EUROPEAN TERRESTRIAL DIGITAL TELEVISION RECEIVER PERFORMANCE COMPARISON STUDY UNDER STRONG MULTIPATH INTERFERENCE

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by
Oktay KARAKUŞ

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We approve the thesis of **Oktay KARAKUŞ**

Assist. Prof. Dr. Şevket GÜMÜŞTEKİN
Supervisor

Prof. Dr. Ferit Acar SAVACI
Committee Member

Assist. Prof. Dr. Mustafa A. ALTINKAYA
Committee Member

Assist. Prof. Dr. Emre ÇEK
Committee Member

Assist. Prof. Dr. Canan AYDOĞDU
Committee Member

16 December 2011

Prof. Dr. Ferit Acar SAVACI
Head of the Department of
Electrical and Electronics Engineering

Prof. Dr. R. Tuğrul SENGER
Dean of the Graduate School of
Engineering and Sciences

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ABSTRACT

EUROPEAN TERRESTRIAL DIGITAL TELEVISION RECEIVER PERFORMANCE COMPARISON STUDY UNDER STRONG MULTIPATH INTERFERENCE

The main purpose of this thesis is to implement a complete simulation of the European Digital Terrestrial Broadcasting standards known as “Digital Video Broadcasting – Terrestrial” (DVB-T) and “Second Generation Digital Video Broadcasting – Terrestrial” (DVB-T2). These standards have been developed primarily for Europe (especially DVB-T in early 90s), but these two standards are in the process of getting wider acceptance among several countries in Africa, Asia, Middle East and Oceania as well as Europe. One of the most important aspects of these standards is the Orthogonal Frequency Division Multiplexing (OFDM) which has been simulated in this thesis. A comparative study between DVB-T and DVB-T2 has been provided in detail when both of these transmission standards are exposed to strong multipath interference. Various strong multipath scenarios have been created and simulated with respect to different power delay profiles and mobility conditions. The strong multipath indicates a channel profile whose scattered paths have strong power and relatively high delay spread. It has been shown that DVB-T2 standard outperforms DVB-T standard under strong multipath interference and achieves nearly from three to nine decibels power gain according to applied channel profile, code rate and modulation parameters.

ÖZET

GÜÇLÜ ÇOKYOLLU GİRİŞİM ETKİSİNDEKİ AVRUPA KARASAL SAYISAL TELEVİZYON ALICI PERFORMANSININ KARŞILAŞTIRMA ÇALIŞMASI

Bu tezin en temel amacı, Avrupa Sayısal Karasal Televizyon Yayın standartları olarak bilinen Sayısal Karasal Televizyon Yayını (DVB-T) ve İkinci Nesil Sayısal Karasal Televizyon Yayını (DVB-T2) ile ilgili genel bir benzetim gerçekleştirmektir. Bu standartlar öncelikli olarak, özellikle 90lı yılların başlarında, Avrupa ülkeleri için geliştirilmişti ancak şuanda bu iki standart Afrika, Asya, Orta Doğu ve Okyanusya ülkelerinde de en az Avrupa ülkelerindeki kadar kabul görme sürecinden geçmektedir. Bu yayın standartlarının en temel öğelerinden biri olan Dikgen Frekans Bölmeli Çoğullama (OFDM) kavramının bu çalışma içerisinde benzetimi yapılmıştır. Ayrıca DVB-T ve DVB-T2 standartlarının güçlü çok yollu girişim etkisi altındaki karşılaştırması detaylı olarak işlenmektedir. Çeşitli güçlü çokyollu kanal senaryoları, değişik güç-gecike profillerine ve gezginlik koşullarına bağlı kalınarak oluşturulmuş ve benzetimi yapılmıştır. Güçlü çokyollu kanal, geciken yollardaki sinyallerin güçlerinin fazlalığını ve gecikme sürelerinin yüksekliğini işaret etmektedir. Bu karşılaştırmalar ışığında, DVB-T2 standardının, güçlü çok yollu girişim etkisinde, DVB-T standardına göre çok iyi sonuçlar verdiği ve uygulanan kanal profili, kod oranı ve modülasyon tekniği parametrelerine göre değişiklik gösteren beş ila dokuz desibel güç kazancı elde edildiği gösterilmiştir.

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LIST OF ABBREVIATIONS

16QAM	16-ary Quadrature Amplitude Modulation
256QAM	256-ary Quadrature Amplitude Modulation
64QAM	64-ary Quadrature Amplitude Modulation
ATSC	Advanced Television System Committee
AWGN	Additive White Gaussian Noise
BB	BaseBand
BBHEADER	BaseBand Header
BBFRAME	BaseBand Frame
BCH	Bose - Chaudhuri - Hocquenghem code
BCHFEC	Parity bits of BCH encoder
BER	Bit Error Ratio
BICM	Bit Interleaved Coding and Modulation
C/N	Carrier-to-Noise
CI	Cell Interleaver
COST	European Cooperation in Science and Technology
CRC	Cyclic Redundancy Check
D	Decimal notation
DAB	Digital Audio Broadcasting
DAC	Digital to Analogue Conversion
DFL	Data Field Length
DFT	Discrete Fourier Transform
DTMB	Digital Terrestrial/Television Multimedia Broadcasting
DTTB	Digital Terrestrial Television Broadcasting
DVB	Digital Video Broadcasting
DVB-C	DVB-Cable
DVB-H	DVB-Handheld
DVB-S	DVB-Satellite
DVB-S2	2nd Generation DVB-S
DVB-T	DVB-Terrestrial
DVB-T2	2nd Generation DVB-T
EBU	European Broadcasting Union

EDTV	Enhanced Definition TeleVision
ERA	European Research Area
ETSI	European Telecommunications Standards Institute
FEC	Forward Error Correction
FECFRAME	BCH/LDPC encoded Frame
FEF	Future Extension Frame
FFT	Fast Fourier Transform
FIFO	First-In, First-Out shift register
GF	Galois Field
GSM	Global System for Mobile Communications
GUI	Graphic User Interface
HDTV	High Definition TeleVision
HEX	Hexadecimal notation
IFI	Inter Frame Interference
IFFT	Inverse Fast Fourier Transform
ISDB-T	Integrated Services Digital Broadcasting – Terrestrial
ISI	Inter Symbol interference
LDPC	Low Density Parity Check (codes)
LDPCFEC	Parity Bits of LDPC Encoder
LDTV	Limited Definition TeleVision
LS	Least Squares
MISO	Multiple Input, Single Output
MMSE	Minimum Mean Square Error
MPEG	Moving Picture Experts Group
MUX	MultipleX
OCT	Octal notation
OFDM	Orthogonal Frequency Division Multiplexing
OOP	Object Oriented Programming
P/S	Parallel to Serial
PAPR	Peak to Average Power Ratio
PI	Portable Indoor channel
PLP	Physical Layer Pipe
PN	Pseudo-Random Noise
PO	Portable Outdoor channel

PRBS	Pseudo-Random Binary Sequence
QAM	Quadrature Amplitude Modulation
QEF	Quasi Error Free
QPSK	Quaternary Phase Shift Keying
RA6	6-tap Rural Area channel
RF	Radio Frequency
RS	Reed-Solomon
S/P	Serial to Parallel
SDTV	Standard Definition TeleVision
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
TI	Time Interleaver
TPS	Transmission Parameter Signaling
TS	Transport Stream
TU6	6-tap Typical Urban channel
TV	TeleVision
WiMAX	Worldwide interoperability for Microwave Access
WLAN	Wireless Local Area Networks
XOR	eXclusive OR

CHAPTER 1

INTRODUCTION

Television can be defined as a “best friend” for the people in the world nowadays. People organize their lives according to television programs such as football matches, entertainment programs, films and etc. This story begins with first television picture broadcast from one room to another in 1926 by John Logie Baird. After this big step, in 1927, he used telephone cables to transmit a moving image from London to Glasgow and in 1928 he succeeded first trans-Atlantic television broadcast (Burns 1998).

Digital television appeared as a natural evolution of analog television. Early on all the parts of television use sound and image which are generated in the studios as analog. Every improvement in technology enables the creation of new possibilities for the transition from analog to digital.

Depending on the rapid advancement of the technology in recent years, significant improvements are observed in the television broadcasting standards. The current technologies allow broadcasting in High Definition (HD) and 3-Dimension (3D) and watching the content at fixed or mobile locations. In addition to these, development on every area of the wireless communications, affects terrestrial broadcasting used analog standards, and gives rise to an idea of digital terrestrial television broadcasting. With these developments, since the beginning of the nineties, digital terrestrial television broadcasting became an important study area in the whole world.

Digital Video Broadcasting (DVB) project started to prepare specifications about terrestrial television in Europe in 1993. DVB can be defined as an industry-led consortium of broadcasters, manufacturers, network operators, software developers and regularity bodies committed to designing open technical standards for the digital television and data services (DVB Organization 2003). For this purpose, DVB firstly published specifications for three different standards which are DVB-C (ETSI EN 300 429 1998) for cable systems, DVB-S (ETSI EN 300 421 1997) for satellite systems and DVB-T for terrestrial systems. DVB-H (ETSI TR 102 377 2001) for handheld systems can be defined as a derivative of DVB-T and it is meant for handheld mobile terminals.

DVB-T specification was firstly published in 1997. In this document a baseline transmission system is described for digital terrestrial television broadcasting (ETSI EN 300 744 2009). DVB-T offers efficient use of available frequency spectrum and also it can be defined as a flexible system because it offers many services such as Limited Definition Television (LDTV), Standard Definition Television (SDTV), Enhanced Definition Television (EDTV) and High Definition Television (HDTV) and also it supports fixed, portable reception.

Although DVB-T deserves a great success in digital broadcasting area, it is thought that DVB-T requires some improvements. However DVB-T systems are developed for the stationary and portable devices, by the vast increase in the mobile communication technology, it requires adaptation for the portable devices that moves faster and that is inside of the buildings. These facts provide a new and updated standard for DVB-T and this led to the standardization of DVB-T2. DVB-T2 specification was firstly published in September 2009 and in this document, new baseline transmission system is described (ETSI EN 302 755 2011).

In addition to European-based standards DVB-T and DVB-T2, there are also three more Digital Terrestrial Television Broadcasting (DTTB) standards which are used in the world. These are;

- USA-based ATSC (Advanced Television System Committee) standard.
- Japan-based ISDB-T (Integrated Services Digital Broadcasting – Terrestrial) standard.
- Chinese-based DTMB (Digital Terrestrial/Television Multimedia Broadcasting) standard, which is also known as GB206.

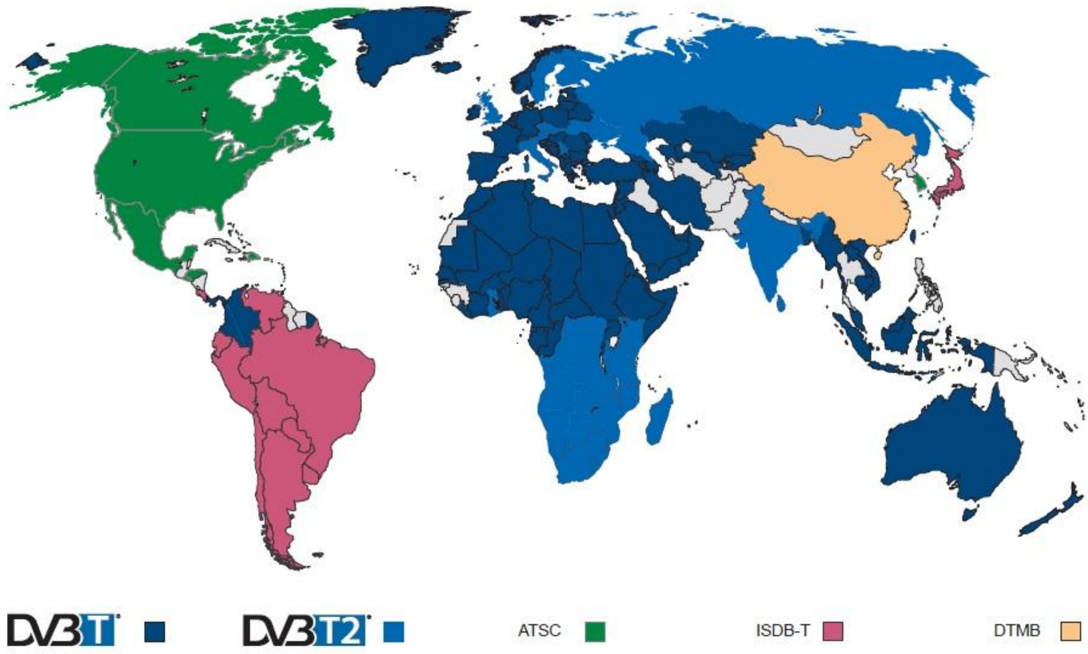


Figure 1.1. Digital Terrestrial Systems
(Source: DVB Organization 2003)

1.1. Thesis Objective & Background

The main purpose of this thesis is to make a comparison between European terrestrial television standards DVB-T and DVB-T2 where our main focus is to investigate their performance under strong multipath and mobility conditions. The main parts in transmitter and receiver for both standards will be implemented by using computational software program Matlab®.

In addition to implementation of transmitter as described in DVB-T and DVB-T2 standards, various channel conditions has been simulated and a receiver has been implemented which is capable of receiving T/T2 signals. The system performance has been compared with respect to Bit Error Rates (BER) for the measured Carrier-to-Noise Ratio (C/N) in decibels (dB) at the input of the receiver under strong multipath interference.

After the comparison, it is expected that the 2nd generation standard DVB-T2 to achieve better performance than DVB-T, for all the parameters such as code rate, modulation type, guard interval, etc., under various multipath channel and mobility effects.

In literature, some studies focus on DVB-T systems and its performance, some of the studies focus on DVB-T2 (Jiang et al. 2009), (Ulovec and Vysin 2010), (Onet et al. 2010), (Stukavec and Kratochvil 2009), (Stukavec and Kratochvil 2010), (Polak and Kratochvil 2010) and (Hüttl and Kratochvil 2009).

