are implemented and integrated into the DVB-T system model and their performances are tested under some situations. Comparing the performances revealed that the LS channel estimation method resulted in an acceptable performance for 4-QAM and 16-QAM techniques but unacceptable performance for the 64-QAM.

1.3 Organization of Thesis

The research is organized as follows: Chapter 2 reviews the OFDM modulation and Chapter 3 concentrates on the DVB-T system in general. Then in Chapter 4, the channel estimation and detection techniques continuing with a brief representation of channel models. Chapters 5 and 6 cover the simulation results and conclusions respectively.

Chapter 2

PRINCIPLES OF OFDM

Development growth in the communications field is undeniable, in order to follow up this huge request of data transmission in such a system, many methods have been provided by researchers. Among all of them, OFDM has proved itself as one of the best modulation methods. The basic concept of OFDM comes from Multi-Carrier Modulation (MCM) transmission method. Many wireless communication systems have been adapted to OFDM such as Digital Audio Broadcasting (DAB) system, DVB system, Digital Subcarrier Line (DSL) standards and wireless (LAN) standards [16].

In multi-carrier communication, the role of OFDM is undeniable because of its flexibility. Applying the orthogonality through the frequency domain make the system robust against large delay and when a high-rate data stream is sending, the stream will split up into low rate sub-streams therefor bandwidth for each sub-carrier became smaller. In this chapter, fundamentals of OFDM have been provided as it is the main core of DVB-T systems.

2.1 System Model and Orthogonality

Discrete Fourier transform and Inverse Fourier Transform (IFT) are the basic mathematical procedure to modify OFDM in order to transform information through time domain and frequency domain, which can be mapped onto orthogonal subcarriers [17]. Equations 2.1 and 2.2 describe the orthogonality of OFDM [7]:

$$\frac{1}{T_{sym}}\int_0^{T_{sym}} e^{j2\pi f_k t} e^{-j2\pi f_i t} dt = \frac{1}{T_{sym}}\int_0^{T_{sym}} e^{j2\pi\frac{k}{T_{sym}}t} e^{-j2\pi\frac{i}{T_{sym}}t} dt$$

$$= \frac{1}{T_{sym}}\int_0^{T_{sym}} e^{j2\pi\frac{k-i}{T_{sym}}t} dt \qquad (2.1)$$

$$= \begin{cases} 1 & \forall integer\ k = i \\ 0 & otherwise \end{cases}$$

In equation above, f_k is subcarrier frequency, *N* is number of symbols, T_{sym} is duration of transmission for *N* symbols, T_s is frequency domain symbol duration and index k changes from 0 to *N*-1 i.e. k= 0, 1, 2,…, *N*-1. To introduce subcarriers at $f_k = k/T_{sym}$ between $0 \le t \le T_{sym}$, time limited signal $\{e^{j2\pi f_k t}\}_{k=0}^{N-1}$ has been used. These signals can be orthogonal where their common products integral be zero. Equation 2.1 has been established in discrete time domain in equation 2.2, where sampling has been taken at $t = nT_s = \frac{nT_{sym}}{N}$ for $n = 0,1,2,\ldots,N-1$:

$$\frac{1}{N}\sum_{n=0}^{N-1} e^{j2\pi\frac{k}{T_{sym}}nT_s} e^{-j2\pi\frac{i}{T}nT_s} = \frac{1}{N}\sum_{n=0}^{N-1} e^{j2\pi\frac{k}{T_{sym}}.\frac{nT}{N}} e^{-j2\pi\frac{i}{T_{sym}}.\frac{nT_{sym}}{N}}$$

$$= \frac{1}{N}\sum_{n=0}^{N-1} e^{j2\pi\frac{(k-i)}{N}n} \qquad (2.2)$$

$$= \begin{cases} 1 & \forall integer\ k = i \\ 0 & otherwise \end{cases}$$

Equation 2.2 is a fundamental condition for an OFDM signal to be Inter-Carrier Interference (ICI) free. In the real implementation of OFDM, the combination of Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) has been used to correlate frequency domain. The correlation is just like mapping input onto sinusoidal basis function. In general by sending data which is in frequency domain through OFDM transmitter, it will turn to the time domain by IFFT block. By choosing the number of subcarriers as *N*, the input for IFFT will be *N* point transmitted symbols from modulation block to produce *N* orthogonal subcarrier signal. The output will be all of sinusoids signal with different frequencies which has been added up to each other [7, 17]. Amplitude and phase of the carrier calculations are based on modulation which can be Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), or QAM. The reverse procedure will be performed in the receiver. FFT block will take data and transform it to the time domain in the equivalent frequency spectrum. OFDM system model has been illustrated in Figure 2.1.

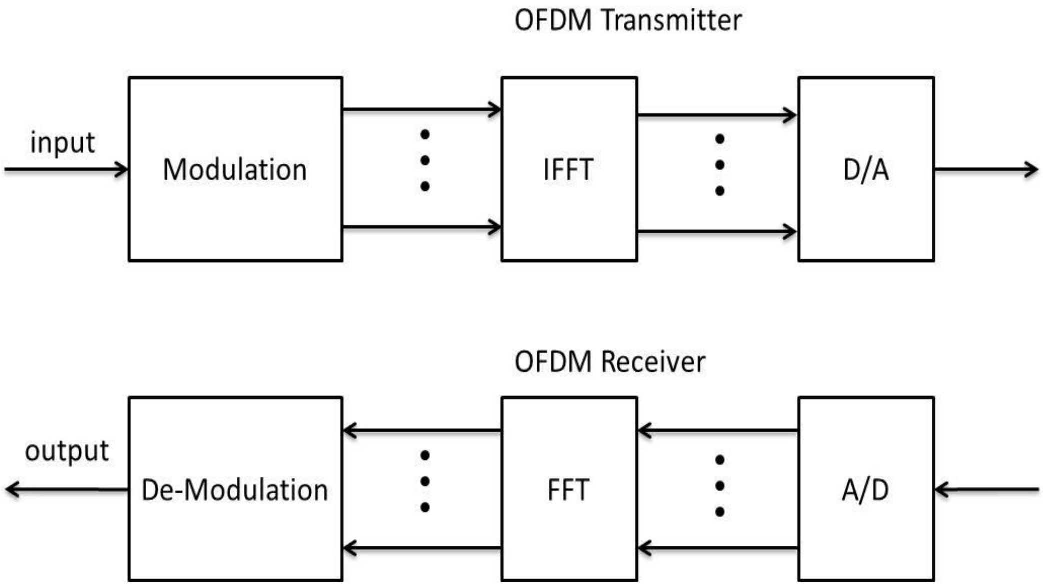


Figure 2.1: General Block Diagram of OFDM Transmitter and Receiver

2.2 Modulation and Demodulation

Basic primary aspects of the communication system are the way which data lay on radio carriers. Methods which are used to make this aim are called modulation. Modulation can be divided to analog and digital method; each of them has four different ways. In analog systems Amplitude Modulation (AM), Phase Modulation (PM), Frequency Modulation (FM) and QAM can be used. In the other side, for the digital systems, Phase Shift Keying (PSK), Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK) and QAM can be used. QAM is a combination of ASK and PSK which is widely used in OFDM systems.

QAM symbols are represented by the amplitude and the phase. For example, 8-QAM uses four carrier phases plus two amplitude levels to transmit 3 bits per symbol. Constellation diagrams which are used to describe QAM modulation for 4-QAM, 16-QAM and 64-QAM are shown in Figure 2.2, Figure 2.3 and Figure 2.4 respectively.

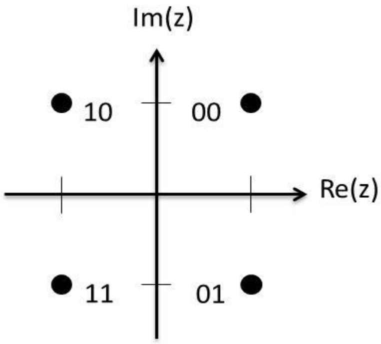


Figure 2.2: Constellation Diagram for 4-QAM

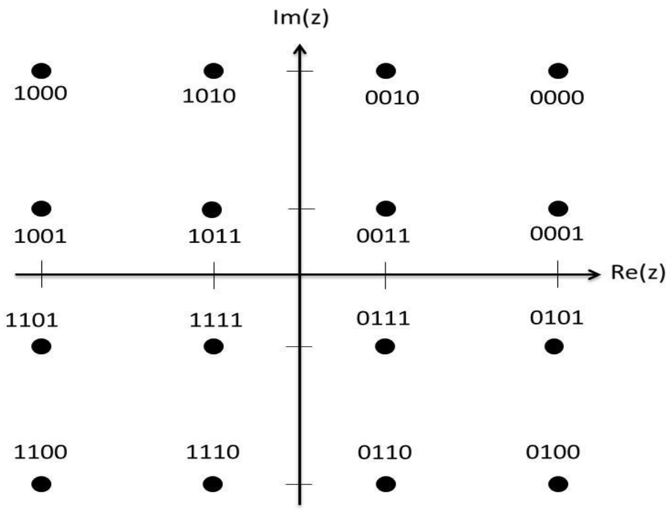


Figure 2.3: Constellation Diagram for 16-QAM

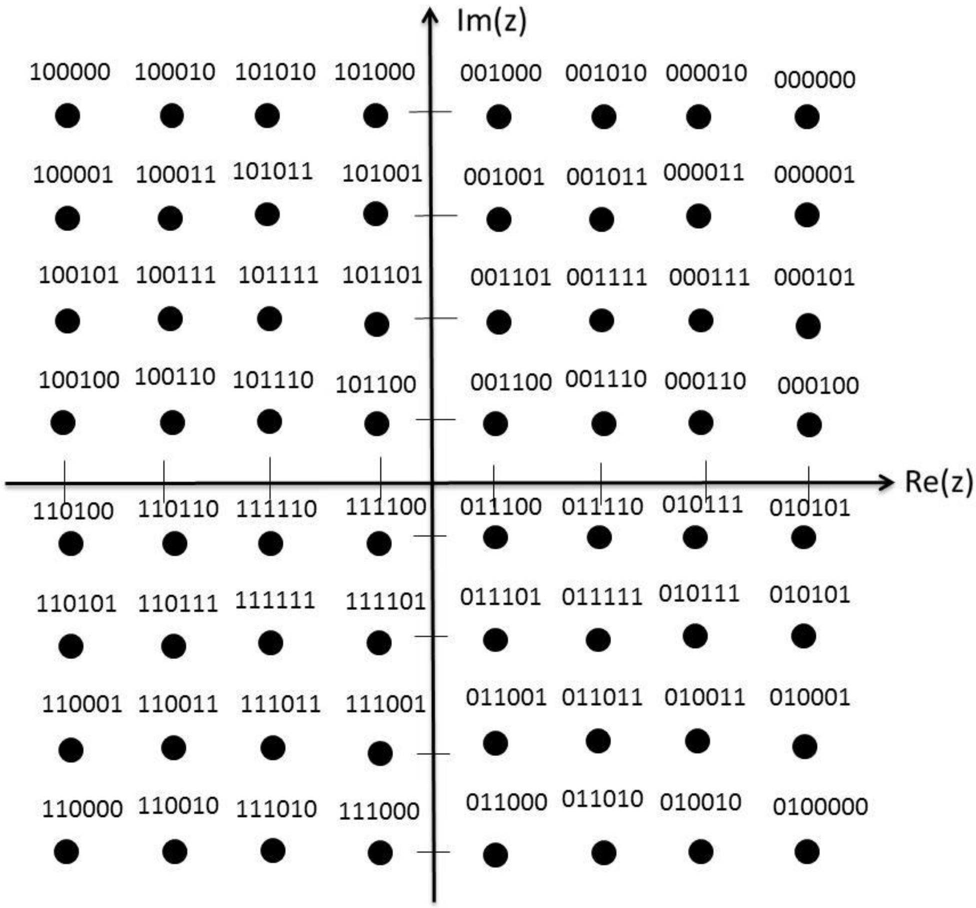


Figure 2.4: Constellation Diagram for 64-QAM

Each symbol after serial to parallel (S/P) block is carried by different subcarriers which will change the transmission time for N symbols to NT_s. Equation 2.3 is the calculation for OFDM signal at kth subcarrier [4]:

$$\Psi_{l,k}(t) = \begin{cases} e^{j2\pi f_k(t-lT_{sym})} & 0 < t < T_{sym} \\ 0 & elsewhere \end{cases} \tag{2.3}$$

$$x_l(t) = Re\left\{\frac{1}{T_{sym}} \sum_{l=0}^{\infty} \left\{\sum_{k=0}^{N-1} X_l[k] \Psi_{l,k}(t)\right\}\right\} \tag{2.4}$$

$$x_l(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{N-1} X_l[k]\, e^{j2\pi f_k(t-lT_{sym})} \tag{2.5}$$