1.2. Thesis Outline

This thesis is comprised of seven chapters. OFDM principle of DVB-T and DVB-T2 is discussed in Chapter 2. Then, transmitter structures of these two standards are explained in Chapter 3 that provides sufficient background about DVB-T and DVB-T2 systems. Chapter 4 provides the detailed study of multipath channel that are simulated throughout the rest of the thesis.

Since DVB-T and DVB-T2 standards have no definitions with respect to how the receivers should be implemented, the receiver structures and simulation scenarios are studied in Chapter 5. In Chapter 6, simulation performance results are presented under various channel conditions. Finally, Chapter 7 concludes and summarizes the main contributions of this thesis.

CHAPTER 2

THE OFDM PRINCIPLE

Orthogonal Frequency Division Multiplexing (OFDM) is used in many modern digital communication systems and various applications such as DVB-T, Digital Audio Broadcasting (DAB), Worldwide interoperability for Microwave Access (WiMAX) and Wireless Local Area Networks (WLAN). This chapter is organized to describe the basic principles of OFDM and to show why it has a widespread usage area in communication systems.

2.1. Multi Carrier Modulation

The basic idea of multicarrier modulation is very simple, and it follows naturally from the competing desires for high data rates and InterSymbol Interference (ISI) free channels. To overcome this, in multi carrier modulation, the available bandwidth W is divided into N_C number of sub-carriers, separated by $\Delta f = \frac{W}{N_C}$. This idea was firstly proposed in sixties and forms a basis for OFDM concept. The subdivision of the bandwidth is illustrated in Figure 2.1 (Engels 2001).

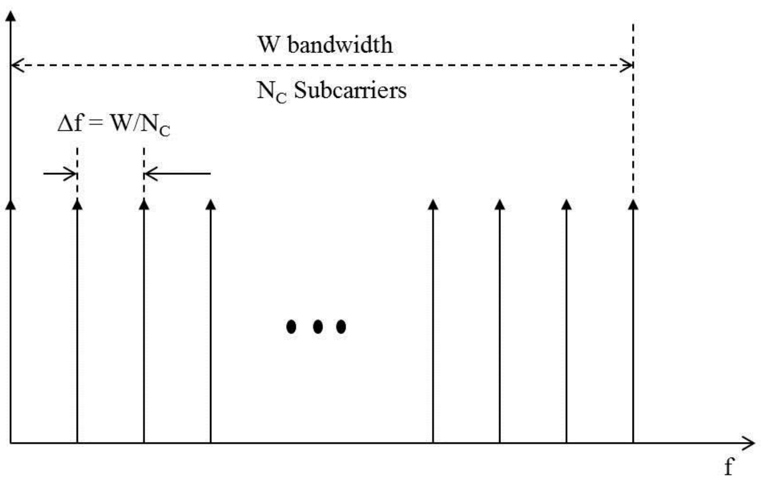


Figure 2.1. Subdivision of Bandwidth into N_C Subcarriers
(Source: Engels 2001)

Instead of transmitting symbols serially, the multi-carrier transmitter partitions the data into blocks of N_C data symbols that are transmitted in parallel by modulating the N_C carriers. The symbol duration for a modulated carrier is $T_S = \frac{1}{W}$.

The multi-carrier signal can be written as a set of modulated carriers as (Engels 2001)

$$s(t) = \sum_{k=0}^{N_C-1} x_k \psi_k(t) \tag{2.1}$$

Where $s(t)$ is the multicarrier modulated signal, x_k is the data symbol modulating the kth carrier and ψ_k is the modulation waveform at kth subcarrier.

A simple implementation of multicarrier transmission is given in Figure 2.2 and receiver version of it is given in Figure 2.3 (Bingham 1990).

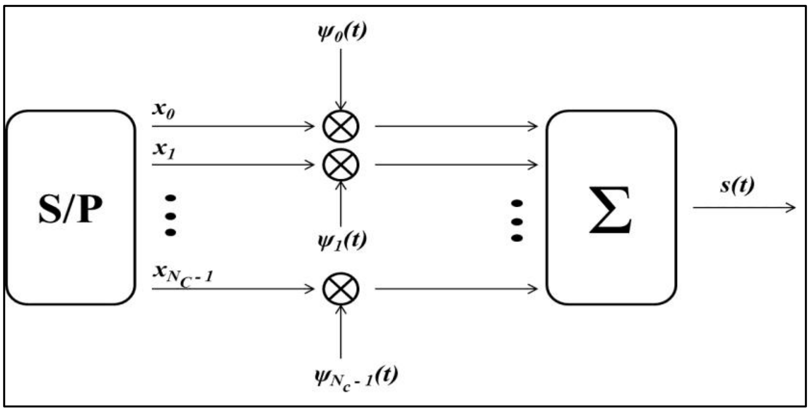


Figure 2.2. Multicarrier modulation
(Source: Bingham 1990)

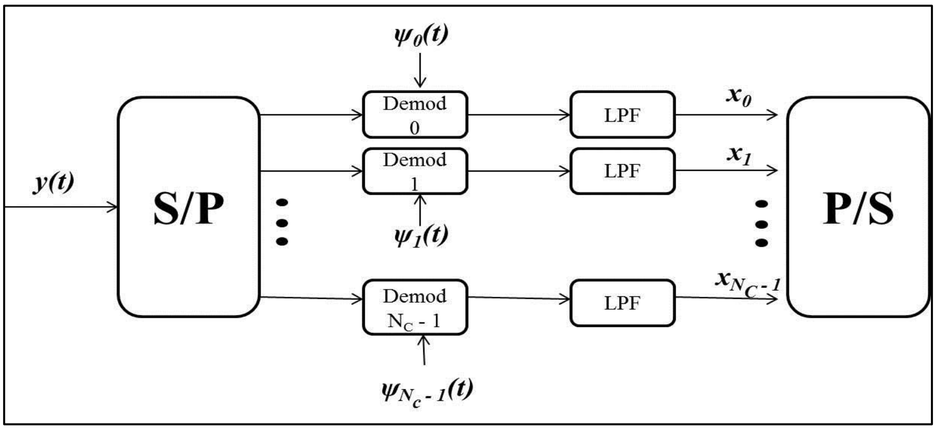


Figure 2.3. A Basic Multicarrier Receiver
(Source: Bingham 1990)

The multicarrier technique has an interesting interpretation in both the time and frequency domains. In the time domain, the symbol duration on each subcarrier has increased to $T = N_C . T_S$, so by letting N_C grow larger, it can be assured that the symbol duration exceeds the channel delay spread, i.e. $T \gg \tau$, which is a requirement for ISI-free communication. In the frequency domain, the subcarriers have bandwidth $W/_{N_C} \ll W_C$, which assures “flat fading”, the frequency domain equivalent to ISI-free communication (Andrews 2006). This can be clearly seen in the Figure below.

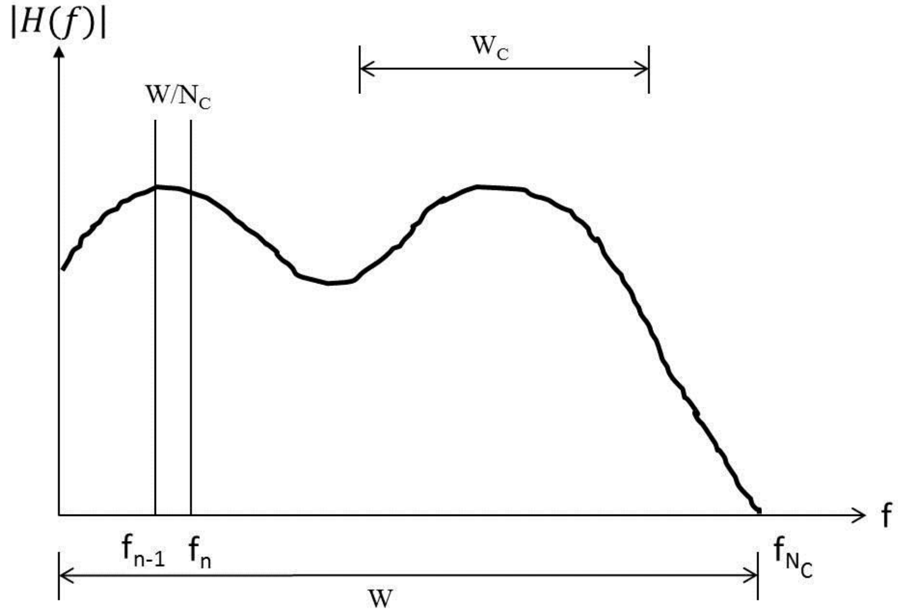
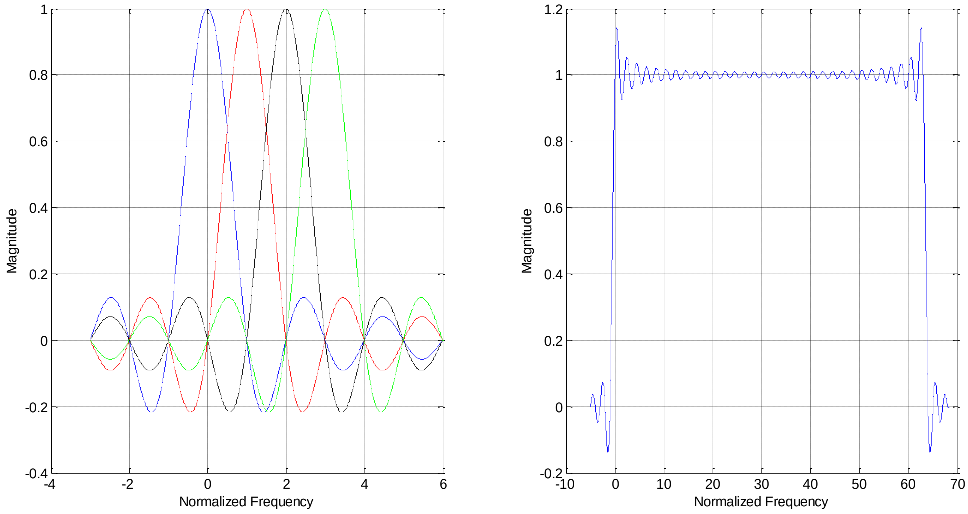


Figure 2.4. The Transmitted Multicarrier Signal Experiences Approximately Flat Fading on each Sub channel. (Source: Andrews 2006)

2.2. OFDM and Its Implementation

OFDM is a specific version of multicarrier modulation. First of all, to achieve high spectral efficiency, sub-carriers must have overlapping transmit spectra. So they need to be orthogonal for enabling simple separation of these overlapping sub channels at the receiver. Multicarrier modulation that fulfills these conditions is called OFDM (Engels 2001).

To have orthogonally separated sub-carriers, Discrete or Fast Fourier Transform (DFT or FFT) is the main solution for this purpose. The sinusoids of the DFT form an orthogonal basis set, and a signal in the vector space of the DFT can be represented as a linear combination of the orthogonal sinusoids. One view of the DFT is that the transform essentially correlates its input signal with each of the sinusoidal basis functions. If the input signal has some energy at a certain frequency, there will be a peak in the correlation of the input signal and the basis sinusoid that is at that corresponding frequency. This transform is used at the OFDM transmitter to map an input signal onto a set of orthogonal subcarriers. Similarly, the transform is used again at the OFDM receiver to process the received subcarriers. The signals from the subcarriers are then combined to form an estimate of the source signal from the transmitter.



(a) N_C = 4 Sub-Carriers (b) N_C = 64 Sub-Carriers

Figure 2.5. Overlapping Spectrum of an OFDM Signal

The orthogonal and uncorrelated nature of the subcarriers is exploited in OFDM with powerful results. Since the basis functions of the DFT are uncorrelated, the correlation performed in the DFT for a given subcarrier only sees energy for that corresponding subcarrier. The energy from other subcarriers does not contribute because it is uncorrelated. This separation of signal energy is the reason that the OFDM subcarriers' spectrums can overlap without causing interference.

The N_C point DFT and its inverse DFT are defined as; (Andrews 2006)

$$DFT\{x[n]\} = X[m] \triangleq \frac{1}{\sqrt{N_C}} \sum_{n=0}^{N_C-1} x[n] e^{-j\frac{2\pi nm}{N_C}} \tag{2.2}$$

$$IDFT\{X[m]\} = x[n] \triangleq \frac{1}{\sqrt{N_C}} \sum_{m=0}^{N_C-1} X[m] e^{j\frac{2\pi nm}{N_C}} \tag{2.3}$$

2.2.1. Cyclic Prefix

The key to making OFDM realizable in practice is the utilization of the FFT algorithm, which has low complexity. If a cyclic prefix is added to the transmitted signal, it can be shown as in Figure 2.6, and if it's thought that the channel impulse response is h[n] and the transmitted signal is $x[n]$, then the received signal $y[n]$ is equal to convolution of $x[n]$ and h[n].($y[n] = x[n] \circledast h[n]$)

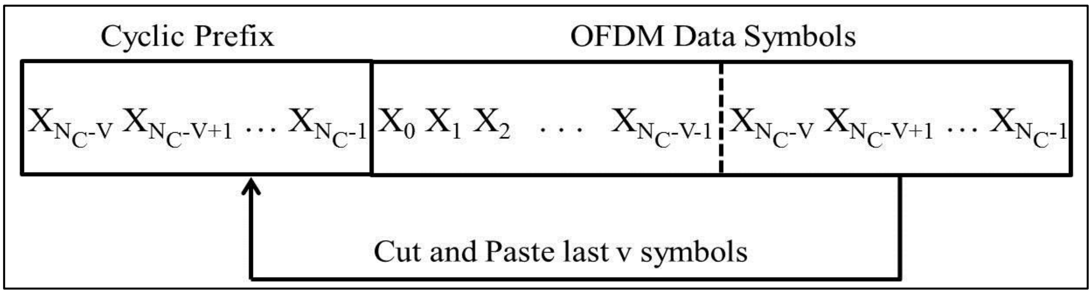


Figure 2.6. The OFDM Cyclic Prefix
(Source: Andrews 2006)

If the maximum channel delay spread has a duration of $v + 1$ samples, then by adding a guard band of at least v samples between OFDM symbols, each OFDM symbol is made independent of those coming before and after it, and so just a single OFDM symbol can be considered. Representing such an OFDM symbol in the time domain as a length N_C vector gives (Andrews 2006)

$$x = \left[x_0\ x_1\ \dots\ x_{N_C-1}\right] \tag{2.4}$$

After applying a cyclic prefix of length v, the actual transmitted signal is

$$x_{cp} = \left[\underbrace{x_{N_C-v}\ x_{N_C-v+1}\ \cdots\ x_{N_C-1}}_{Cyclic\ Prefix}\ \underbrace{x_0\ x_1\ \cdots\ x_{N_C-1}}_{Original\ Symbol}\right] \tag{2.5}$$

The output of the channel is by definition$y_{cp} = h \star x_{cp}$, where h are a length $v + 1$ vector describing the impulse response of the channel during the OFDM symbol. The output y_{cp} has $(N_C + v) + (v + 1) - 1 = N_C + 2v$ samples. The first v samples of y_{cp} contain interference from the preceding OFDM symbol, and so are discarded. The last v samples disperse into the subsequent OFDM symbol, so also are discarded. This leaves exactly N_C samples for the desired output y, which is precisely what is required to recover the N_C data symbols embedded in x (Andrews 2006).

2.2.2. OFDM Block Diagram

As mentioned in the previous sections, OFDM process has some important blocks such as IDFT, DFT and Cyclic Prefix. A discrete time model for such an OFDM system is illustrated in Figure 2.7 (Engels 2001).

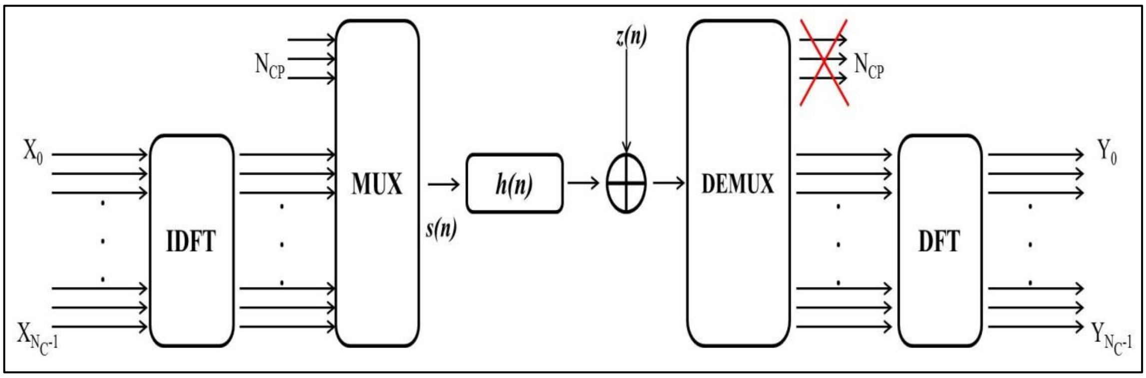


Figure 2.7. Discrete Time Model of an OFDM System
(Source: Engels 2001)

Step-by-Step OFDM system is;

1.) The data bits are grouped into blocks of N_C symbols. These symbols are called OFDM Symbol and they construct a vector $X = \left(X_0\, X_1\, \ldots\, X_{N_C-1}\right)^T$.
2.) To achieve orthogonally separated subcarriers, an IDFT is performed on each data vector X and N_{CP} length cyclic prefix added.
3.) The transmitted signal $s(n)$ is passes through a discrete channel $h(n)$.
4.) After channel effect, signal is corrupted by a zero mean, σ_z^2 variance Additive White Gaussian Channel noise $z(n)$.

5.) At receiver, received signal firstly converted into parallel from series to obtain data vectors back.
6.) Cyclic prefix removed.
7.) A DFT is performed so that N_C symbols are obtained back.

2.3. Advantages and Disadvantages of OFDM

Advantages of OFDM (Yao 2009);

- Makes efficient use of the spectrum by allowing overlap
- By dividing the channel into narrowband flat fading sub-channels, OFDM is more resistant to frequency selective fading than single carrier systems are.
- Eliminates ISI and IFI through use of a cyclic prefix.
- Using adequate channel coding and interleaving one can recover symbols lost due to the frequency selectivity of the channel.
- Channel equalization becomes simpler than by using adaptive equalization techniques with single carrier systems.
- It is possible to use maximum likelihood decoding with reasonable complexity, as discussed in OFDM is computationally efficient by using FFT techniques to implement the modulation and demodulation functions.
- In conjunction with differential modulation there is no need to implement a channel estimator.
- Is less sensitive to sample timing offsets than single carrier systems are.
- Provides good protection against co-channel interference and impulsive parasitic noise.

Disadvantages of OFDM (Yao 2009);

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

CHAPTER 3

TRANSMITTER ARCHITECTURES

Transmitter structures of DVB-T and DVB-T2 systems are defined and published by DVB organization.

DVB-T standard for this purpose is named as “Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for digital terrestrial television” and coded as “ETSI EN 300 744”.

DVB-T standard is named as “Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for a second generation digital terrestrial television broadcasting system (DVB-T2)” and coded as “ETSI EN 302 755”.

In this chapter, main important blocks of transmitters of both systems will be briefly explained according to the standards, (ETSI EN 300 744 2009) and (ETSI EN 302 755 2011) with versions of v1.6.1 and v1.2.1 respectively.

3.1. DVB-T Transmitter

DVB-T systems are designed to perform adaptation of the baseband TV signals from the output of the MPEG-2 transport multiplexer to terrestrial channel characteristics. Data stream which is the output of MPEG-2 block is processed in following processes;

- Transport multiplex adaptation and randomization for energy dispersal
- Outer coding
- Outer interleaving
- Inner coding
- Inner interleaving
- Mapping and modulation
- OFDM transmission

Each of these will be explained further sections.

There are two modes of operations, “2K mode” and “8K mode”, for DVB-T transmission. Exclusively for use in DVB-H systems, a third transmission mode, “4K mode”, is defined and addressing the specific needs of handheld terminals.

The system allows different levels of QAM modulation and different inner code rates to be used to trade bit rate versus ruggedness. In Figure 3.1, the functional block diagram of the DVB-T system is illustrated.

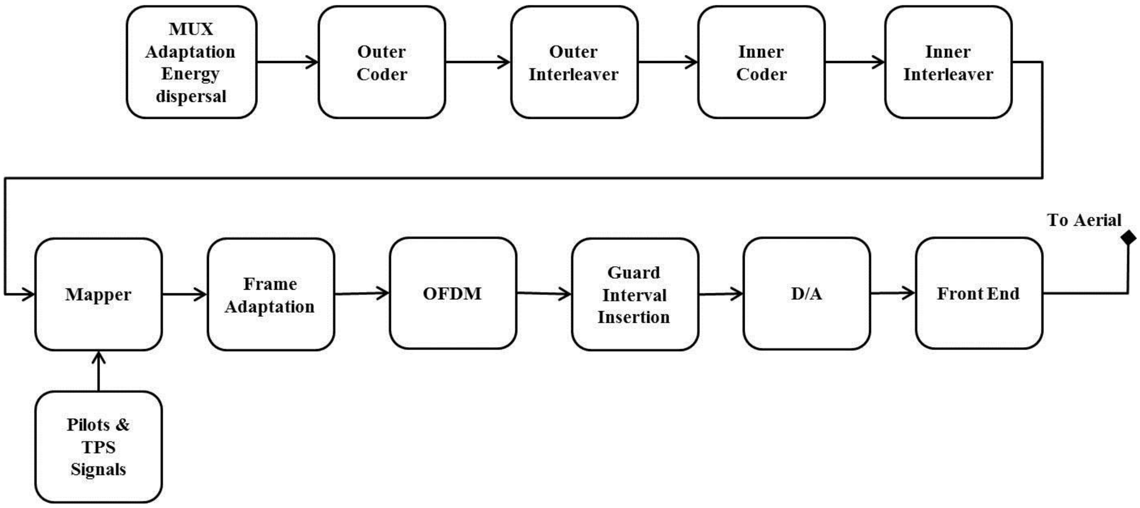


Figure 3.1. Functional Block diagram of the DVB-T Transmitter
(Source: ETSI EN 300 744 2009)

The Baseline System is delimited by the following interfaces.

Table 3.1. Interfaces for the Baseline System
(Source: ETSI EN 300 744 2009)

Location	Interface	Interface Type	Connection
Transmit Station	Input	MPEG-2 transport stream(s) multiplex	From MPEG-2 multiplexer
	Output	RF signal	To aerial
Receive Station	Input	RF	From aerial
	Output	MPEG-2 transport stream multiplex	To MPEG-2 demultiplexer

3.1.1. MUX Adaptation and Energy Dispersal

The system input stream is an MPEG-2 transport MUX packet with same length 188 bytes. The first byte of the packet is SYNC sequence which is equal to 47_{HEX} or $B8_{HEX}$. In order to ensure adequate binary transitions, the input data shall be randomized according to the system which is configured as in Figure 3.2.

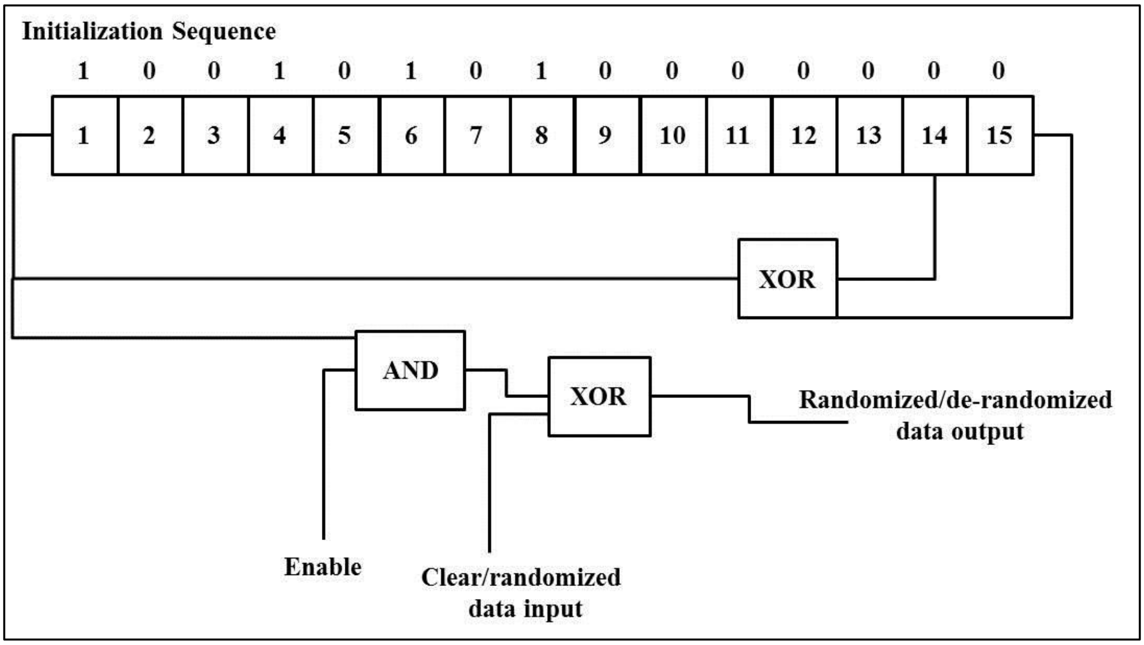


Figure 3.2. Scrambler/descrambler Schematic Diagram
(Source: ETSI EN 300 744 2009)

This system is called Pseudo Random Binary Sequence (PRBS) generator and this systems polynomial shall be;

$$\mathbf{1 + X^{14} + X^{15}} \tag{3.1}$$

This process is repeated for eight transport packets and the sequence "100101010000000" initialized into the PRBS registers to provide an initialization for descrambling. This process is referred to as "transport multiplex adaptation" as seen in Figure 3.4b.

3.1.2. Outer Encoder and Interleaver

Outer encoding and interleaving processes uses the packet structure as seen in Figure 3.4a. DVB-T system uses Reed-Solomon Encoding as its outer encoder. The main purpose is to generate an error corrected packet as seen in Figure 3.4c.

The outer encoder has a Code Generator Polynomial, $g(x)$ and a Field Generator Polynomial, $p(x)$ which is;

$$g(x) = (x + \lambda^0)(x + \lambda^1)(x + \lambda^2) \dots (x + \lambda^{15}) \tag{3.2}$$

$$p(x) = x^8 + x^4 + x^3 + x^2 + 1 \tag{3.3}$$

The encoding process of Reed-Solomon encoder is;

1. Original code $RS(255, 239, t = 8)$ shall be applied to each randomized transport packets with length of 188 bytes by adding 51 bytes all set to zero, before information bytes.
2. The 51 null bytes discarded from original RS code and obtained shortened $RS(204, 188, t = 8)$ code with length $N = 204$.

Outer interleaving process is a convolutional byte-wise interleaving with interleaving depth $I = 12$. The input packets is RS outputs with length of 204 bytes and the resulting sequence is as seen in Figure 3.4d. Interleaving will be applied according to conceptual scheme of Figure 3.3.

The interleaver may be composed of 12 Branches which is cyclically connected to the input stream by the input switch. Each branch j shall be a First-In-First-Out (FIFO) shift register.