Equation 2.4 and 2.5 are meant to describe passband and baseband OFDM signal in continues time domain. To convert equation 2.5 into discrete time, t can be represented by $t = lT_{sym} + nT_s$ where $T_s = \frac{T_{sym}}{N}$ and $f_k = k/T_{sym}$ so that equation 2.6 is obtained:

$$x_l[k] = \sum_{k=0}^{N-1} X_l[k] e^{\frac{j2\pi kn}{N}} \qquad \text{for} \qquad n=0,1,2,\ \dots\ ,N\text{-}1 \qquad (2.6)$$

As a final result, if $\{y_l[n]\}_{n=0}^{N-1}$ is the sample value of received OFDM symbol, *N* point DFT of y_l can be computed as it is in equation 2.7 and it can be evaluated by FFT algorithm.

$$Y_{l[k]} = \frac{1}{N} \sum_{n=0}^{N-1} \sum_{i=0}^{N-1} X_l[i] e^{j2\pi(i-k)n/N} = X_l[k] \qquad (2.7)$$

2.3 Guard Interval

In multipath channels, inter-symbol interference can happen as the signals transmitted through far distances. ISI makes symbols deploy further their time interval so that they will interfere with former or following symbols. In this situation, subcarriers are not orthogonal anymore. In order to prevent such a mess during communication some features are added to OFDM frames, this is called guard interval. There are some different ways to add guard interval [7, 17].

One of the most commonly used methods is Cyclic Prefix (CP). To add CP into frames, last sample of OFDM symbol will be copied and added to the front. If T_G is considered as length of CP and T_{sub} is considered as effective symbol duration, then:

$$T_{sym} = T_{sub} + T_G \qquad (2.8)$$

To keep orthogonality during the transmission, guard interval (T_G) must be longer than the maximum delay of the multipath channel. It means, each symbol has a bit of more time then IFFT symbol. Also Cyclic Suffix (CS) is a method as a cyclic extension for OFDM system. This will stop ISI among upstream and downstream. The difference between CP and CS is that: time in CP is set in order to cover distribution of channel while CS makes this setting according to the difference between upstream and downstream. There is another way to make guard interval in OFDM structure which is called Zero Padding (ZP). In this approach, zeros are added into last part of the signal in time domain. It maps length *N* signal to length *M* signal where $M > N$ [18].

$$ZP_{M,m(x)} \triangleq \begin{cases} x_m & |m| < N/2 \\ 0 & otherwise \end{cases} \qquad (2.9)$$

Where $m = 0, \pm 1, \pm 2, \dots, \pm M$ and $M_h \triangleq \frac{M-1}{2}$ for *M* odd and *M/2 -1* for M even. OFDM with ZP has smaller symbol duration than the OFDM with CS or CP. In other words, symbols with ZP have Power Spectral Density (PSD) such that narrower band ripple and bigger out of band power so that more power can be used in transmission [18].

2.4 OFDM Frame structure

As it was mentioned before OFDM can be in different transmission modes. In this thesis, frame structure of the system will be studied only for 2K and 8K transmission mode. Also, depending on the channel, OFDM can have different setting over 5MHz, 6MHz, 7MHz and 8MHz channels. Data will be transmitted as frames such that each frame has a period of T_F and includes 68 OFDM symbols. Each symbol has been set to *K*=6817 carriers in 8K mode and *K*=1705 carriers in 2K mode and will be transmitted by a duration of T_s. Each adjacent carrier has 1/T_{sub} space between each other and spacing between carriers is $\frac{K-1}{T_{sub}}$. It is also possible to produce super frames by combining four frames. The symbols in each frame will be assigned a number from 0 to 67. Each frame has two main parts; the first part is guard interval with duration T_G and after that data will be added with T_{sub}. To complete the OFDM frame structure in order to transmit through channel, three other parts must be added to the frame. First scattered pilot cells which are used for frame, frequency and time synchronization, channel estimation, transmission mode identification and also useful for tracking the noise phase are inserted [5]. Pilot carriers are added up next and after that Transmission Parameters Signaling (TPS) is added to complete the structure. The parameters of OFDM symbols for 2MHz and 8MHz for 2K and 8K modes have been shown in Table 2.1.

2.5 Hierarchical and Non- Hierarchical Modulation

A sudden change in the acceptable signal into loss service in the receiver is called cliff effect and it is caused by reducing the SNR which will change the signal modulation in the time axis. In order to prevent this problem, DVB-T employs two different modulations namely hierarchical and none-hierarchical. Hierarchical works with a lower bit rate and has a robust encoding and modulation. In the other side, non-hierarchical method has great advantages which work with enormous bit rate, but the disadvantage is that the encryption has less solidarity. After transmitting the data, it will be divided into two streams with a splitter which are different from each other and treated with a different method than the other stream.

The difference between High Priority (HP) data flow and Low Priority (LP) data flow, lays in bit rate and error protection which is visible in their names as in HP has a high error protection with a low bit rate compared to LP which has low error protection with high bit rate. From a far distance to the transmitter HP data flow will be received with a less rate of signal to noise, different from LP data flow which is exactly reverse of HP, because from short distance to the transmitter is the LP data flow which will be received with a higher rate of signal to noise ratio.

Table 2.1: Non- Hierarchical DVB-T in 2K mode parameters for 8 MHz channel [5]

Parameters	2K Mode
Elementary Period (T)	7/64 μs
Number of Carriers (K)	1705
Value of carrier number (K_{min})	0
Value of carrier number (K_{max})	1704
Duration (T_{sub})	224 μs
Carrier Spacing ($1/T_{sub}$)	4464 Hz
Spacing between carriers K_{min} and K_{max}	7.61 MHz
Allowed Guard Interval (T_G/T_{sub})	1/4, 1/8, 1/16, 1/32
Duration of Symbol part (T_{sub})	224 μs
Duration of guard interval (T_G)	56 μs, 28 μs, 14 μs, 7 μs
Symbol Duration (T_s)	280μs, 252μs, 238μs, 231 μs

2.6 Advantages and Disadvantages of OFDM

After studying basics of OFDM we can summarize advantages and disadvantages of it as follows; first of all OFDM inclusively separates channel into multiple narrowband signals so that the system is more stable in frequency selective fading then single carrier system. Secondly, OFDM has efficient bandwidth usage by making close spaced overlapping subcarriers. On the other hand, as it was mention in Section 2.4 OFDM system provide ISI free transmission and the simplicity of channel equalization in OFDM makes it strongest modulation methods. It is clear that every system regardless of its advantages has also some problems as for OFDM. First of all we can say that system is not resistance to carrier frequency offset and drift. Secondly, signals in OFDM consists an amplitude variation noise and it has a large peak to average power ratio. This means that booster cannot work with high turnover levels.

Chapter 3

DIGITAL VIDEO BROADCASTING AND CHANNEL MODELLING

In order to implement DVB system, knowledge of basics for this transmission method is critical. The elementary block diagram for DVB-T system and the procedure through each block has been studied in this Chapter. To complete the implementation, different kind of channel models used in DVB-T transmission has been modeled. Later on this Chapter, channels and their modeling has been introduced. A quick review of the median filter is also presented.

3.1 Review of DVB-T System

As it was discussed in Chapter 1, digital video broadcasting terrestrial is one of the European Telecommunications Standards Institute (ETSI) standards for broadcasting the digital TV through different channels and it has been designed for various receivers in order to have better quality of voice and image. Digital video broadcasting may apply through three different ways such as cable, terrestrial and satellite as shown in Figure 3.1. Video coding in all of these ways is MPEG-2 so that same coding source can be used for all. This section takes a look more deeply into the DVB-T system to clarify the basic instruction for this standard. The functional block diagram of DVB-T system has been shown in Figure 3.2 [5]. Simply after getting the signal from MPEG-2 transport multiplexer, six different changes will come into data before sending it through OFDM system.

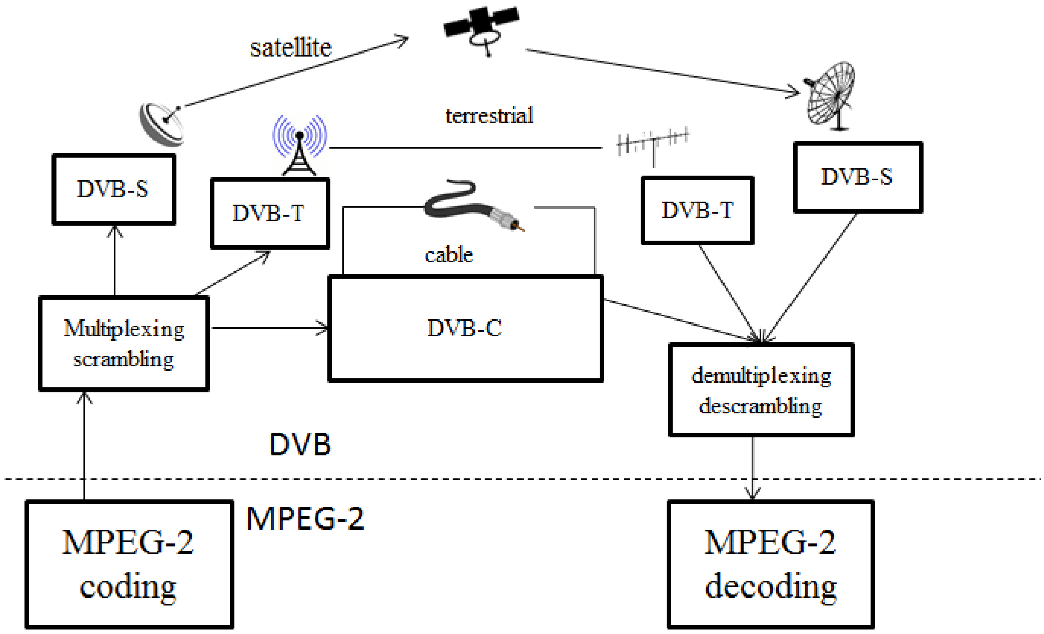


Figure 3.1: Three Main Structures of DVB Transmission Systems

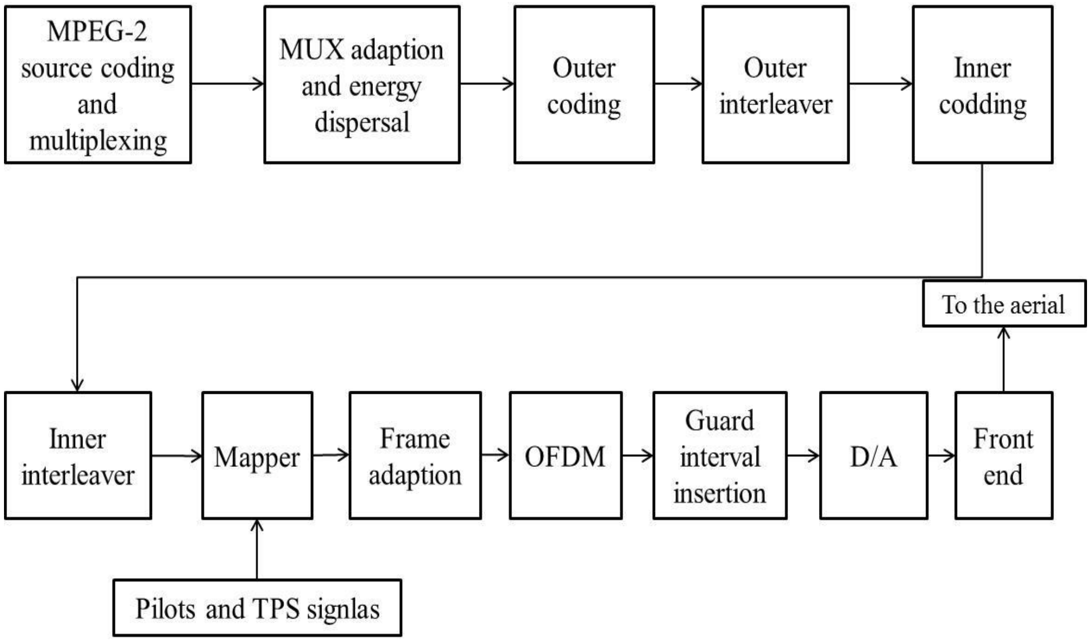


Figure 3.2: Terrestrial Channel Adapter [5]

They are known as transport multiplex adaptation and randomization for energy dispersal, outer coding (i.e. Reed-Solomon code), outer interleaving (i.e. convolutional interleaving), inner coding (i.e. punctured convolutional code), inner interleaving (either native or in-depth), mapping and modulation [5,19].

MPEG-2 transport Multiplex (MUX) packet consists of 188 bytes; each includes 1 sync-word byte. After getting the MPEG-2 stream, the aim is to achieve a flat power density spectrum and avoid accordance of long strings of zeros and ones. By randomizing the data in this section in accordance with scrambler structure adequate binary transitions is ensured [5]. In outer coding, by use of Reed-Solomon code each 188-byte data is added 16-byte redundancy to form the 204-byte transmission stream. By outer interleaving with depth I = 12, packets will be error protected [5, 19, 20]. In DVB system, selection of the most proper level of error correction for the data rate in either non-hierarchical or hierarchical transmission mode is critical. In inner coding block, error correction level will be selected by punctured convolutional codes. Mother code has been set to 1/2 in polynomials generator so that encoder takes one-bit symbols as inputs and generates 2-bit symbols as outputs. By using the mother code, generating the different punctured convolutional code (such as 2/3, 3/4, 5/6 and 7/8) has made the system flexible in different purposes [5, 20]. Inner coding is used to lower the redundancy of the mother code.

Inner interleaving which includes bit-wise inter-leaver and symbol inter-leaver has modified to avoid burst ISI and reduce the error rate. In this section, OFDM modulation takes part and the choosing of the inter-leaver for both part depend on the mode of OFDM. Bit-wise inter-leaver is demultiplexed into V sub-streams, where V = 2 for QPSK, V = 4 for 16-QAM, and V = 6 for 64-QAM. The demultiplexing is defined as a mapping of the input bits onto the output bits [5]. Bit inter-leaver has the size of 126 bits but in each case it may have a different sequence. Thus in 2K mode each process repeated twelve times and in 8K mode 48 times per symbol. Symbol inter-leaver has planned to map V bit words onto 1512 carriers in 2K mode and 6048 carriers in 8K mode per OFDM symbol and the output is used for the signal constellation in next block. To complete the process, constellations and the details of the Gary mapping is applied to the OFDM modulation which could be QPSK, 16-QAM or 64-QAM. The frame is formed by inserting pilots and TPS in this block. Parameter α define the exact proportion of constellation. The α is the minimum distance between two constellations that carrying different values, divided by the minimum distance of any constellation [5, 21]. Table 3.1 shows normalized modulation values c for each constellation point z where α can be set to 1, 2 or 4 [5].

Table 3.1: Normalization factors for data symbols [5]

Modulation scheme		Normalization factor
QPSK		$c = z/\sqrt{2}$
16-QAM	α=1	$c = z/\sqrt{10}$
	α=2	$c = z/\sqrt{20}$
	α=4	$c = z/\sqrt{52}$
64-QAM	α=1	$c = z/\sqrt{42}$
	α=2	$c = z/\sqrt{60}$
	α=4	$c = z/\sqrt{108}$

In DVB-T nearly 10% of total subcarriers are transmitted by 2.5dB power which is higher than the rest. These subcarriers are repeated for each four OFDM symbols duration [1]. The core of the DVB-T system lies on OFDM which by its own advantages make the system tunable into 2 sub-carriers known as 2K and 8K modes, and 3 different modulations which are 64-QAM, 16-QAM and QPSK. DVB-T also has specified for two-level hierarchical modulations and coding. In this case mapper and modulator map two independent MPEG transport streams onto the signal constellation. The streams are known as high-priority and low-priority [5,20]. In the non-hierarchical mode, the single input stream is demultiplexed into V sub-streams.

3.2 Enhancement through DVB-T

Since DVB-T has been developed and it has been adapted to almost every digital TV transmission, it was the time to go one step farther and increase the capacity and robustness of the system. By introducing DVB-T2 as an enhancement over the first version, the goal has been achieved. Table 3.2 compares these two standards with each other [22].

Table 3.2: Comparison of DVB-T and DVB-T2 [22]

	DVB-T	DVB-T2
FEC	Convolutional coding + Reed Solomon 1/2, 2/3, 3/4,7/8	LPDC+BCH 1/2, 3/5, 2/3, 3/4, 4/5, 5/6
Modes	QPSK,16QAM,64QAM	QPSK,16QAM, 64QAM, 256QAM
Guard Interval	1/4,1/8,1/16,1/32	1/4,19/128,1/8,19/256,1/16,1/32,1/128
FFT Size	2K, 8K	1K, 2K, 4K, 8K, 16K, 32K
Scattered Pilots	8% of total	1%, 2%, 4%, 8% of total
Continual Pilots	2.0% of total	0.4%-2.4% (0.4%-0.8% in 8K-32K)
Bandwidth	6, 7, 8 MHz	1.7, 5, 6, 7, 8, 10 MHz
Typical data rate (UK)	24 Mbit/s	40 Mbit/s
Max. data rate	37 Mbit/s	45.5 Mbit/s
Required C/N ratio	16.7 dB	10.8 dB

Both system relay on OFDM structure due to its flexibility but the difference is, in DVB-T2 modulation 256-QAM is also employed. Having a robust signal is one of the main goals in this development which has been achieved by using Low-Density Parity Check (LDPC) coding combined with Bose Chaudhuri Hocquengham (BCH) coding. These codings are used in DVB-Cable (DVB-C) and DVB-Satellite (DVB-

S). LDPC is a kind of linear block codes which in their matrix there are more zeroes then ones. One of the most important benefits of this coding is that: their performance can handle the capacity of time complex algorithm for decoding. This can be used for error correction in cell communication systems. On the other side, BCH is a family of multiple random or cyclic error-correcting codes. There are two types of BCH coding, binary and none binary. In transmission system code words are assigned as polynomials. The polynomial of codes can be generalized in terms of coefficients but in BCH coding, it is generated by roots. The combination of these two coding has made DVB-T2 system suitable for any transmission channel.

3.3 Channel Modeling

The channel referred to the path between transmitter and receiver which in that the signal passes. Determining the reception environment and its behavior brings channel modeling. Types and scenarios of reception of the DVB-T are shown in Table 3.3. DVB-T structure has been modified such that it is flexible in order to provide different kind of services in SFN such as LDTV, SDTV or HDTV [6].

In this thesis, 4 types of channel models is discussed. These channel models are: Portable Indoor (PI), Portable Outdoor (PO), Rural Area reception (RA6) and Typical Urban reception (TU6) [6, 23]. In addition to these models, a Rayleigh channel which is a theoretical channel with 6 paths reflected signals with no speed and fixed receptions using a rooftop outdoor antenna is employed [6, 23].

Table 3.3: DVB-T/H transmission channel profile [6]

Profile	Characteristics	Paths	Reception
Rayleigh	Rayleigh fading without Doppler shift	6 all is randomly realized with exponentials power delay profile with a dynamic range of 20dB	Fixed
PI	Direct path echoes with Doppler shift speed 3k/h	12 all pure Doppler	Portable
PO	Direct path echoes with Doppler shift speed 3km/h	12 all pure Doppler	Portable
TU6	Rayleigh fading Urban area-speed 50 km/h	6 Rayleigh	Mobile
RA6	Rician fading Rural area-speed 100 km/h	1 Rician and 5 Rayleigh	Mobile

3.3.1 Fixed Receptions

Receiver with a fixed rooftop antenna is called fixed reception which the antenna can be changed into two different usages. This outdoor antenna first can be set to receive the direct signal or in the worst case it can be set in order to receive the signal which has been reflected by different obtrusive objects such as buildings, hills or cars. In the last stage, this antenna can reduce the echo of received signal and determine the main signal from distorted one [6]. Table 3.4 despites the Rayleigh channel model.

Table 3.4: Rayleigh channel model

Path	1	2	3	4	5	6
Delay (μs)	0	0.11	0.22	0.33	0.44	0.55
Power (dB)	0	-10	-13.3	-15	-16	-16.7

3.3.2 Portable Indoor and Portable Outdoor

Portable is referred to devices moving from one point to another. In this scenario, the reception is not moving very fast and the speed is assumed to be 3km/h. Wing-TV project has developed PI and PO channel models to define the slowly moving hand held reception for indoors and outdoors [6,23]. The amount of maximum delay in these two channels has made the difference between them. Maximum delay spread PI channel is higher than PO channel model but the paths in PO channel have higher attenuation. Definitions of the tap delays and tap gains of the PI and PO channels are given in tables 3.5 and 3.6 [23].

Table 3.5: PI channel model [23]

Path	Delay (μs)	Power (dB)
1	0.0	0.0
2	0.1	-6.4
3	0.2	-10.4
4	0.4	-13.0
5	0.6	-13.3
6	0.8	-13.7
7	1.0	-16.2
8	1.6	-15.2
9	8.1	-14.9
10	8.8	-16.2
11	9.0	-11.1
12	9.2	-11.2

Table 3.6: PO channel model [23]

Path	Delay (μs)	Power (dB)
1	0.0	0.0
2	0.2	-1.5
3	0.6	-3.8
4	1.0	-7.3
5	1.4	-9.8
6	1.8	-13.3
7	2.3	-15.9
8	3.4	-20.6
9	4.5	-19.0
10	5.0	-17.7
11	5.3	-18.9
12	5.7	-19.3

3.3.3 Rural Area Reception and Typical Urban Reception

Arguing about mobile receptions brings the high-speed movement above 50 km/h. Mobile receptions are suffering from the factors such as AWGN, multipath propagation, narrowband interferers, and impulse interferes. Following the channel variation, in time and frequency, in addition to noise handling needs strong synchronization [6]. TU6 and RA6 channel models reproduce the terrestrial propagation in an urban area and rural area respectively which in TU6 Doppler effect is half in comparison to RA6. TU6 has been defined by COST 207 as a typical urban profile and is made of 6 propagations paths having wide dispersion in delay and relatively strong power [6]. By setting up the subcarriers in 2K mode, the high-frequency brunt which made by Doppler shift in high speed, became minimized.

Characteristics of the taps of the TU6 and RA6 channels are given in tables 3.7 and 3.8 [32].

Table 3.7: TU6 channel model [32]

Tap number	Delay(μs)	Power(dB)
1	0.0	-3
2	0.2	0
3	0.5	-2
4	1.6	-6
5	2.3	-8
6	5.0	-10

Table 3.8: Definition of RA6 channel [32]

Tap number	Delay(μs)	Power(dB)
1	0.0	0
2	0.1	-4
3	0.2	-8
4	0.3	-12
5	0.4	-16
6	0.5	-20

3.4 Median Filter

In digital image processing, many different filters have been modified in order to get rid of the noisy image and replace it with a healthy one. Depending on which domain the filtering will be applied, two different methods can be introduced generally namely spatial and frequency. These methods introduce a range of variable kind of filters in digital image processing, also having knowledge about the channel and noise makes it easier to choose more effective and economic filter in the receiver. Order statistics filters are frequency enhancement subsets which are nonlinear spatial filters. Basically, each pixel is filtered by ordering of neighborhoods of that pixel. The median filter has a wide range of usage in the filter class of order statistics [24].