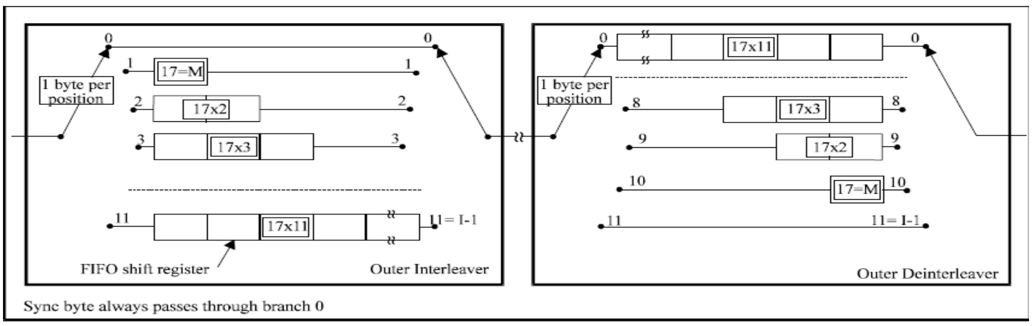


Figure 3.3. Conceptual diagram of the outer interleaver and deinterleaver
(Source: ETSI EN 300 744 2009)

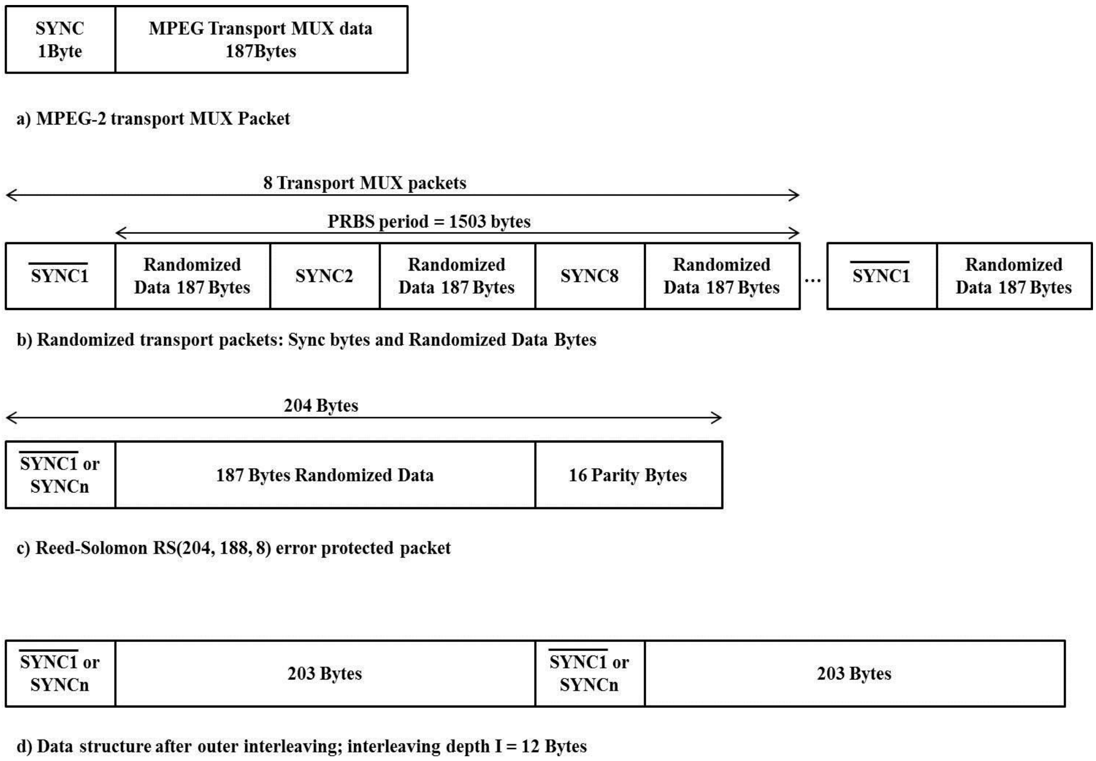


Figure 3.4. Steps in the process of adaptation, energy dispersal, outer coding and interleaving (Source: ETSI EN 300 744 2009)

3.1.3. Inner Encoder

DVB-T system uses punctured convolutional encoder as its inner encoder block. Inner encoder process has two steps.

1. Encoding with mother convolutional encoder with code rate of $1/2$
2. Puncturing according to system code rate.

Mother convolutional code concept is illustrated in Figure 3.5. The generator polynomials of mother code are $G1 = 171_{OCT}$ for output X, $G2 = 133_{OCT}$ for output Y.

In addition to mother code with code rate of $1/2$ the system shall allow punctured rates of $2/3$, $3/4$, $5/6$ and $7/8$. The punctured convolutional code shall be used as given in table 3.2.

Table 3.2. Puncturing pattern and transmitted sequence after parallel-to-serial conversion for possible code rates. (Source: ETSI EN 300 744 2009)

Code Rate	Puncturing Pattern	Transmitted Sequence
1/2	X: 1 Y: 1	X_1 Y_1
2/3	X: 1 0 Y: 1 1	X_1 Y_1 Y_2
3/4	X: 1 0 1 Y: 1 1 0	X_1 Y_1 Y_2 X_3
5/6	X: 1 0 1 0 1 Y: 1 1 0 1 0	X_1 Y_1 Y_2 X_3 Y_4 X_5
7/8	X: 1 0 0 0 1 0 1 Y: 1 1 1 1 0 1 0	X_1 Y_2 Y_3 Y_4 X_5 Y_6 X_7

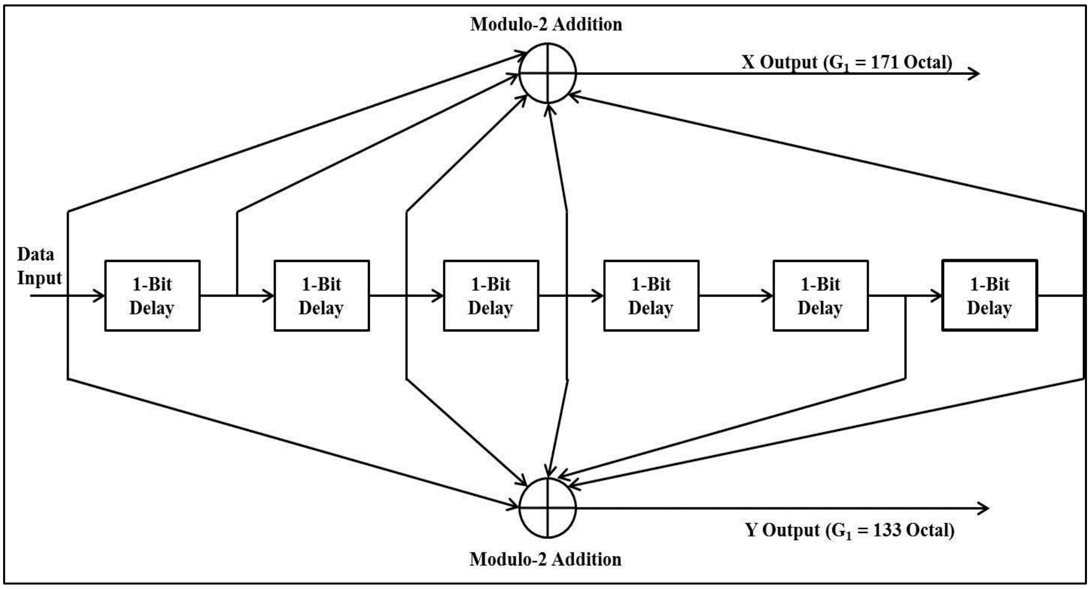


Figure 3.5. The Mother Convolutional Code of Rate ½
(Source: ETSI EN 300 744 2009)

3.1.4. Inner Interleaver

Inner interleaving in DVB-T systems consists of three main blocks before mapping and constellation block as seen in Figure 3.6. These are;

- Demultiplexer
- Bitwise Interleaver

- Symbol Interleaver

Firstly, the input of the inner interleaver is demultiplexed in v sub-streams, where $v = 2$ for QPSK, $v = 4$ for 16QAM and $v = 6$ for 64QAM.

The Demultiplexing is defined as a mapping of the input bits, x_{di} onto the output bits $b_{e,do}$ according to bit mappings as seen in table 3.3 where the indices are;

di → Input bit number

e → The demultiplexed bit streams ($0 \leq e < v$)

do → The bit number of a given stream at the output of the demultiplexer

Table 3.3. Demultiplexing bit mappings
(Source: ETSI EN 300 744 2009)

QPSK	x0 maps to b0,0
	x1 maps to b1,0
16QAM	x0 maps to b0,0
	x1 maps to b2,0
	x2 maps to b1,0
	x3 maps to b3,0
64QAM	x0 maps to b0,0
	x1 maps to b2,0
	x2 maps to b4,0
	x3 maps to b1,0
	x4 maps to b3,0
	x5 maps to b5,0

Each sub-stream from the demultiplexer is processed by a separate bit interleaver up to six interleavers depending on v. The block size of bit interleaver is 126 bits. This process is a repeated process according to OFDM symbol size.

For each interleaver the input bit vector $B(e) = \left(b_{e,0}, b_{e,1}, b_{e,2}, \ldots, b_{e,125}\right)$.

The interleaved output vector $A(e) = \left(a_{e,0}, a_{e,1}, a_{e,2}, \ldots, a_{e,125}\right)$ is;

$$a_{e,w} = b_{e,H_e(w)} \tag{3.4}$$

The permutation functions $H_e(w)$ are different for each interleaver and defined as;

$$
\begin{aligned}
H_0(w) &= w, \\
H_1(w) &= (w + 63) mod\ 126, \\
H_2(w) &= (w + 105) mod\ 126, \\
H_3(w) &= (w + 42) mod\ 126, \\
H_4(w) &= (w + 21) mod\ 126, \\
H_5(w) &= (w + 84) mod\ 126.
\end{aligned}
\tag{3.5}
$$

The purpose of the symbol interleaver is to map v bit words onto the 1512(2K Mode) or 6048(8K Mode) active carriers per OFDM Symbol. Firstly, the output of the bitwise interleaver converted to v bit word y' which is;

$$
y'_w = \left(a_{0,w}, a_{1,w}, \ldots, a_{v-1,w}\right) \tag{3.6}
$$

The interleaved vector $Y = \left(y_0, y_1, y_2, \ldots, y_{N_{max}-1}\right)$is defined by;

$$
\begin{aligned}
y_{H(q)} &= y'_q\ for\ even\ symbols\ for\ q = 0, \ldots, N_{max} - 1 \\
y_q &= y'_{H(q)}\ for\ odd\ symbols\ for\ q = 0, \ldots, N_{max} - 1
\end{aligned}
\tag{3.7}
$$

Where $N_{max} = 1512$ in the 2K mode and $N_{max} = 6048$ in the 8K mode. $H(q)$ is a permutation function defined according to the Figure 3.7.

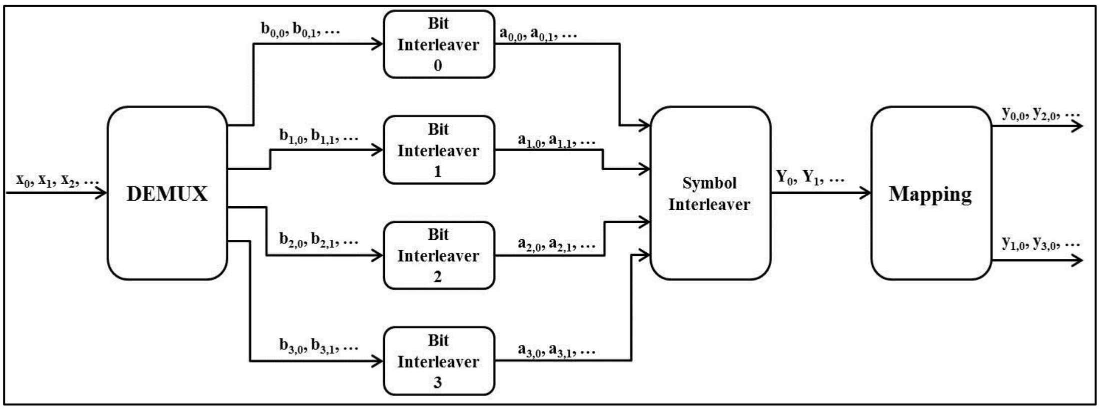


Figure 3.6. Mapping of input bits onto output 16QAM modulation symbols
(Source: ETSI EN 300 744 2009)

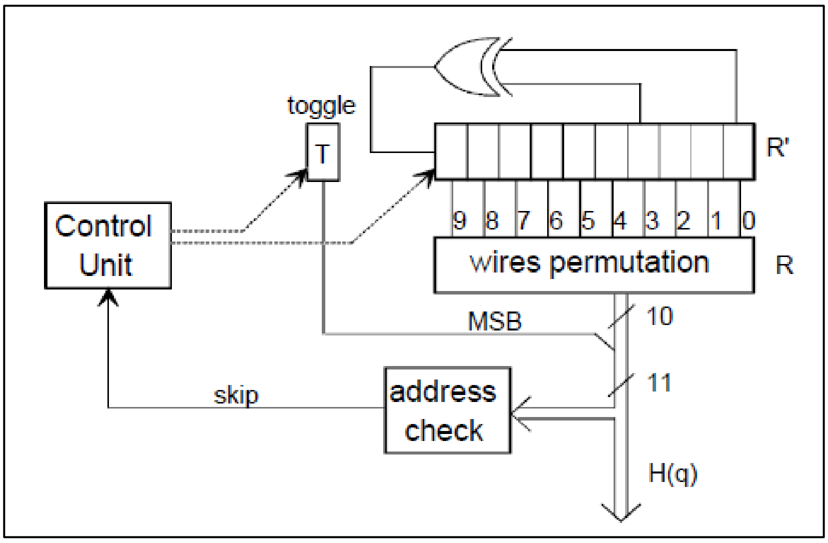


Figure 3.7. Symbol interleaver address generation scheme for the 2K mode
(Source: ETSI EN 300 744 2009)

3.1.5. Constellation and Mapping

The system uses OFDM transmission and all data carriers in one OFDM frame are modulated using QPSK, 16QAM or 64QAM. The constellations and the details of the Gray mapping applied to them are illustrated in Figure 3.8.

The exact values of the constellation points are $z \in \{n + jm\}$ with values of n, m given in the table 3.4 for the various constellations.

The data stream at the output of the inner interleaver consists of v bit words. These are mapped onto complex number z, according to Figure 3.8.

The complex constellation points are normalized with the factors which are given in table 3.5 according to the modulation alphabet used for data. The normalization factors yield $E = [c\ x\ c^*] = 1$.