In this method, filtered pixels will not take real amount of intensity which has been distorted by the noise. In other words, each pixel in the image is compared to its nearby neighbors and the filter then decides whether it is respective to them or not and if it was not, first it sorts all surrounded value into numerical order and then picks up the middle one and replace it instead of noisy pixel. If considered neighbors have even number of ranking, then the average of two in the middle will be used. Let $S_{x,y}$ be the coordinates in a sub-image window of size *m x n* centered at point (*x*,*y*). The value of the restored image at any point (*x*,*y*) is given by:

$$\hat{f}_{(x,y)} = median\,\{g(s,t)\} \quad (\mathrm{s,t})\epsilon S_{x,y} \tag{3.1}$$

As it was discussed before different noises have different effects on our data. Impulsive noise appears as black and white dots on an image and median filter has been approved that in this kind of noise it gives the best performance and it has less blurring compared to others filters. Also, it is more robust and gives realistic value to the pixels so that it works quite well on sharp edges then mean-filter [24].

Figure 3.3 is a representative example of a median filtering. In this example, a pixel is selected from the original image with its 3 by 3 neighbors. Values of all nine pixels have been sorted in next stage by their values and the one in the middle (which is 95 in this example), is replaced by the filtered pixel. In this research, appearance of salt and pepper noise made us to use this filter to improve the quality of the noisy image and replace it with the healthy one.

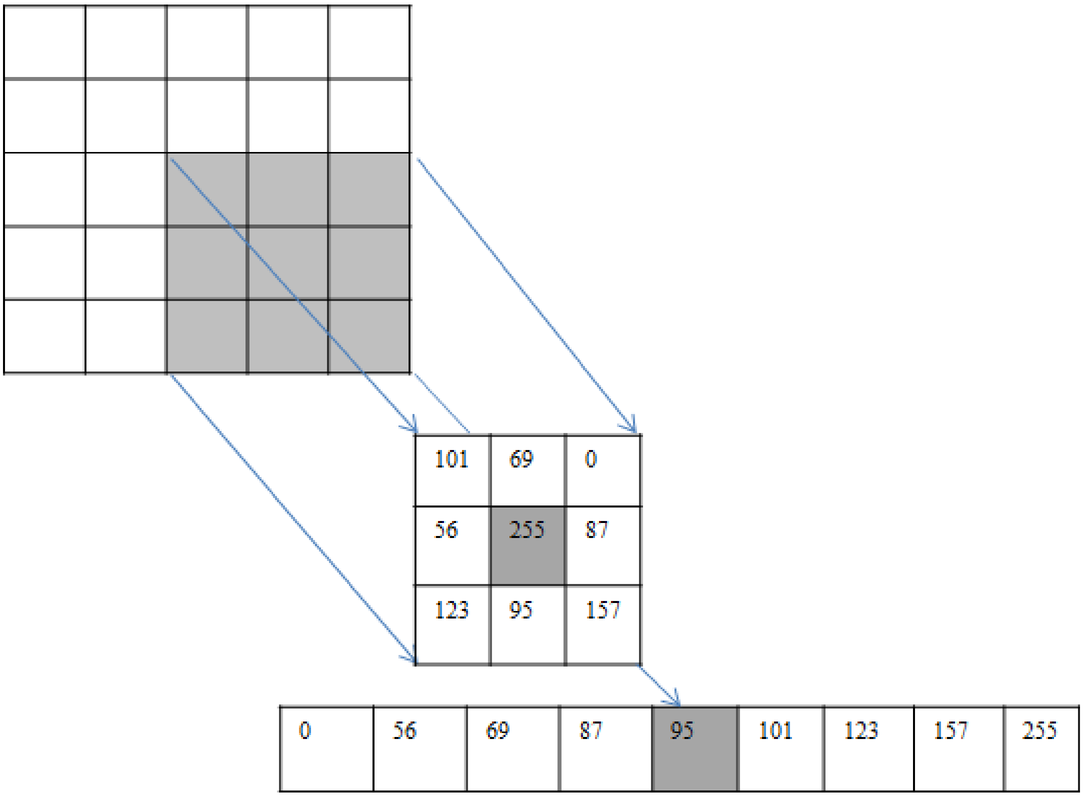


Figure 3.3: An Example of Median Filtering

Chapter 4

CHANNEL ESTIMATION

As it was discussed in Chapter 2, in an OFDM system the modulated message bit sequence has to be converted into time domain signals in order to pass through the channel. The received signal has been distorted by the characteristics of the channel. Recovering the main signal from the distorted signal in the receiver is called estimation [7, 25]. In other words, channel estimation is the estimation of the filter coefficient through received signal and other known information such as the type of the modulation. In OFDM system, effective channel estimation is critical for reliable communication under time-varying and frequency selective multipath channels.

4.1 Pilot Structure

The response of the channel at each subcarrier can be estimated through different interpolation techniques which are based on known symbols that have been inserted into both transmitter and receiver. These symbols are called preamble symbols or pilots. The pilot can be inserted to the subcarriers in different ways which will be discussed in following sections.

4.2.1 Block Type

Time domain is where this estimation method will be applied. As it is shown in Figure 4.1, S_t is the period of pilot tones which is applied on the time axis. In other words, estimation error will be zero while each block is constant and it is the result of using all the subcarriers as pilots [26]. Inequality 4.1 shows that in order to follow

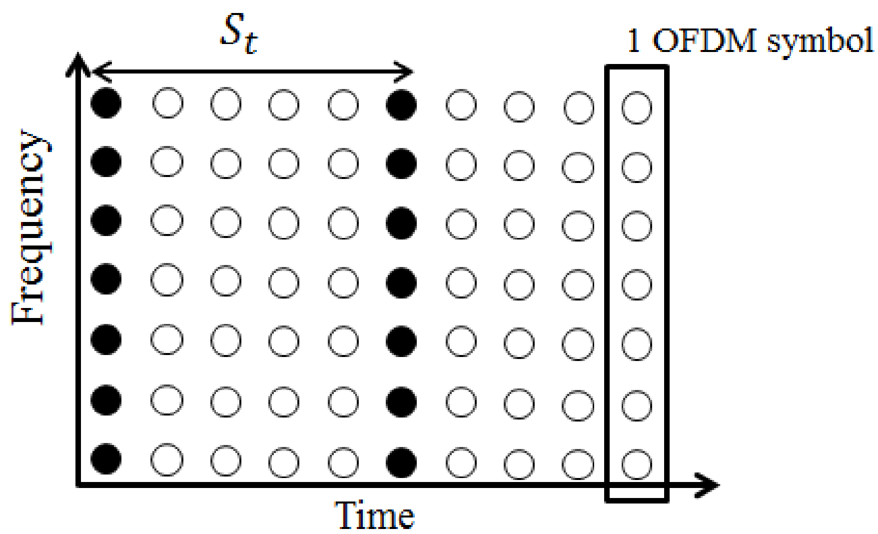


Figure 4.1: Block Type Pilot Insertion [7]

the variations of time-varying channels, pilot intervals must be less than the inverse of Doppler frequency ($f_{Doppler}$) [7].

$$S_t \leq \frac{1}{f_{Doppler}} \tag{4.1}$$

This inequality makes sure that we do not lose track of the characteristics of time varying channel. Block type is not suitable for fast fading channel but because the structure is applied on time domain, it is more suitable for frequency selective channels.

4.2.2 Comb Type

In this type of pilot arrangement, the channel estimation is performed in the frequency domain as shown in Figure 4.2. Each OFDM subcarrier is included pilot tones periodically through frequency axis. If S_f is the period of pilot tones and σ_{max} is the maximum delay spread, equation (4.2) has to be satisfied in this type.

$$S_f \leq \frac{1}{\sigma_{max}} \tag{4.2}$$

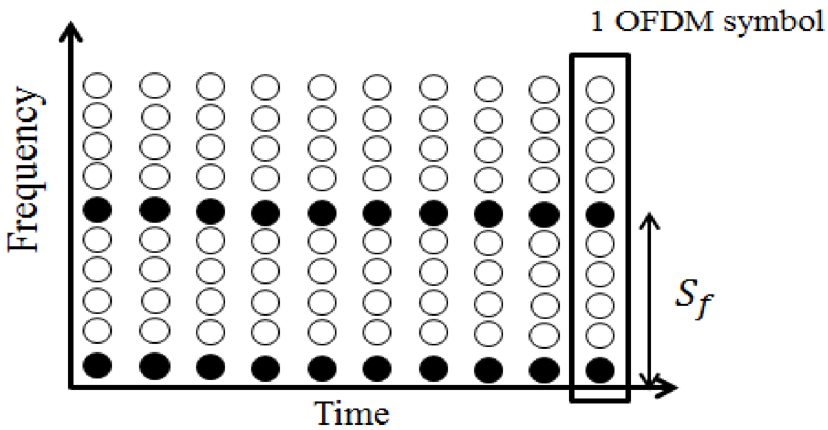


Figure 4.2: Comb Type Pilot Insertion [7]

This inequality makes sure that we do not lose track of the characteristics of frequency selective channel. Comb type is suitable for fast fading channel but because the structure is applied on the frequency domain, it is not suitable for frequency selective channels.

4.2.3 Lattice type

Both time and frequency take action in this method and pilot tones are inserted into both time and frequency axes as they are represented in Figure 4.3. Both equations 4.1 and 4.2 must be satisfied at the same time. This improves the estimation performance of both time-varying and frequency selective channels.

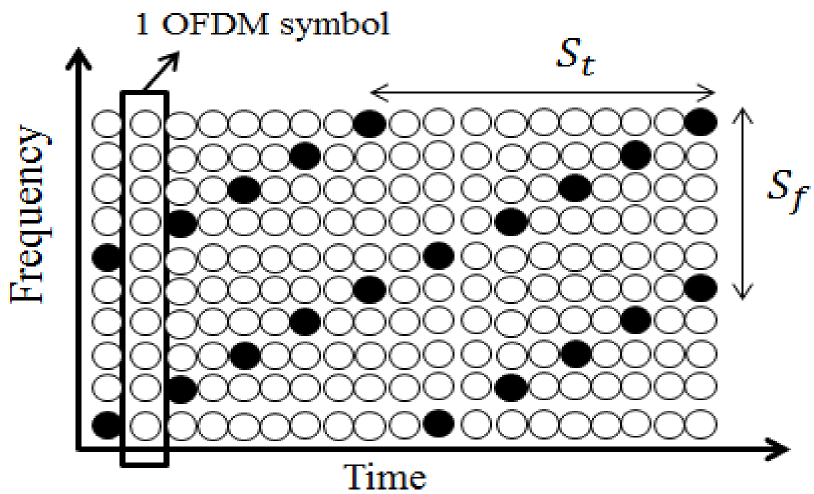


Figure 4.3: Lattice type pilot Insertion [7]

4.2 LS Channel Estimation

Between the observed data and its expected value there are always some differences. Minimizing the square of these discrepancies gives the chance of estimating the parameters, which is called least square estimation method [7, 27]. We use this linear estimation method when we assume that there is no ISI and the OFDM uses a cyclic prefix to be discarded at the receiver to cancel out ISI [7, 28]. The Lower complexity of LS and unnecessary statistical information about channel and noise [29] makes LS estimation an ideal estimation method for this research. As the subcarriers in OFDM are orthogonal, pilot tones as $X[k]$ for N subcarriers are represented as given in 4.3, where X represents the training symbol for N subcarriers [4]:

$$\mathbf{X} = \begin{bmatrix} X[0] & 0 & \dots & 0 \\ 0 & X[1] & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \dots & 0 & X[N\text{-}1] \end{bmatrix} \tag{4.3}$$

Noise and channel gain also affect the pilot symbols. Equation 4.4 represent the received training signal as $Y[k]$ where $\mathbf{Z}$ is the noise vector:

$$\mathbf{Y} \triangleq \begin{bmatrix} Y[0] \\ Y[1] \\ \vdots \\ Y[N-1] \end{bmatrix} = \begin{bmatrix} X[0] & 0 & \dots & 0 \\ 0 & X[1] & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \dots & 0 & X[N-1] \end{bmatrix} \begin{bmatrix} H[0] \\ H[1] \\ \vdots \\ H[N-1] \end{bmatrix} + \begin{bmatrix} Z[0] \\ Z[1] \\ \vdots \\ Z[N-1] \end{bmatrix}$$

$$= \mathbf{XH} + \mathbf{Z} \tag{4.4}$$

With respect to $\widehat{H}$, the vector of estimated channel, minimizing the equation 4.5 and 4.6 give the solution to LS channel estimation as:

$$J(\widehat{\mathbf{H}}) = \|\mathbf{Y} - \mathbf{X}\widehat{\mathbf{H}}\|^2 = (\mathbf{Y} - \mathbf{X}\widehat{\mathbf{H}})^H(\mathbf{Y} - \mathbf{X}\widehat{\mathbf{H}})$$

$$= \mathbf{Y}^H\mathbf{Y} - \mathbf{Y}^H\mathbf{X}\widehat{\mathbf{H}} - \widehat{\mathbf{H}}^H\mathbf{X}^H\mathbf{Y} + \widehat{\mathbf{H}}^H\mathbf{X}^H\mathbf{X}\widehat{\mathbf{H}} \tag{4.5}$$

$$\frac{\partial J(\widehat{\mathbf{H}})}{\partial \widehat{\mathbf{H}}} = -(\mathbf{X}^H\mathbf{Y})^* + (\mathbf{X}^H\mathbf{X}\widehat{\mathbf{H}})^* = 0 \tag{4.6}$$

After the FFT the pilots are extracted from the received OFDM symbols. The estimated channel response $\widehat{H}_{LS}[k]$ based on LS is expressed as [30]:

$$\widehat{\mathbf{H}}_{LS}[k] = \frac{\mathbf{Y}[k]}{\mathbf{X}[k]} \quad k = 0,1,2, \ldots N-1 \tag{4.7}$$

Computing the mean square error of LS channel estimation shows that MSE is inversely proportional to signal to noise ratio. This means that LS provides minimum error, i.e. performs best, at high SNR values [7, 31].

$$MSE_{LS} = E\left\{\left(\mathbf{H} - \widehat{\mathbf{H}}_{LS}\right)^H \left(\mathbf{H} - \widehat{\mathbf{H}}_{LS}\right)\right\} = E\{(\mathbf{H} - \mathbf{X}^{-1}\mathbf{Y})^H (\mathbf{H} - \mathbf{X}^{-1}\mathbf{Y})\}$$

$$MSE_{LS} = E\{(\mathbf{X}^{-1}\mathbf{Z})^H (\mathbf{X}^{-1}\mathbf{Z})\} = \frac{\sigma_z^2}{\sigma_x^2} \tag{4.8}$$

4.3 MMSE Channel Estimation

There is another method called minimum mean square error estimation that can also be used as a linear estimation method and uses one of the second order statistics. In general, MMSE estimates the MSE between the actual channel and estimated channel correlation in slow fading channel and minimizes it. By using the result of LS estimator which is described in equation 4.7, and multiplying it by a weight matrix the result of MMSE estimation is obtained [7]. Equation 4.9 describes the MSE of this estimation:

$$J(\widehat{\mathbf{H}}) = E\{\|\mathbf{e}\|^2\} = E\left\{\left\|\mathbf{H} - \widehat{\mathbf{H}}\right\|^2\right\} \tag{4.9}$$

To complete the MMSE procedure, equation 4.9 has to be minimized. The elementary rule of orthogonality makes estimated signal orthogonal to the estimated error vector (**e**) before multiplying the weight matrix (**W**) with the estimated signal. Equations 4.10 to 4.13 show the process to get into MMSE channel estimation ($\widehat{H}$) where $\mathbf{R}_{H\widetilde{H}}$ is the cross-correlation matrix between the true channel vector and temporary channel estimate vector in the frequency domain and $\widetilde{\mathbf{H}}$ is LS channel estimate [7]:

$$\mathbf{W} = \mathbf{R}_{\mathbf{H}\widetilde{\mathbf{H}}}\mathbf{R}_{\widetilde{\mathbf{H}}\widetilde{\mathbf{H}}}^{-1} \tag{4.10}$$

$$\begin{aligned}\mathbf{R}_{\widetilde{\mathbf{H}}\widetilde{\mathbf{H}}} &= E\left\{\widetilde{\mathbf{H}}\widetilde{\mathbf{H}}^{H}\right\} = E\{\mathbf{H} + \mathbf{X}^{-1}\mathbf{Z}(\mathbf{H} + \mathbf{X}^{-1}\mathbf{Z})^{H}\} \\ &= E\{\mathbf{H}\mathbf{H}^{H}\} + E\{\mathbf{X}^{-1}\mathbf{Z}\mathbf{Z}^{H}(\mathbf{X}^{-1})^{H}\}\end{aligned} \tag{4.11}$$

$$R_{\widetilde{\mathbf{H}}\widetilde{\mathbf{H}}} = E\{\mathbf{H}\mathbf{H}^{H}\} + \frac{\sigma_z^2}{\sigma_x^2}\mathbf{I} \tag{4.12}$$

$$\widehat{\mathbf{H}} = \mathbf{W}\widetilde{\mathbf{H}} = \mathbf{R}_{\mathbf{H}\widetilde{\mathbf{H}}}\mathbf{R}_{\widetilde{\mathbf{H}}\widetilde{\mathbf{H}}}^{-1}\widetilde{\mathbf{H}} = \mathbf{R}_{\mathbf{H}\widetilde{\mathbf{H}}}(\mathbf{R}_{\mathbf{H}\mathbf{H}} + \frac{\sigma_z^2}{\sigma_x^2}\mathbf{I}\,)^{-1}\widetilde{\mathbf{H}} \tag{4.13}$$

In this method, a large matrix inverse is required that makes MMSE estimation complex. When the input data matrix changes its inverse will be needed repeatedly that will make this approach computationally complex. Simplicity of LS estimation and dependence of its algorithm from channel model has made LS estimation method more suitable in this research.

Chapter 5

SIMULATION RESULTS

In this Chapter, simulation result will be presented to discuss the performance of the channel estimation approaches for DVB-T systems under different channel conditions.

5.1 Simulation Progress

The simplest OFDM that can be simulated is a system under AWGN noise as shown in Figure 2.1. Evaluating the system BER performance under these conditions brings a basic figure for comparing the channel performances in different channels conditions. At the last stage, transmission of some sample data such as an image through the channel help us to find a solution in order to get a better result by using a proper filter. The simulations performed are intended for the 4, 16 and 64-QAM with 2K subcarriers. The aim in the simulations is to rich a sufficient BER in a specific SNR interval. The simulations have been run for 5 different channels which their characteristics have been described in Table 3.2. AWGN has been also added to the channels. The BER performance has been measured after removal of energy dispersal in each three constellations. For the simulations, the guard interval is set to 1/4 of the length of the transmitted frames, convolutional encoder is set to 3/4, FFT size is assumed to be 2048, pilot spacing is 4 per OFDM symbols and number of frames to be transmitted is 2000. We also assumed that the carrier frequency is 626MHz.

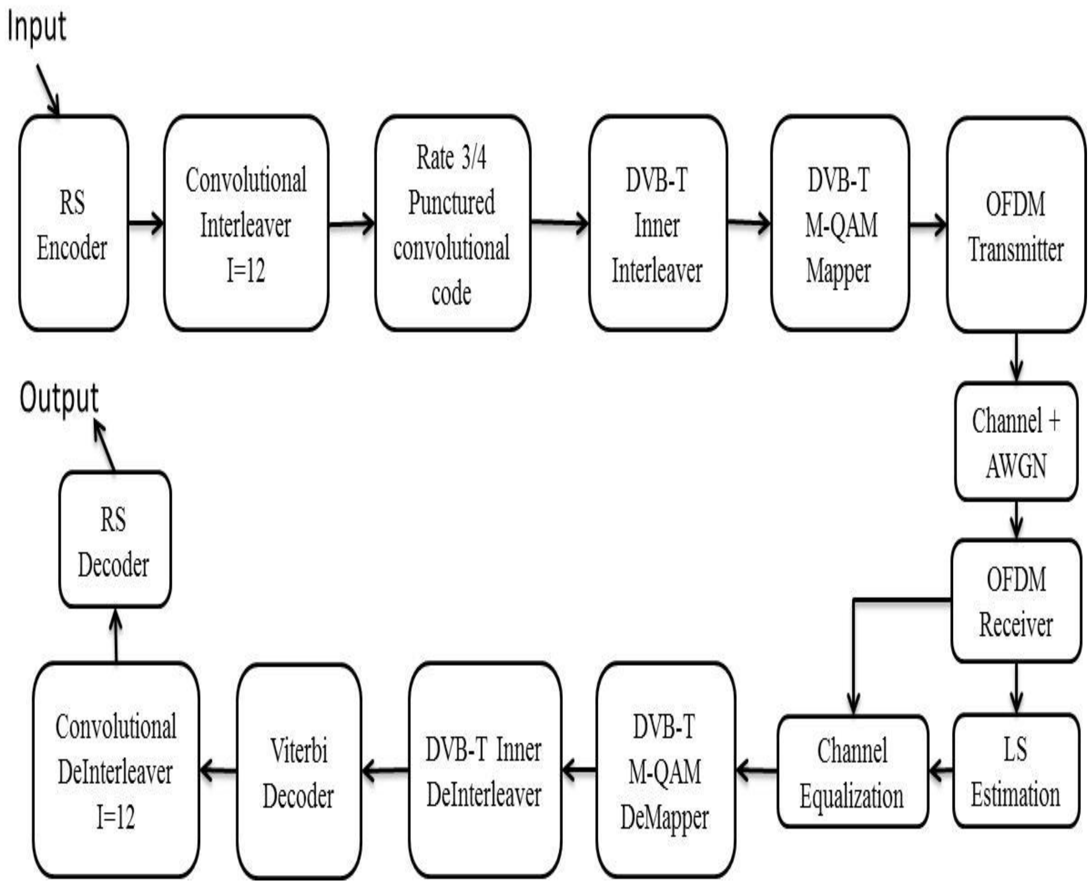


Figure 5.1: DVB-T Non-Hierarchical 2K Mode Transmission Block Diagram

To make the comparison reasonable Quasi Error Free (QEF) is defined as a threshold where the system can work in order to be able corrects the errors. This threshold has been used in DVB-T and DVB-S and the maximum value depends on code error rate. In DVB- T systems QEF is equal to $2x10^{-4}$ [32]. DVB-T system codes have been implemented according to ETSI standards in MATLAB block by block. The block diagram representation of the simulated system is illustrated in Figure 5.1. As it is shown in Figure 5.1, channel is estimated after OFDM receiver with LS based channel estimation by the help of known training symbols transmitted together with the actual data symbols. The estimated channel response is used for channel equalization to remove the imperfections resulting from the multipath fading channel.