Table 3.4. Values of the constellation points
(Source: ETSI EN 300 744 2009)

Modulation	n	m
QPSK	{-1, 1}	{-1, 1}
16QAM	{-3, -1, 1, 3}	{-3, -1, 1, 3}
64QAM	{-7, -5, -3, -1, 1, 3, 5, 7}	{-7, -5, -3, -1, 1, 3, 5, 7}

Table 3.5. Normalization factors for data symbols
(Source: ETSI EN 300 744 2009)

Modulation	Normalization factor
QPSK	$c = \frac{1}{\sqrt{2}}$
16QAM	$c = \frac{1}{\sqrt{10}}$
64QAM	$c = \frac{1}{\sqrt{42}}$

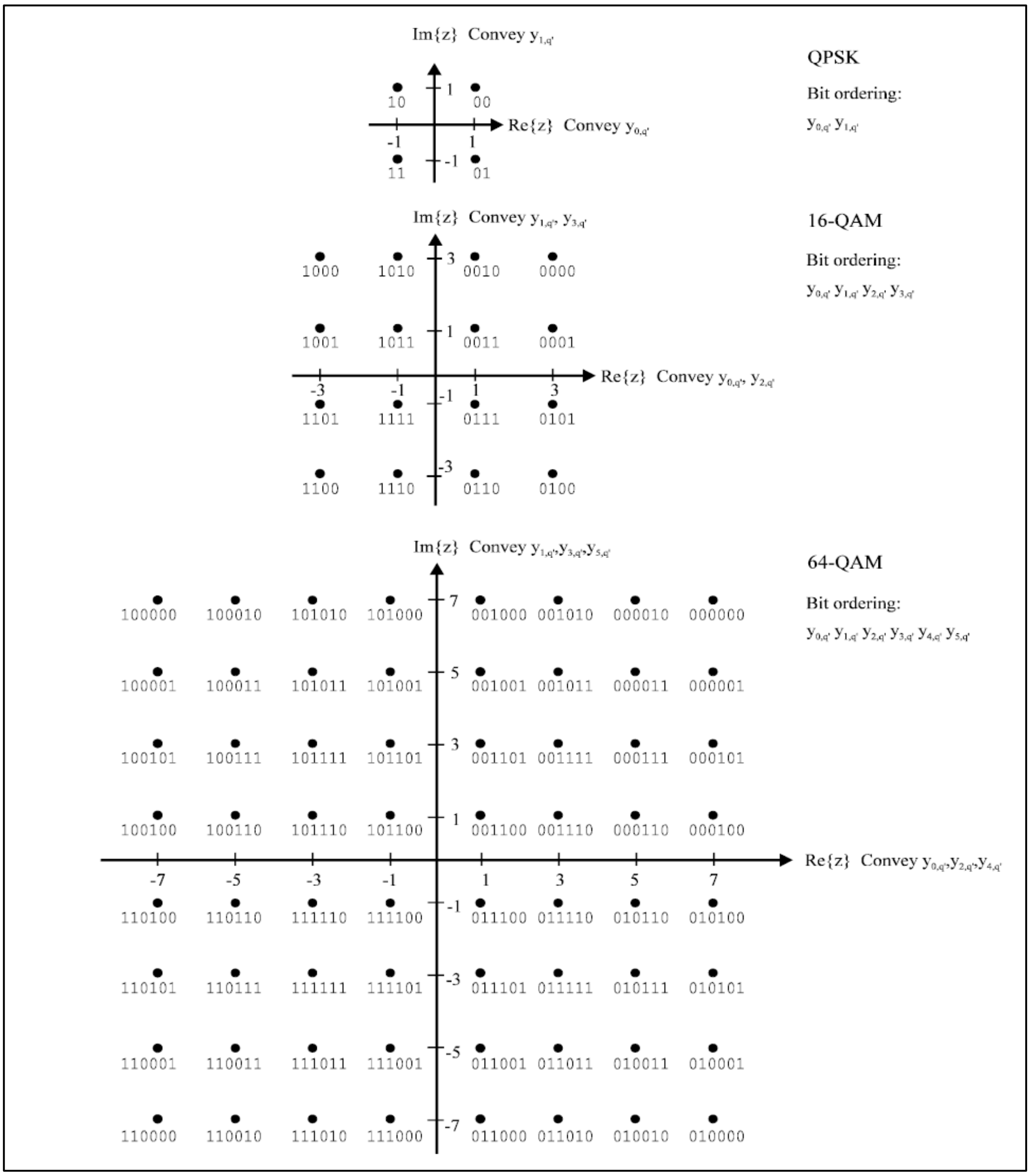


Figure 3.8. The QPSK, 16QAM and 64QAM mappings and corresponding bit patterns
(Source: ETSI EN 300 744 2009)

3.1.6. Pilots & TPS Signals

An OFDM Frame consists of data symbols and pilot symbols. In DVB-T systems three types of pilot symbols transmitted which are;

- Scattered pilots
- Continual Pilots
- Transmitter Parameter Signaling (TPS) pilots

The pilots can be used for the frame synchronization, frequency synchronization, time synchronization, channel estimation, transmission mode identification and can also be used to follow the phase noise.

The continual and the scattered pilots are modulated according to a PRBS sequence, w_k, where k is the carrier index. The PRBS sequence is generated according to Figure 3.9. The polynomial for the PRBS generator shall be;

$$X^{11} + X^2 + 1 \tag{3.8}$$

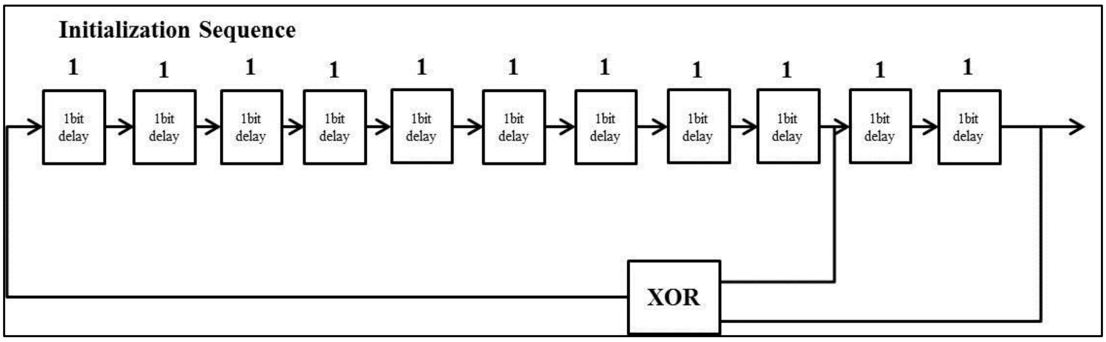


Figure 3.9. Generation of PRBS sequence
(Source: ETSI EN 300 744 2009)

Pilots have some specific locations in the OFDM frame depending on frame length and transmission mode. It’s mentioned in previous sections, all the data cells are is normalized so that $E = [c\ x\ c^*] = 1$.

All cells which are continual and scattered pilots are transmitted at boosted power so that for these $E = [c\ x\ c^*] = 16/9$. According to this, modulation of pilot cells is given in the table 3.6.

Table 3.6. Modulation of Pilot Cells
(Source: ETSI EN 300 744 2009)

Scattered Pilots	$Re\{c_{m,l,k}\}$	$\frac{4}{3} \times 2\left(\frac{1}{2} - w_k\right)$
	$Im\{c_{m,l,k}\}$	0
Continual Pilots	$Re\{c_{m,l,k}\}$	$\frac{4}{3} \times 2\left(\frac{1}{2} - w_k\right)$
	$Im\{c_{m,l,k}\}$	0
TPS Pilots	$Re\{c_{m,l,k}\}$	$2\left(\frac{1}{2} - w_k\right)$
	$Im\{c_{m,l,k}\}$	0

The TPS carriers are used for purpose of signaling parameters related to the transmission scheme. Every TPS carrier in the same symbol conveys the same differentially encoded information bit.

The TPS carriers convey information on;

- Modulation
- Hierarchy information
- Guard interval
- Inner code rates
- Transmission mode
- Frame number in a super frame

Each OFDM symbol conveys one TPS bit. So each OFDM frame contains 68 bits, defined as follows;

- 1 initialization bit
- 16 Synchronization bits
- 37 information bits
- 14 redundancy bits for error correction

The 53 bits containing the TPS synchronization and information bits are extended with 14 parity bits of the $BCH(67, 53, t = 2)$ shortened code, derived from the original code $BCH(127, 113, t = 2)$. Code generator polynomial,$h(x)$ is;

$$h(x) = x^{14} + x^9 + x^8 + x^6 + x^5 + x^4 + x^2 + x + 1 \tag{3.9}$$

3.1.7. OFDM Process

The transmitted signal is organized in frames. Each frame has duration of TF and consists of 68 OFDM symbols. Four frames constitute one super frame. Each symbol is constituted by a set of 6817 carriers for 8K mode and 1705 carriers for 2K mode and transmitted with duration of T_S.

An OFDM symbol is composed of two parts, a useful part with duration T_U and a guard interval with duration Δ. The guard interval consists in a cyclic continuation of useful part T_U and inserted before it. Four values of guard intervals and usage of these are in table 3.7.

Table 3.7. Duration of symbol part for the allowed guard intervals
(Source: ETSI EN 300 744 2009)

Mode	**8K Mode**				**2K Mode**			
Guard Interval	1/4	1/8	1/16	1/32	1/4	1/8	1/16	1/32
$\mathbf{T_U}$	896 µs				224µs			
Δ	224 µs	112 µs	56 µs	28 µs	56 µs	28 µs	14 µs	7 µs
$\mathbf{T_S=T_U+\Delta}$	1120 µs	1008 µs	952 µs	924 µs	280 µs	252 µs	238 µs	231 µs

The carriers are indexed by $k \in [K_{min}; K_{max}]$ and determined by $K_{min} = 0$ and $K_{max} = 1704$ for 2K mode and $K_{max} = 6816$ for 8K mode. The numerical values for OFDM parameters for 8K and 2K modes are given in table 3.8.

Table 3.8. Numerical values for the OFDM parameters for the 8K and 2K modes
(Source: ETSI EN 300 744 2009)

Parameter	**8K mode**	**2K mode**
Number of carriers, K	6817	1705
Value of carrier number, K_{min}	0	0
Value of carrier number, K_{max}	6816	1704
Duration T_U	896 µs	224 µs
Carrier Spacing, $1/T_U$	1 116 Hz	4464 Hz
Spacing between carriers K_{min} and K_{max}	7,61 MHz	7,61 MHz

The emitted signal is described by following expression:

$$s(t) = Re\left\{e^{j2\pi f_c t}\sum_{m=0}^{\infty}\sum_{l=0}^{67}\sum_{k=0}^{K_{max}} c_{m,l,k} \times \psi_{m,l,k}(t)\right\} \tag{3.10}$$

Where

$$\psi_{m,l,k}(t) = \begin{cases} e^{j2\pi\frac{k'}{T_U}(t-\Delta-l\times T_S-68\times m\times T_S)}, & \mathrm{S}\times T_S \le \mathrm{t} \le (\mathrm{S}+1)\times T_S \\ 0, & \text{else} \end{cases} \tag{3.11}$$

Where:

k → The carrier number

l → The OFDM symbol number

m → The transmission frame number

S → The total number of symbols, $S = l + 68 \times m$

K → The number of transmitted carriers

T_S , T_U → the symbol duration - the inverse of the carrier spacing

Δ → The duration of the guard interval

f_c → The central frequency of the RF signal

k' → The carrier index relative to the center frequency, $k' = k - (K_{max} + K_{min})/_2$

$c_{m,0,k}$ → Complex symbol for carrier k of the data symbol no.1 in frame m

$c_{m,67,k}$ → Complex symbol for carrier k of the data symbol no.68 in frame m

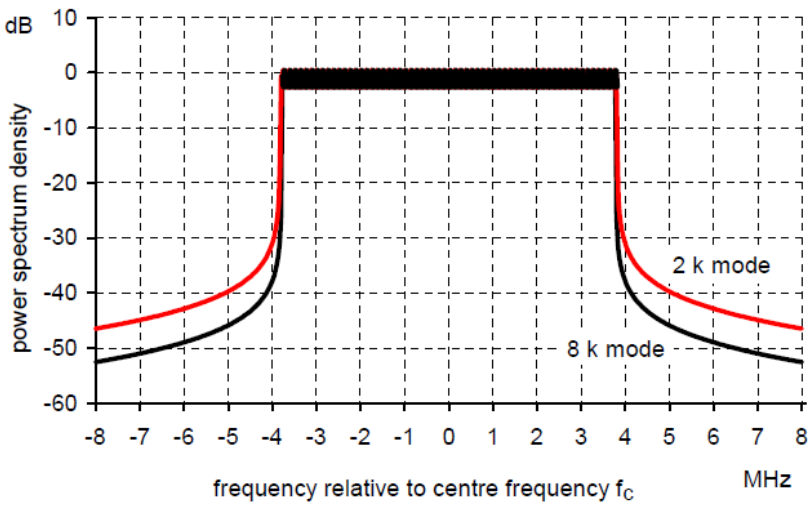


Figure 3.10. OFDM signal spectrum
(Source: ETSI EN 300 744 2009)

3.2. DVB-T2 Transmitter

DVB-T2 system's general high level block diagram is represented in Figure 3.11. The inputs of the system may be one or more;

- MPEG-2 Transport Streams (TS)
- Generic Streams (GS)

The systems output can be a single signal to be transmitted or optionally can be two signals to be conveyed two sets of antennas in what is called MISO transmission mode. All input data streams are then carried in individual Physical Layer Pipes (PLPs).

A DVB-T2 system mainly consists of four blocks which are;

- Input Processing
- Bit Interleaved Coding & Modulation
- Frame Builder
- OFDM Generation

DVB-T2 system is designed to provide a "Quasi Error Free (QEF)" quality target. The meaning of QEF can be defined as "less than one uncorrected error event per transmission hour at the level of a 5 $Mbit/s$ single TV service decoder".