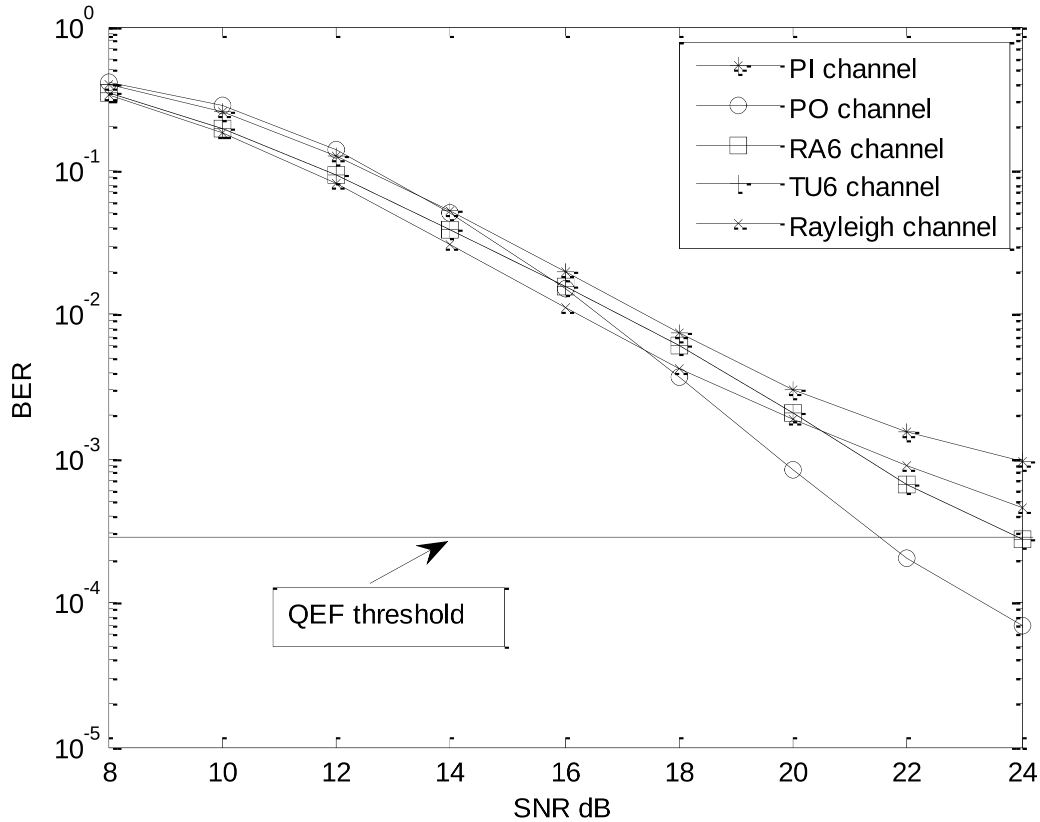
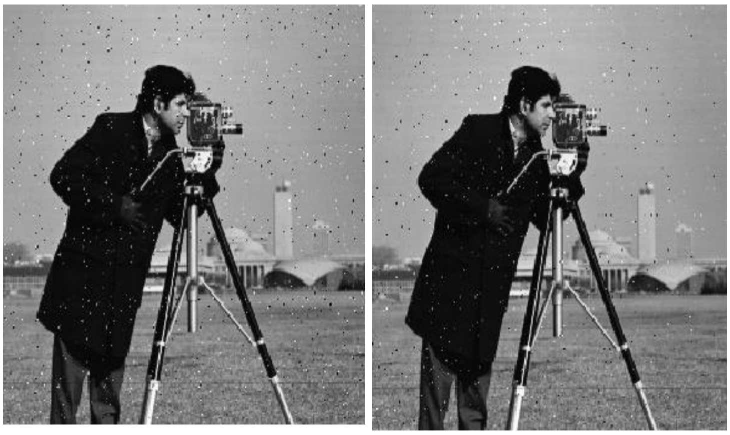


Figure 5.2: BER Performance of DVB-T with 4-QAM in 5 Different Channels

5.2 DVB-T Performance with 4-QAM

The simulation settings have been explained in section 5.1. The BER performance of 4-QAM constellation in 5 different channels is shown in Figure 5.2. This constellation gives the best performance and smoother curves among all three as it was expected. As it is obvious from the graph above, RA6 and TU6 channels have almost the same performances in the given SNR interval although they have different channel characteristics. In TU6 channel model, the reception speed is 50 Km/h without any line of sight, all 6 paths are Rayleigh distributed. In RA6 channel model, the speed rises to 100 Km/h with 5 Rayleigh paths and one direct way. In order to recover the data in the high-speed communication, even one path with a line of sight

6-path rayleigh Chanel (PI) Chanel (PO) Channel



(RA6) Channel (TU6) Channel

Figure 5.3: Image Transmission with 4-QAM in 5 Different Channels at 20 dB

can rescue the data from being too much distorted. DVB-T system with 4-QAM shows a better performance under PO channel with one direct path and fewer attenuation then PI channel, for the SNR values greater than 18dB SNR. Also, the performance of DVB-T in fixed reception with 6 Rayleigh paths without any movement is not better than the performance obtained with PO channel. Despite the fact that BER measures the quality objectively, sometimes BER may not be the only indicator of quality. Another measurement that can be used, which is not objective, could be Quality of Experience (QoE). This can be observed where the original image is presented together with channel as illustrated in Figure 5.3. The worst image was received with the PI channel. However, we can have acceptable image output in the receiver by using a median filter as shown in Figure 5.4 where SNR is set to 14dB.

Original after median filter before median filter

Figure 5.4: Image Transmission with 4-QAM through PI Channel at 14 dB

5.3 DVB-T Performance with 16-QAM

The settings of the simulated DVB-T system for 16-QAM is the same as the settings of the DVB-T system with 4-QAM. The BER Performance of DVB-T system with 16-QAM is shown in Figure 5.5 under 5 different channels. The BER performance from 8 dB to 14 dB does not show any improvement but as the signal power increases a better performance improvement is achieved. Similar to the system with 4-QAM, we have almost the same performance both in TU6 and RA6 channels. It could be concluded that improvement obtained from having even one direct path to the receiver is much more effective than the distortions caused by the Doppler shift. In this constellation (16-QAM), Rayleigh channel with fixed reception has more acceptable BER performance. But, the performance of DVB-T system under other channels could be improved significantly by the use of a median filter. As shown in

Figure 5.6 a good image quality could be obtained at the receiver. This figure shows the improvement obtained on the received image in PI channel at 20 SNR by using a median filter.

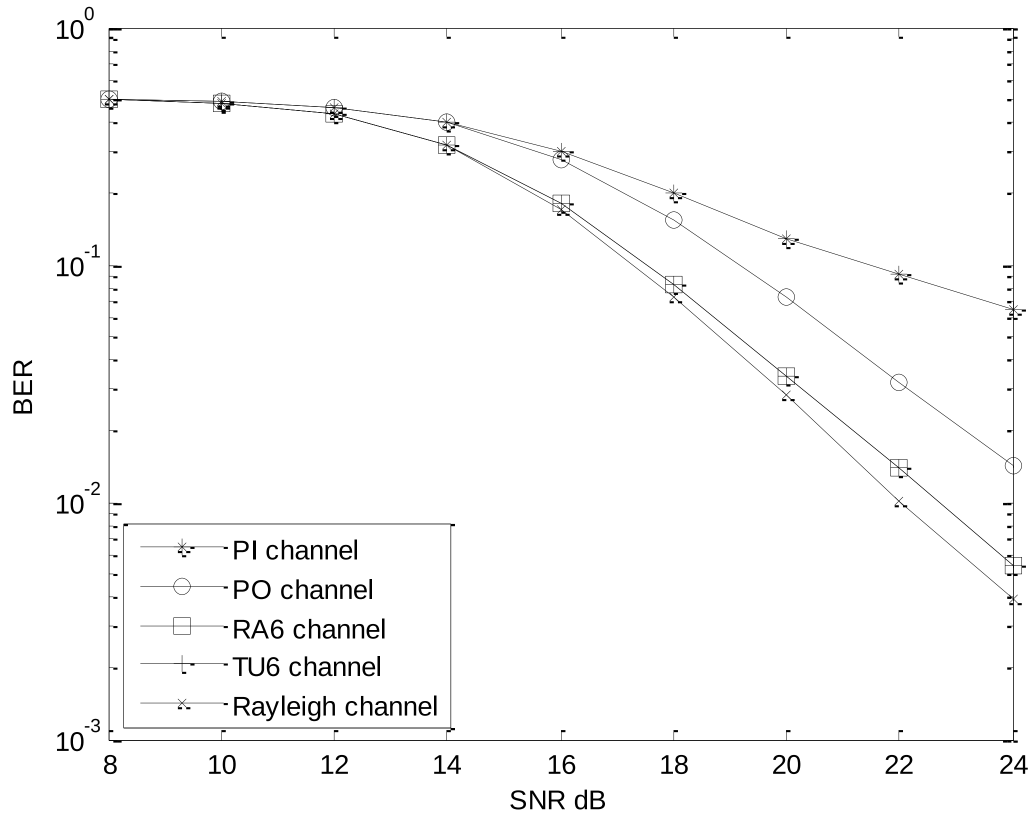


Figure 5.5: BER Performance of DVB-T with 16-QAM in 5 Different Channels

Figure 5.6: Image Transmission with 16-QAM through PI Channel at 20 dB

Results of a sample image transmission have been shown for all channels in Figure 5.7 without using a median filter in order to make actual comparison. It is obvious from the results of Figure 5.7 that PI channel gives the worst performance among all the channel models even at 20 dB SNR.

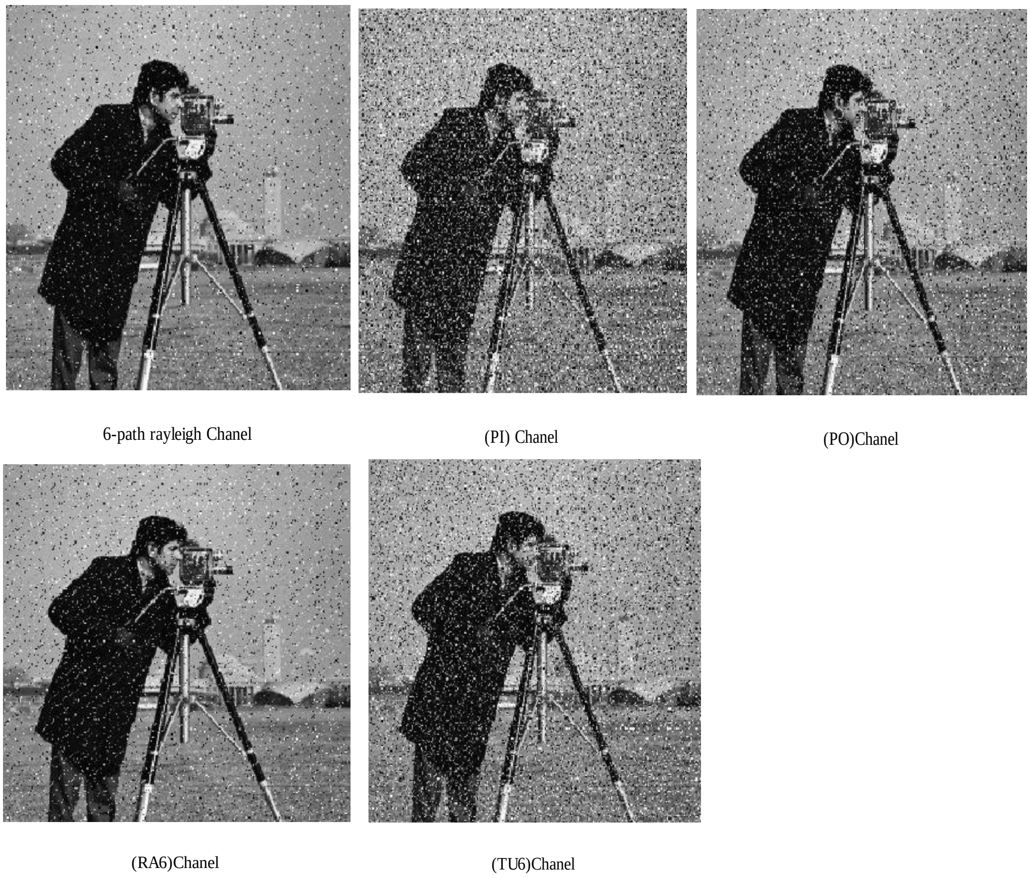


Figure 5.7: Image Transmission with 16-QAM in 5 Different Channels at 20 dB

5.4 DVB-T Performance with 64-QAM

DVB-T system with 64-QAM in the absence of direct path, using fixed receiver in Rayleigh channel has made the performance best among channels as shown in Figure 5.7. By comparing Figures 5.1, 5.4 and 5.7, the DVB-T system with 64-QAM demonstrates the worst performance between 3 constellations as it was expected. The performance of the system is not acceptable and very close for all the channel models up to 16 dB SNR. It is obvious from Figure 5.8 that between the simulated SNR intervals, this constellation (64-QAM) the BER is not acceptable. Even at 24 dB SNR, the BER does not reach to 10^{-2}.

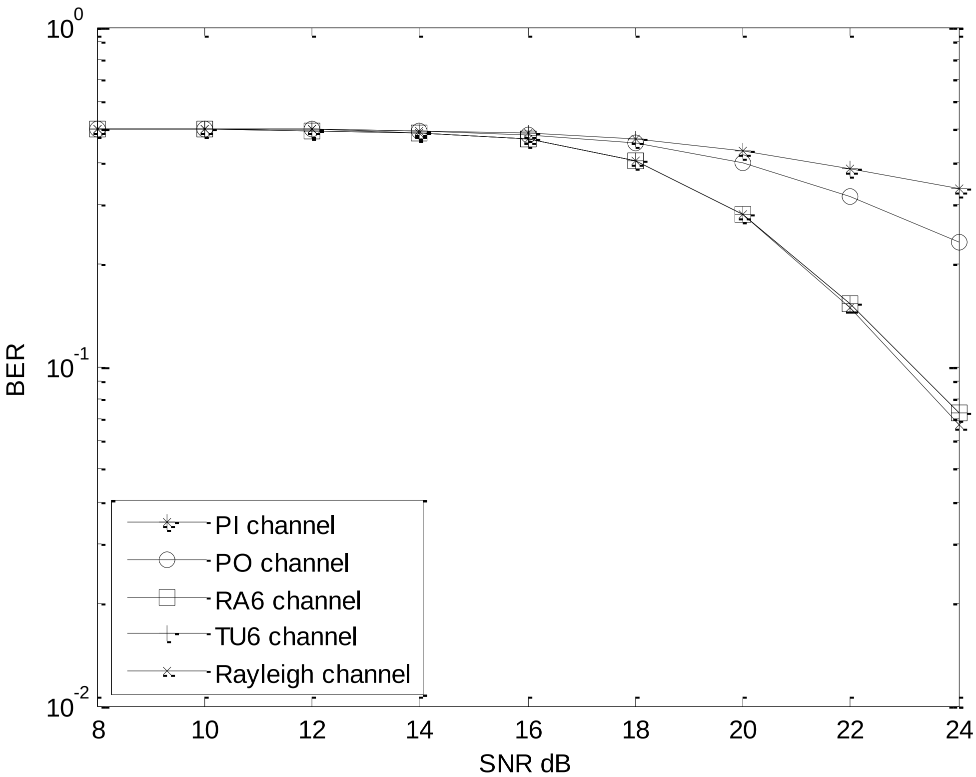
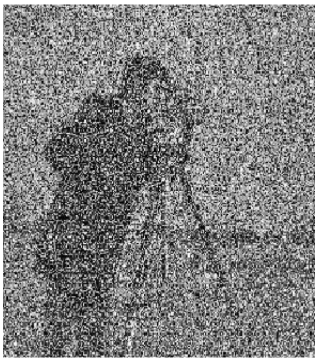


Figure 5.8: BER Performance of DVB-T with 64-QAM in 5 Different Channels

Figure 5.9 and Figure 5.10 represents the image transmission under different channel conditions and the usage of median filtering respectively. Figure 5.9 is a different way of illustrating that even at 24 dB SNR the performance of the simulated DVB-T system is very poor. But even in this poor situation, although the noise could not be removed completely, a good improvement could be obtained by using a median filter. This is illustrated in Figure 5.10 at 24 dB under RA6 channel model.

6-path rayleigh Chanel



(PI) Chanel

(PO) Chanel

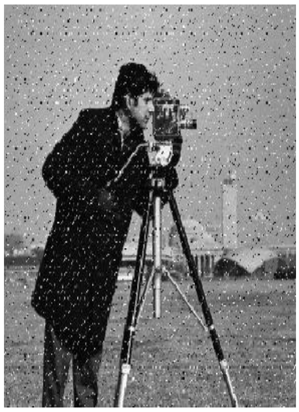
(RA6) Chanel

(TU6) Chanel

Figure 5.9: Image Transmission with 64-QAM in 5 Different Channels at 24 dB

Original

after median filter



before median filter

Figure 5.10: Image Transmission with 64-QAM through RA6 Channel at 24 dB

5.5 BER Performance Comparison of DVB-T System with All Constellations under Different Channels

The main target in this part is to compare the BER improvement for all three constellations in each channel model. Results of DVB-T with 64-QAM have very big distances from ideal BER then two other constellations. The worst performance is obtained under PI channel with 0.3353 BER even at 24 SNR which makes this constellation nearly useless under this channel condition, as it can be seen in figure 5.11. However, according to Table 5.1, it is possible to increase SNR to 28 dB in Rayleigh channel by changing code rate from 3/4 to 7/8 [33]. As long as our system has been set to 3/4 code rate, the maximum SNR can be 22 dB where DVB-T with 64-QAM gives 0.1529 BER in Rayleigh channel.

Table 5.1: Minimum C/N Required for Non-Hierarchical Modulation [35]

Modulation	Code rate	Rayleigh Channel [dB]
QPSK	1/2	5.4
	2/3	8.4
	3/4	10.7
	5/6	13.1
	7/8	16.3
16-QAM	1/2	11.2
	2/3	14.2
	3/4	16.7
	5/6	19.3
	7/8	22.8
64-QAM	1/2	16.0
	2/3	19.3
	3/4	21.7
	5/6	25.3
	7/8	27.9

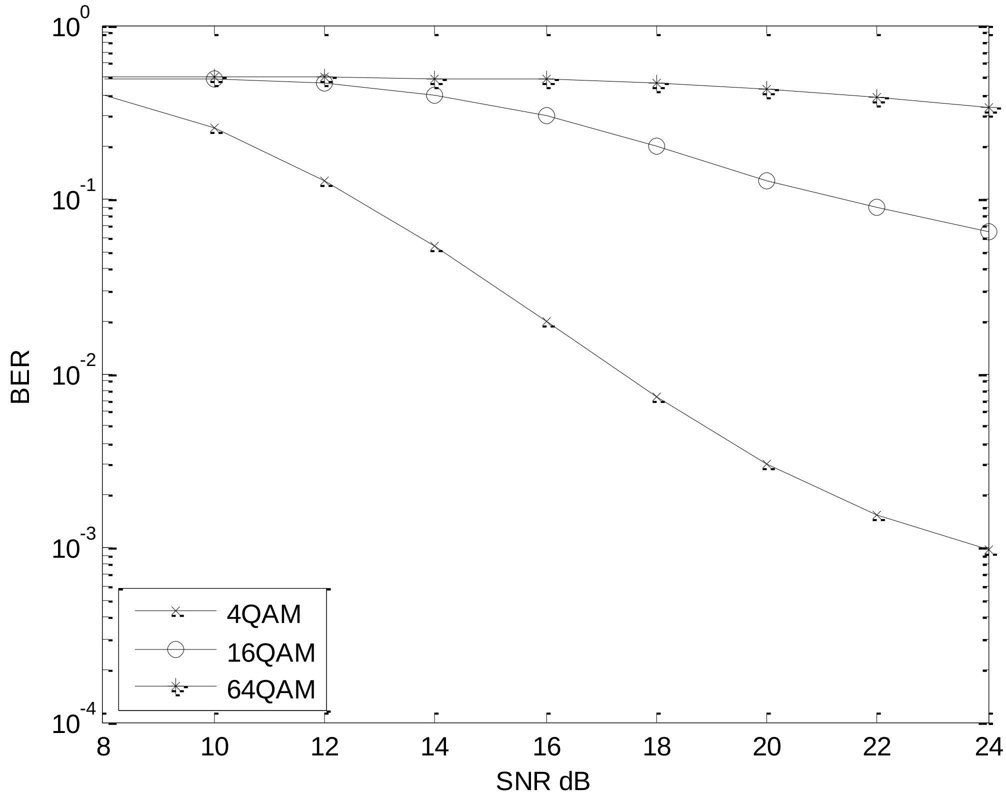


Figure 5.11: DVB-T with LS Channel Estimation in PI Channel

Depending on channel characteristics, results in each channel have a different speed in their improvement this can be seen in difference of slopes. Smoother improvements in 4-QAM and 16-QAM explain the better results in image transmission. DVB-T system with 4-QAM shows a superior performance in all five channels after 10dB SNR. The performance of DVB-T system with 16-QAM improves after 14 dB SNR. However, for the DVB-T system with 64-QAM, BER performance reaches to the acceptable rate after 18 dB only for RA6 a Rayleigh channels. It can be seen in figure 5.12 that in PO channel, 4-QAM could reach 10^{-2} BER where the SNR is 16dB. For two other constellation this can be achieve with SNR higher than 24dB this can be done where the terrestrial communication is in microcells so that the SNR threshold is higher.

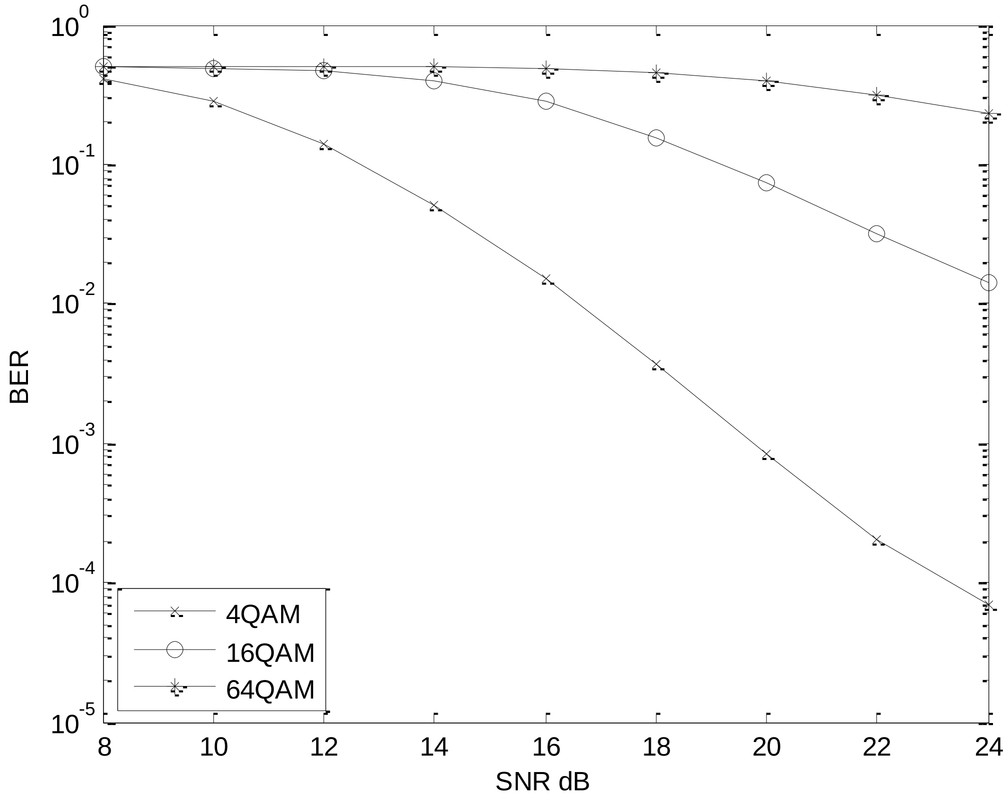


Figure 5.12: DVB-T with LS Channel Estimation in PO Channel

In RA6 channel 64-QAM shows better improvement according to figure 5.13. System performance starts to improve from 16dB SNR where there is one Rician path. This improvement also is much better for 4 and 16-QAM as well, where it starts from 12dB SNR in 16-QAM and 8dB SNR in 4-QAM. The results also are so similar in TU6 channel, as it can be seen in figure 5.14 where their difference in BER performance at each specific SNR can be calculated less then 10^{-3}.