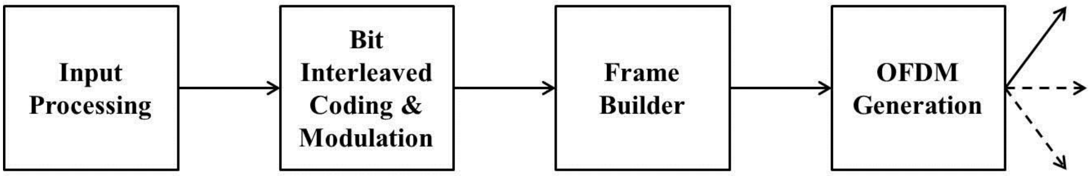


Figure 3.11. High level T2 Block diagram
(Source: ETSI EN 302 755 2011)

Each of these blocks will be explained in next sections of this study.

3.2.1. Input Processing

The input of the system shall be one or more logical data streams. Here there occurs an important word for DVB-T system. This is PLP, which carries one logical data stream.

Input processing block consists of two main sub block which are;

- Mode Adaptation
- Stream Adaptation

The first three blocks in Figure 3.12 form as “Mode Adaptation” and the other two of them form as “Stream Adaptation”.

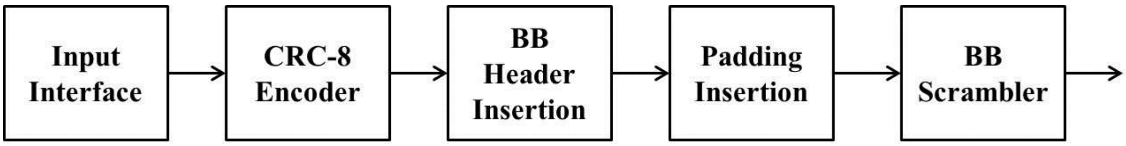


Figure 3.12. Input processing module block diagram
(Source: ETSI EN 302 755 2011)

3.2.1.1. Mode Adaptation

The mode adaptation block operates separately for each PLP and slice the input data into data fields. The mode adaptation block comprises three main blocks which are;

- Input Interface
- CRC-8 Encoder
- BB Header.

The input interface sub-block slices input data into internal logical bit format. If there are more than one PLP, input interfacing is applied separately for each of these PLPs. The input interface shall read a data field, composed of Data Field Length (DFL) bits where;

$$0 \le DFL \le (K_{bch} - 80). \quad (3.12)$$

The maximum value of DFL depends on the chosen LDPC code, carrying a protected payload of K_{bch} bits.

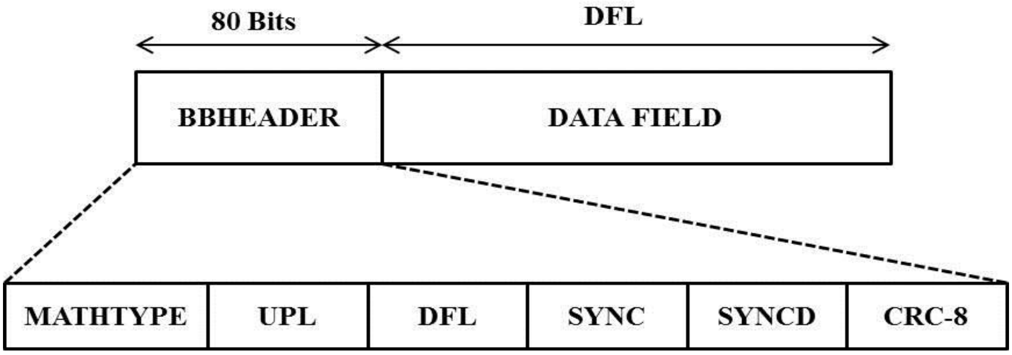


Figure 3.13. Stream format at the output of the MODE ADAPTER
(Source: ETSI EN 302 755 2011)

Base Band Header (BBHEADER) is a fixed length of 10 bytes and inserted in front of the baseband data field. The main purpose to add this to the data field is to describe the format of the data field.

BBHEADER consists of some specific bit field as seen in Figure 3.13. This field values change according to input packet type, user packet length, data field length and etc.

3.2.1.2. Stream Adaptation

The input stream of the stream adaptation block shall be a BBHEADER followed by a DATA FIELD. The output stream shall be a BBFRAME, as shown in Figure 3.14.

Stream adaptation provides;

- Padding → It is used to complete a constant length BBFRAME.

- Scrambling → It is used for energy dispersal.

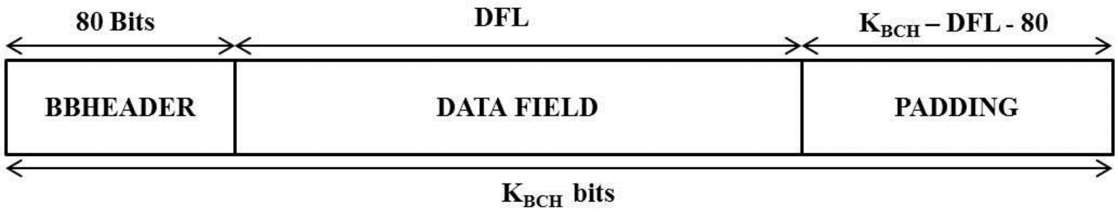


Figure 3.14. BBFRAME format at the output of the STREAM ADAPTER
(Source: ETSI EN 302 755 2011)

3.2.2. BICM Block

Bit Interleaved Coding & Modulation (BICM) block provides some important parts as seen in Figure 3.15. These parts will be explained in the sections below.

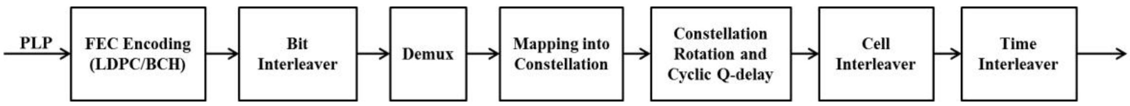


Figure 3.15. Bit Interleaved Coding and Modulation (BICM)
(Source: ETSI EN 302 755 2011)

3.2.2.1. FEC Encoding

Forward Error Correction (FEC) Encoding is a subsystem of BICM block. This subsystem shall perform;

- Outer Encoding (BCH)
- Inner Encoding (LDPC)
- Bit Interleaving.

The input to the subsystem is a BBFRAME and the output is a FECFRAME with length of K_{bch} and N_{ldpc} bits respectively.

The encoding process starts with appending the parity check bits (BCHFEC) of the BCH outer code after BBFRAME. Then the parity check bits (LDPCFEC) of the LDPC inner code is appended after the BCHFEC. As a result, Error correction coded FECFRAME is obtained output of the inner encoder. This process is shown in Figure 3.16.

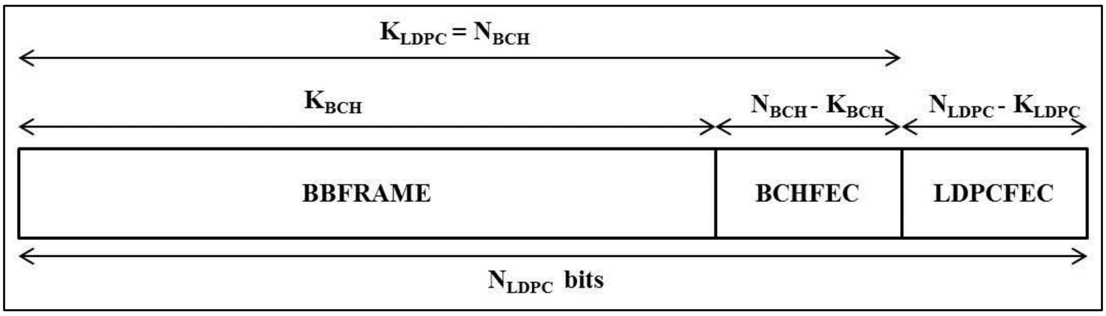


Figure 3.16. Format of data before bit interleaver
(Source: ETSI EN 302 755 2011)

There is two different length values for FECFRAME which are the normal FECFRAME ($N_{ldpc} = 64800$) and the short FECFRAME ($N_{ldpc} = 16200$). FEC encoding parameters according to length of FECFRAME is given in table 3.9a and 3.9b.

Table 3.9. FEC Encoding parameters, (a) for Normal FECFRAME N_{ldpc} = 64800, (b) for Short FECFRAME N_{ldpc} = 16200 (Source: ETSI EN 302 755 2011)

(a)

LDPC Code	BCH Uncoded Block K_{bch}	BCH coded block N_{bch} LDPC Uncoded Block K_{ldpc}	BCH t-error correction	N_{bch} - K_{bch}	LDPC Coded Block N_{ldpc}
1/2	32208	32400	12	192	64800
3/5	38688	38880	12	192	64800
2/3	43040	43200	10	160	64800
3/4	48408	48600	12	192	64800
4/5	51648	51840	12	192	64800
5/6	53840	54000	10	160	64800

(b)

LDPC Code	BCH Uncoded Block K_{bch}	BCH coded block N_{bch} LDPC Uncoded Block K_{ldpc}	BCH t-error correction	N_{bch} - K_{bch}	LDPC Coded Block N_{ldpc}
1/2	7032	7200	12	168	16200
3/5	9552	9720	12	168	16200
2/3	10632	10800	12	168	16200
3/4	11712	11880	12	168	16200
4/5	12432	12600	12	168	16200
5/6	13152	13320	12	168	16200

3.2.2.1.1. Outer Encoder

Bose – Chaudhuri – Hocquenghem (BCH) code is one of the most important error correcting codes which were firstly discovered by Hocquenghem in 1959 and independently by Bose and Chaudhuri in 1960.

BCH codes can be defined as a member of cyclic codes. Bose, Chaudhuri, Hocquenghem just discovered the code not the decoding algorithm. First decoding algorithm was discovered by Peterson in 1960. After this, it's revised by Berlekamp, Massey, Chien, Forney and etc.

Table 3.10. BCH polynomial, (a) for Normal FECFRAME, (b) for Short FECFRAME
(Source: ETSI EN 302 755 2011)

(a)

$g_1(x)$	$1 + x^2 + x^3 + x^5 + x^{16}$
$g_2(x)$	$1 + x + x^4 + x^5 + x^6 + x^8 + x^{16}$
$g_3(x)$	$1 + x^2 + x^3 + x^4 + x^5 + x^7 + x^8 + x^9 + x^{10} + x^{11} + x^{16}$
$g_4(x)$	$1 + x^2 + x^4 + x^6 + x^9 + x^{11} + x^{12} + x^{14} + x^{16}$
$g_5(x)$	$1 + x + x^2 + x^3 + x^5 + x^8 + x^9 + x^{10} + x^{11} + x^{12} + x^{16}$
$g_6(x)$	$1 + x^2 + x^4 + x^5 + x^7 + x^8 + x^9 + x^{10} + x^{12} + x^{13} + x^{14} + x^{15} + x^{16}$
$g_7(x)$	$1 + x^2 + x^5 + x^6 + x^8 + x^9 + x^{10} + x^{11} + x^{13} + x^{15} + x^{16}$
$g_8(x)$	$1 + x + x^2 + x^5 + x^6 + x^8 + x^9 + x^{12} + x^{13} + x^{14} + x^{16}$
$g_9(x)$	$1 + x^5 + x^7 + x^9 + x^{10} + x^{11} + x^{16}$
$g_{10}(x)$	$1 + x + x^2 + x^5 + x^7 + x^8 + x^{10} + x^{12} + x^{13} + x^{14} + x^{16}$
$g_{11}(x)$	$1 + x^2 + x^3 + x^5 + x^9 + x^{11} + x^{12} + x^{13} + x^{16}$
$g_{12}(x)$	$1 + x + x^5 + x^6 + x^7 + x^9 + x^{11} + x^{12} + x^{16}$

(b)

$g_1(x)$	$1 + x + x^3 + x^5 + x^{14}$
$g_2(x)$	$1 + x^6 + x^8 + x^{11} + x^{14}$
$g_3(x)$	$1 + x + x^2 + x^6 + x^9 + x^{10} + x^{14}$
$g_4(x)$	$1 + x^4 + x^7 + x^8 + x^{10} + x^{12} + x^{14}$
$g_5(x)$	$1 + x^2 + x^4 + x^6 + x^8 + x^9 + x^{11} + x^{13} + x^{14}$
$g_6(x)$	$1 + x^3 + x^7 + x^8 + x^9 + x^{13} + x^{14}$
$g_7(x)$	$1 + x^2 + x^5 + x^6 + x^7 + x^{10} + x^{11} + x^{13} + x^{14}$
$g_8(x)$	$1 + x^5 + x^8 + x^9 + x^{10} + x^{11} + x^{14}$
$g_9(x)$	$1 + x + x^2 + x^3 + x^9 + x^{10} + x^{14}$
$g_{10}(x)$	$1 + x^3 + x^6 + x^9 + x^{11} + x^{12} + x^{14}$
$g_{11}(x)$	$1 + x^4 + x^{11} + x^{12} + x^{14}$
$g_{12}(x)$	$1 + x + x^2 + x^3 + x^5 + x^6 + x^7 + x^8 + x^{10} + x^{13} + x^{14}$

A t-error correcting BCH code shall be applied to each BBFRAME to generate an error protected packet. The generator polynomial of the encoder is obtained by multiplying first t polynomials in table 3.10a for normal FECFRAME and in table 3.10b for short FECFRAME.

3.2.2.1.2. Inner Encoder

Low Density Parity Check (LDPC) codes were invented by Robert Gallager (1963) in his Ph.D. Thesis. After the invention of this code, it's totally forgotten and never used nearly 30 years of time. Their comeback is really interesting because there reinvented two codes from different areas but they are very similar to Gallager's LDPC Codes.

In DVB-T2 systems LDPC encoder is used as inner encoders because of its high error correcting performance. The output of the inner encoder block has the form which is shown in Figure 3.16 with a length of N_{ldpc} bits which changes according to normal or short FECFRAME.

3.2.2.1.3. Bit Interleaver

The output of the LDPC bit interleaving consists in a parity interleaving followed by a twist column interleaving, and it's only applied for 16QAM, 64QAM and 256QAM modulations, in the case of the QPSK modulation, the bit interleaving block is not performed. Firstly the parity bits are interleaved by;

$$
\begin{aligned}
&u_i = \lambda_i \, for \; 0 \leq i \leq K_{ldpc} \\
&u_{K_{ldpc}+360t+s} = \lambda_{K_{ldpc}+\,Q_{ldpc}.s+t}
\end{aligned}
\qquad (3.13)
$$

Where Q_{ldpc} is defined in table 3.11, λ is the output of LDPC encoder and U is the output of the parity interleaver.

Table 3.11. Q_{ldpc} values
(Source: ETSI EN 302 755 2011)

Code Rate	**Q_{ldpc} for Normal FECFRAME**	**Q_{ldpc} for Short FECFRAME**
1/2	90	25
3/5	72	18
2/3	60	15
3/4	45	12
4/5	36	10
5/6	30	8

The configuration of the column twist interleaving for each modulation format is specified in table 3.12.

Table 3.12. Bit Interleaver structure
(Source: ETSI EN 302 755 2011)

Modulation	**Rows N_r**		**Columns N_c**
	N_{ldpc} = 64800	**N_{ldpc} = 16200**	
16QAM	8100	2025	8
64QAM	5400	1350	12
256QAM	4050	--	16
	--	2025	8

Finally, the output of the parity interleaver is written into column-twist interleaver as column wise by using the twisting parameter t_c as the starting index of the column. After that, data read out row-wise as seen in Figure 3.17.

Table 3.13. Column twisting parameter t_c
(Source: ETSI EN 302 755 2011)

Modulation	N_c	N_{ldpc}	Twisting parameter t_c															
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
16QAM	8	64800	0	0	2	4	4	5	7	7	-	-	-	-	-	-	-	-
		16200	0	0	0	1	7	20	20	21	-	-	-	-	-	-	-	-
64QAM	12	64800	0	0	2	2	3	4	4	5	5	7	8	9	-	-	-	-
		16200	0	0	0	2	2	2	3	3	3	6	7	7	-	-	-	-
256QAM	16	64800	0	2	2	2	2	3	7	15	16	20	22	22	27	27	28	32
	8	16200	0	0	0	1	7	20	20	21	-	-	-	-	-	-	-	-

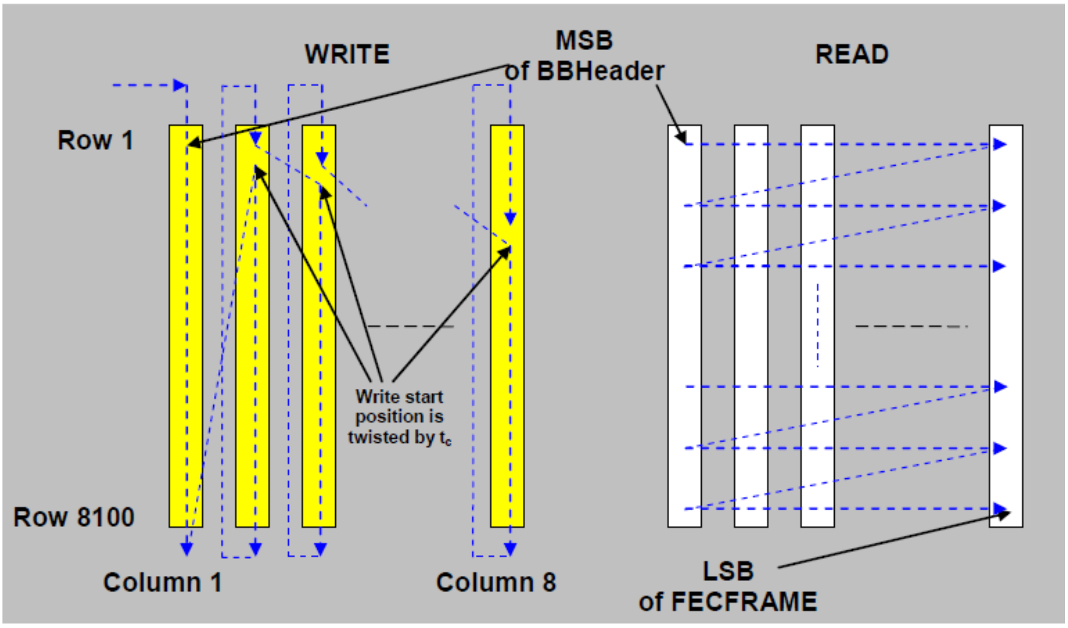


Figure 3.17. Bit interleaving scheme for normal FECFRAME length and 16QAM
(Source: ETSI EN 302 755 2011)

3.2.2.2. Mapping Bits onto Constellations

After bit interleaving of FECFRAMES, they shall be mapped to a coded FEC block. Firstly, the input bits are demultiplexed into parallel cell words and then mapping these cell words into constellation values. Table 3.14 defines the number of output data cells and the effective number of bits per cell (η_{MOD}).

Table 3.14. Parameters for bit-mapping into constellations
(Source: ETSI EN 302 755 2011)

LDPC block length (N_{ldpc})	**Modulation**	**η_{MOD}**	**Number of output data cells**
64800	256QAM	8	8100
	64QAM	6	10800
	16QAM	4	16200
	QPSK	2	32400
16200	256QAM	8	2025
	64QAM	6	2700
	16QAM	4	4050
	QPSK	2	8100

In Demux process, the output bit stream of the bit interleaving is demultiplexed into $N_{substreams}$ sub-streams as shown in Figure 3.18 and the values of $N_{substreams}$ is defined in table 3.15.

Table 3.15. Values of parameter $N_{substreams}$
(Source: ETSI EN 302 755 2011)

Modulation	**N_{ldpc}**	**$N_{substreams}$**
QPSK	Any	2
16QAM	Any	8
64QAM	Any	12
256QAM	64800	16
	16200	8

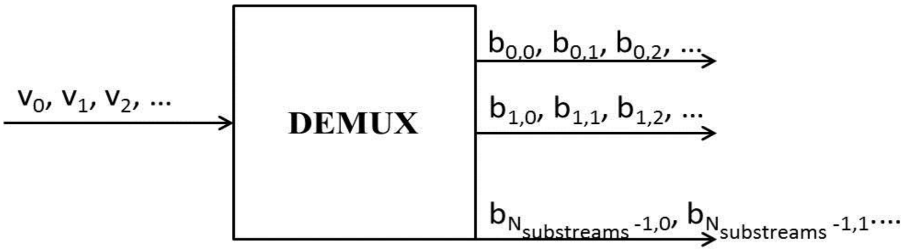


Figure 3.18. Demultiplexing of bits into sub-streams
(Source: ETSI EN 302 755 2011)

Each cell word at the output of the demultiplexer is modulated by using the constellations of QPSK, 16QAM, 64QAM or 256QAM to give a constellation point. Constellations for first 3 of them are the same as in DVB-T system which is showed in Figure 3.8. In addition to them 256 QAM constellation is shown in Figure 3.19.

Every constellation point is normalized according to table 3.16 to obtain the correct complex cell value.

Table 3.16. Normalization factors
(Source: ETSI EN 302 755 2011)

Modulation	Normalization
QPSK	$1/\sqrt{2}$
16QAM	$1/\sqrt{10}$
64QAM	$1/\sqrt{42}$
256QAM	$1/\sqrt{170}$

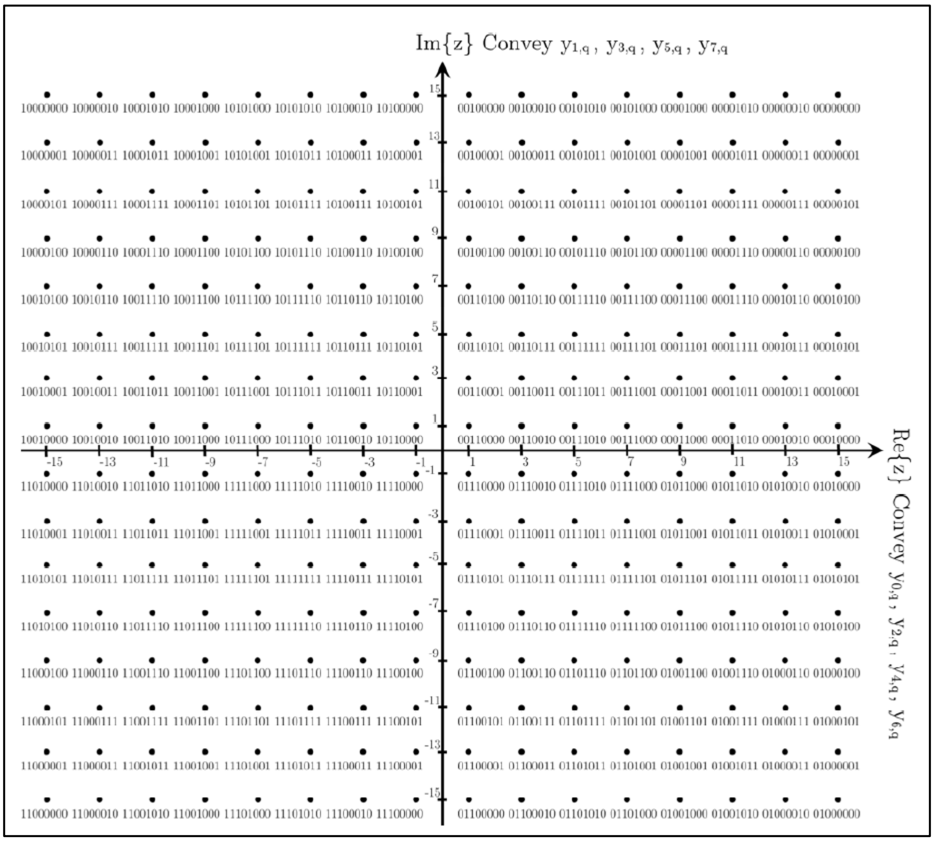


Figure 3.19. The 256QAM mapping and corresponding bit pattern
(Source: ETSI EN 302 755 2011)

3.2.2.3. Cell Interleaver

The Pseudo Random Cell Interleaver shall spread the cells in the FEC code word uniformly. The main purpose of this process is to ensure an uncorrelated distribution of channel distortions and interference along the FEC code word in the receiver.

The Cell Interleaver (CI) process is defined below where "$g_{r,q}$" is the input of the system, d is CI output**,** N_{cells} is given in table 3.17, $L_r(q)$ is the permutation function, and r represents the incremental index of the FEC block within the TI-block (Time Interleaver) and is reset to zero at the beginning of each TI-block.

$$d_{r,L_r(q)} = \; g_{r,q} \; for \; each \; q = 0, 1, \dots, N_{cells} - 1 \tag{3.14}$$

$L_r(q)$ is based on a maximum length sequence of degree $(N_d - 1)$, where $N_d = \lceil \log_2(N_{cells}) \rceil$ which is defined as;

$$L_r(q) = \; [L_0(q) + \; P(r)] \; mod \; N_{cells} \tag{3.15}$$

Where $L_0(q)$ is the basic permutation function and $P(r)$ is the shift value to be used in FEC block r of the TI block. Definition of these parameters is examined deeply in (ETSI EN 302 755 2011).

With those specifications for the cell interleaver, a scheme for the cell interleaver is shown on Figure 3.20.

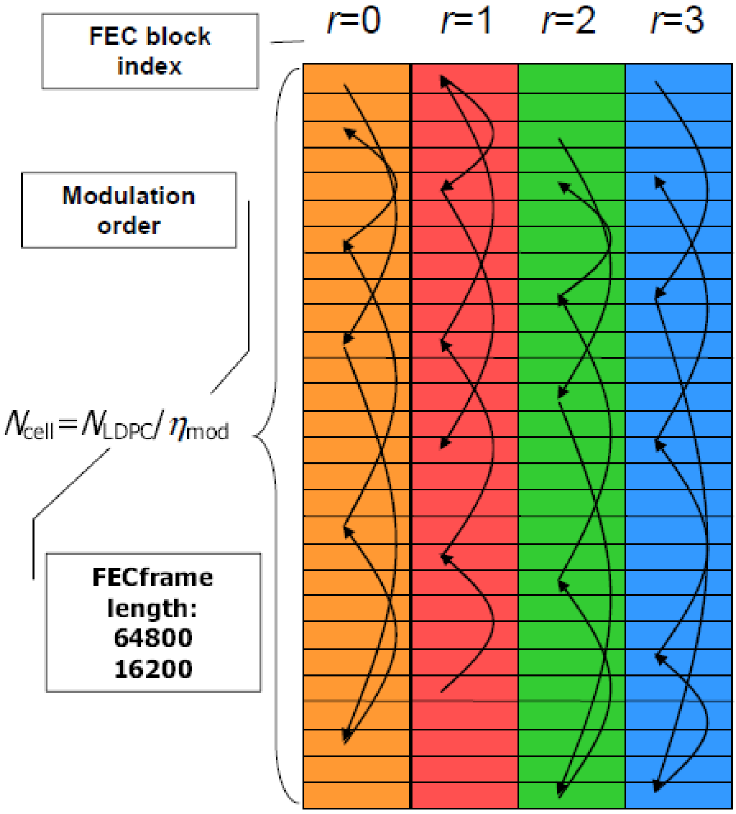


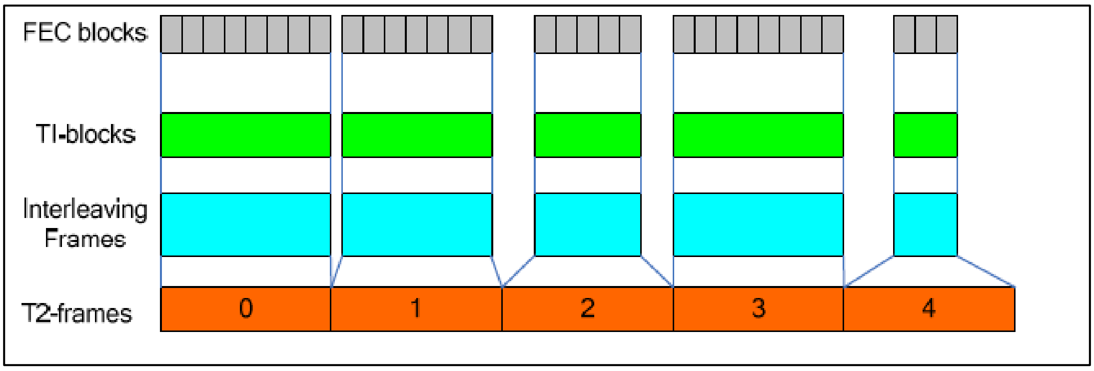
Figure 3.20. Cell Interleaving Scheme
(Source: ETSI EN 302 755 2011)