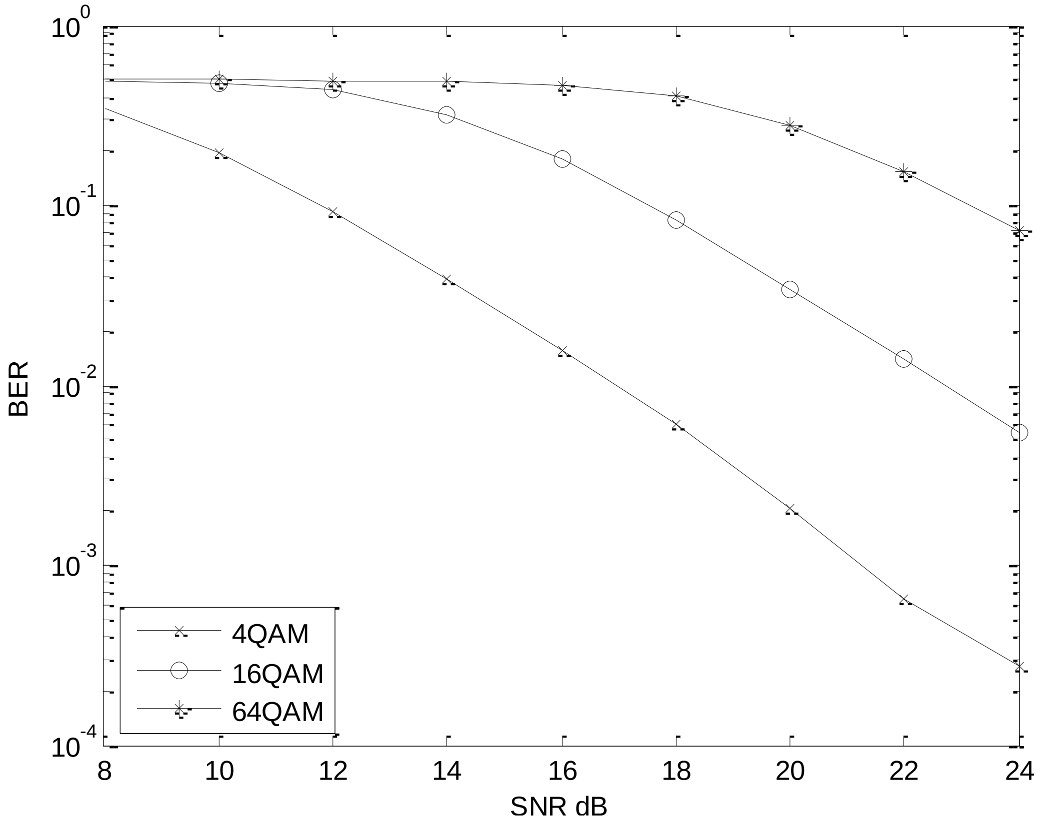


Figure 5.13: DVB-T with LS Channel Estimation in RA6 Channel

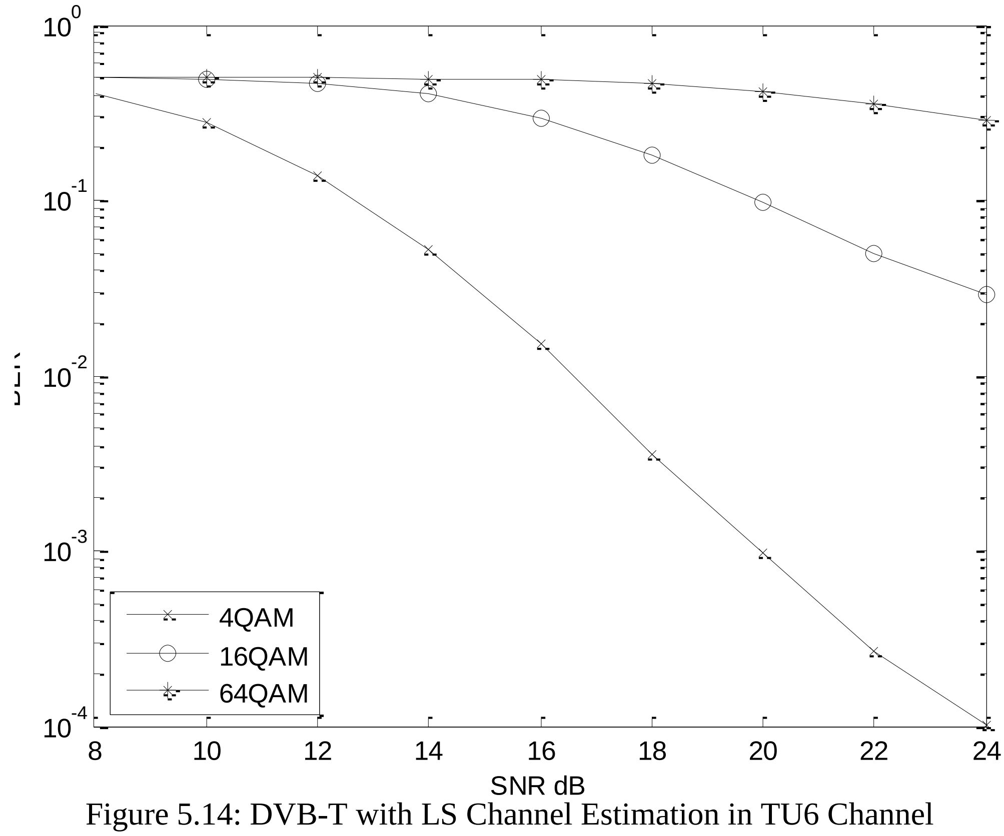


Figure 5.14: DVB-T with LS Channel Estimation in TU6 Channel

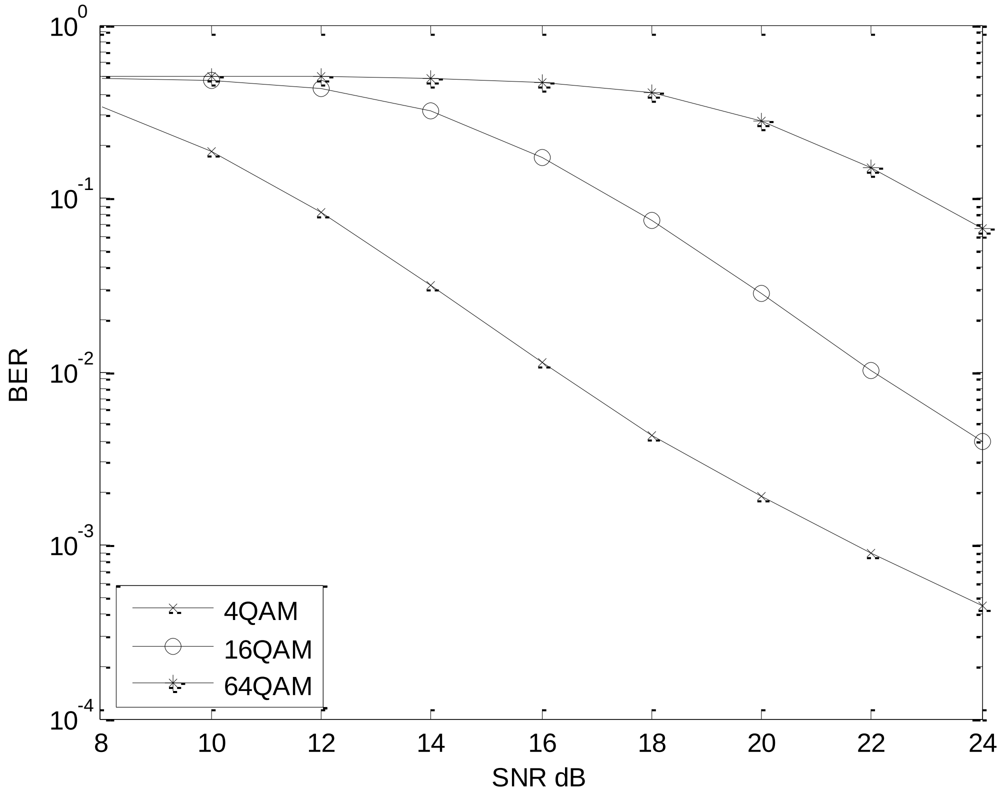
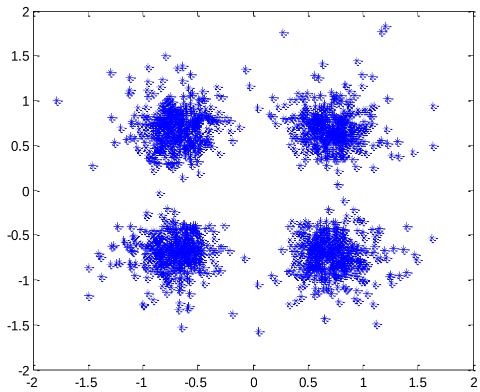


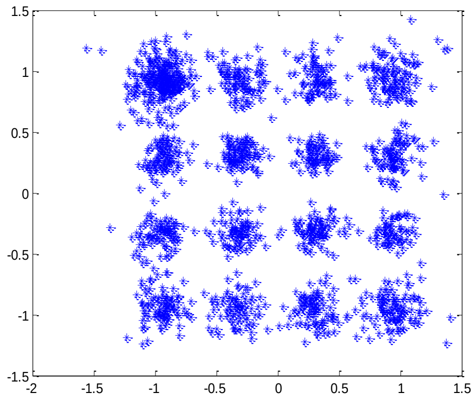
Figure 5.15: DVB-T with LS Channel Estimation in Rayleigh Channel

The simulation result in Rayleigh channel is also better then PI and PO channel. As it is shown in Figure 5.15, same as four other channels 4-QAM has the best result but also 16-QAM reaches 10^{-2} BER at 22db SNR and the improvement has started from 14dB SNR. But in 64-QAM system cannot overcome with the channel noise unless the SNR increases more than 24dB.

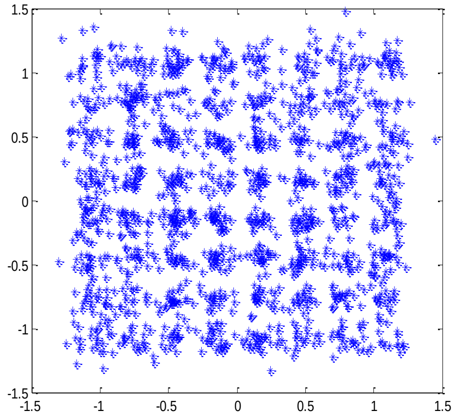
In order to clarify the usage of LS estimation method in this research constellation diagram after channel equalization and before OFDM de-mapper has been presented in Figure 5.16. This simulation has been done in Rayleigh channel with 14, 20 and 24 dB SNR for 4, 16 and 64-QAM respectively. Dispersal of graph in Figure 5.16c can approve the fact that DVB-T transmission in 64-QAM under multipath channel with low SNR has high BER although with the usage of LS estimation method it can be enhanced.



a



b



c

Figure 5.16: Constellation Diagram under Rayleigh Fading with LS Channel Estiamation: a) 4-QAM at 14dB SNR b) 16-QAM at 20dB SNR c) 64-QAM at 20dB SNR

Chapter 6

Conclusions and Future Work

In this research, LS based channel estimation and detection has been implemented for DVB-T broadcasting and the systems performance is evaluated through extensive simulations using MATLAB. The transmitter, receiver and channel models are created with reference to relevant ETSI standards. Simulations have been performed for 4, 16, and 64-QAM constellations in PI, PO, RA6, Rayleigh and TU6 channel models. Transmission and reception of a standard image have also been simulated.

The results have shown that by increasing the number of constellation point, BER performance gets worse. It is caused by loss of orthogonality of the OFDM subcarriers due to the fast varying multipath Rayleigh fading channel conditions at high data rates. Hence, the absence of LOS in the channel has a detrimental effect even when the number of constellations reduced to 4 as in 4-QAM modulation. The use of a median filter seems to play an important role in clearing the raster in the received picture by eliminating the noise in the received signal. Sufficiently good performance is obtained at 20 dB SNR when the transmission is in TU6 channel with 16-QAM. Investigating the simulation results revealed that, DVB-T broadcast systems based on 2K-OFDM has sufficiently good performance for 4-QAM whereas 16-QAM shows unacceptably low performance. However, by using a median filter after detection, the performance of even 16-QAM; seem to be acceptable for clear picture broadcasting.

In order to improve the system performance in 64-QAM, increasing SNR up to 30dB and using different code rates through transmission can be represented as a future work. As it was mentioned before, DVB-T2 has been developed over DVB-T. But the main core is still based on the DVB-T standard so that improvement in basic DVB-T standards can provide a better result in communication systems.

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