3.2.2.4. Time Interleaver

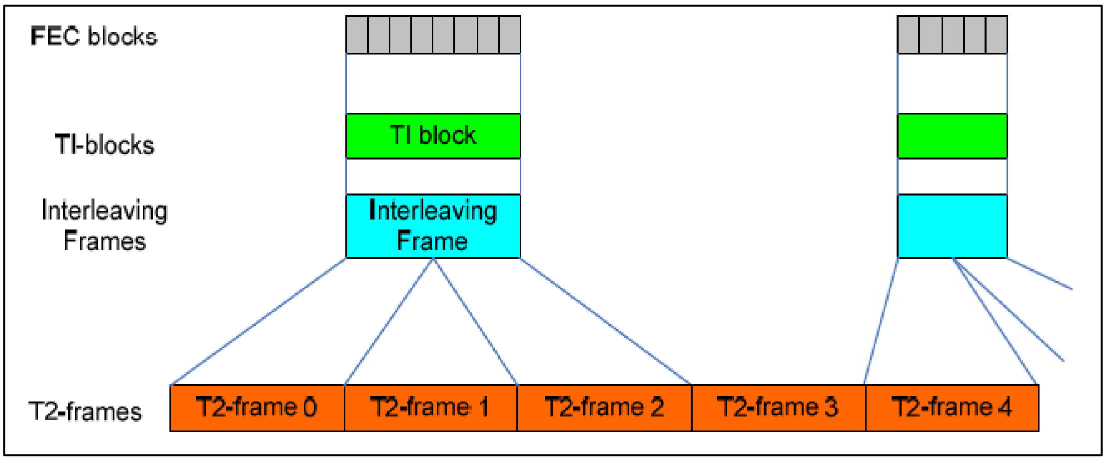
The time interleaver (TI) shall operate at PLP level. The cell interleaved FEC block at the input of TI, shall be grouped in Interleaving Frames which are mapped onto one or more T2-Frames. Each interleaving frame contains a dynamically variable whole number of FEC blocks. The maximum number of a FEC block is 1023.

There are three options for time interleaving for each PLP. These options are shown in Figure 3.21.

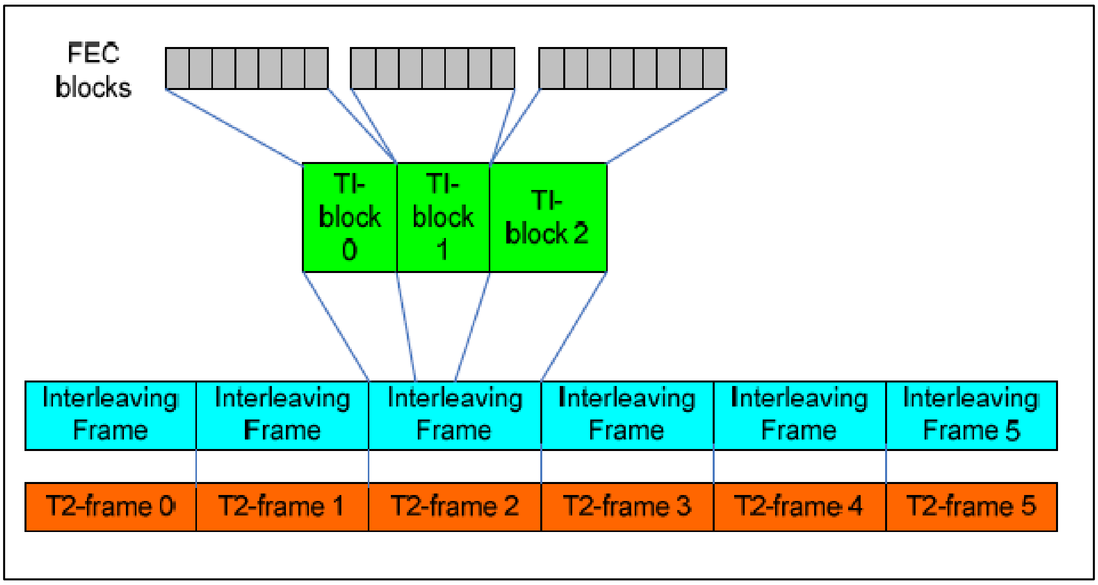
1) Option1; (one TI-Block) → (one Interleaving Frame) → (one T2 Frame)
2) Option2; (one TI-Block) → (one Interleaving Frame) → (more T2 Frame)
3) Option3; (more TI-Block) → (one Interleaving Frame) → (one T2 Frame)



(a)



(b)



(c)

Figure 3.21. Time Interleaving Options, (a) Option 1, (b) Option 2, (c) Option 3
(Source: ETSI EN 302 755 2011)

The Time interleaver can be defined as a row-column block interleaver. The cells which creates TI blocks, firstly written in a $N_r \times N_c$ matrix where the number of rows N_r in the interleaver is equal to the number of cells in the FEC block (N_{cells}) divided by 5, the number of columns $N_c = 5 * N_{FEC}$ and N_{FEC} is the number of FEC blocks in a TI-block. TI parameters are given in table 3.17.

Table 3.17. Parameters for time interleaver
(Source: ETSI EN 302 755 2011)

LDPC block length (N_{ldpc})	**Modulation Mode**	**Number of cells Per LDPC block (N_{cells})**	**Number of rows N_r**
64800	256QAM	8100	1620
	64QAM	10800	2160
	16QAM	16200	3240
	QPSK	32400	6480
16200	256QAM	2025	405
	64QAM	2700	540
	16QAM	4050	810
	QPSK	8100	1620

Time interleaver process is shown in Figure 3.21. The first FEC block is written into first 5 columns of the time interleaver, the second FEC block is written into first 5 columns of the time interleaver and so on. After writing process the cells are read out row-wise.

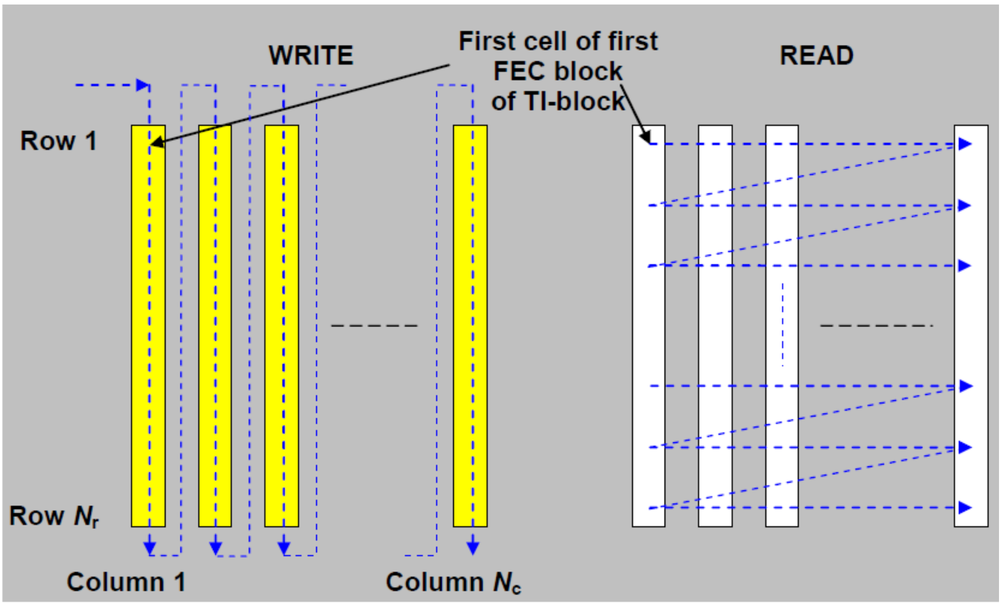


Figure 3.22. Time interleaver
(Source: ETSI EN 302 755 2011)

3.2.3. OFDM Generation

DVB-T2 systems' OFDM generation block is simply indicated in Figure 3.22. As seen in figure, there are 7 sub-blocks and some of these are optional blocks which are not used in all the cases. These blocks are MISO Processing and PAPR Reduction.

The function of the OFDM generation block is to insert the reference information which is described in text as pilots and allow the receiver to compensate for distortions introduced by the channel, and to produce time domain signal for transmission. After that process, guard interval is inserted and if possible PAPR reduction is applied and finally completed T2 signal is produced.

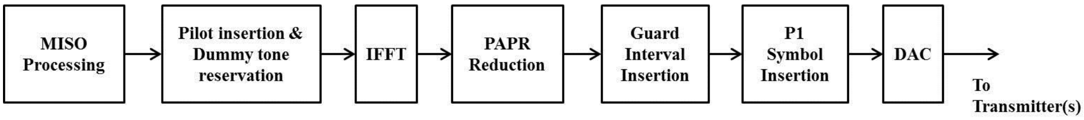


Figure 3.23. OFDM Generation
(Source: ETSI EN 302 755 2011)

Some important blocks of OFDM generation will be explained in next sub-sections.

3.2.3.1. MISO Processing

In DVB-T2 systems, Multiple-Input Single-Output (MISO) processing may have been applied to all symbols of the DVB-T2 signal. It is assumed that all DVB-T2 receivers shall be able to receive signals with MISO processing applied.

MISO processing can be defined as taking the input data cells and producing two similar sets of data cells at the output. As encoding technique, a modified Alamouti encoding is used.

The encoding process is done as it shown in equation below where a is the OFDM cell, e is the output of the MISO processing, $*$ denotes the complex conjugation operation and N_{Data} is the number of data cells at the input of MISO processing block.

$$\begin{array}{ll} e_{m,l,p}(Tx1) = a_{m,l,p} & e_{m,l,p+1}(Tx1) = a_{m,l,p+1} \\ e_{m,l,p}(Tx2) = -a^{*}_{m,l,p+1} & e_{m,l,p+1}(Tx2) = a^{*}_{m,l,p} \\ \multicolumn{2}{c}{where\ p \in \{0,2,4,6,\dots,N_{data}-2\}} \end{array} \tag{3.16}$$

The MISO processing process is also illustrated in Figure 3.23.

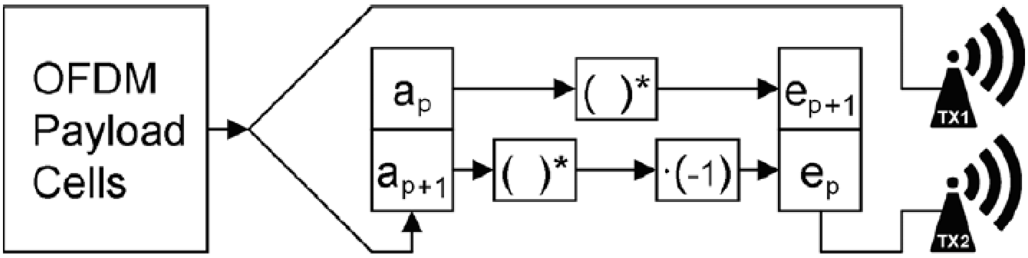


Figure 3.24. MISO processing of OFDM cells
(Source: ETSI EN 302 755 2011)

If MISO is not used, the input cells shall pass directly to the output as;

$$e_{m,l,p} = a_{m,l,p}\ for\ p = 0, 1, 2, \dots, N_{data} - 1 \tag{3.17}$$

3.2.3.2. Pilot Insertion

Some various cells in OFDM frame are modulated with reference information and this reference information's transmission value is known to the receiver. There different types of pilots in DVB-T2 systems which are; scattered, continual, edge, P2 and frame-closing.

Pilots are located into the frames just because they can be used for frame synchronization, frequency synchronization, time synchronization, channel estimation, transmission mode identification and can also be used to follow the phase noise.

The reference sequence $r_{l,k}$, where l and k the symbol and the carrier indices respectively. Reference sequence is derived a symbol level PRBS sequence w_k and a frame level PN-sequence pn_l. After derivation, this reference sequence is applied to all pilots of each symbol of a T2 frame. This process is illustrated in Figure 3.24.

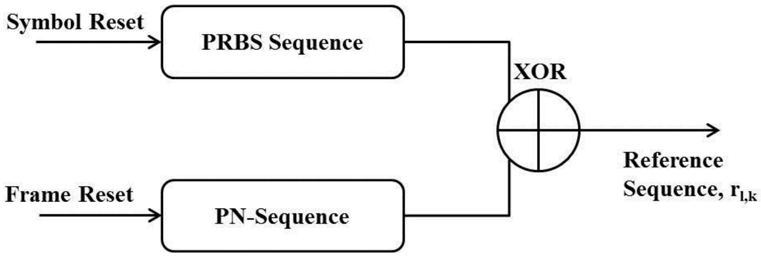


Figure 3.25. Formation of the reference sequence from the PN and PRBS sequences
(Source: ETSI EN 302 755 2011)

The PRBS sequence generator has the same configuration with DVB-T's reference sequence generator which is illustrated in Figure 3.9 in section 3.1.6. The PN sequence which is used in reference sequence formation is defined in table 3.18. The used length of this sequence is changed according to the transmission mode such as 1K, 2K, etc.

Table 3.18. PN-sequence (up to 2624 chips) in Hexadecimal description
(Source: ETSI EN 302 755 2011)

4DC2AF7BD8C3C9A1E76C9A090AF1C3114F07FCA2808E9462E9AD7B712D6F4AC8A59BB069CC50
BF1149927E6BB1C9FC8C18BB949B30CD09DDD749E704F57B41DEC7E7B176E12C5657432B51B0B8
12DF0E14887E24D80C97F09374AD76270E58FE1774B2781D8D3821E393F2EA0FFD4D24DE20C05D0
BA1703D10E52D61E013D837AA62D007CC2FD76D23A3E125BDE8A9A7C02A98B70251C556F6341E
BDECB801AAD5D9FB8CBEA80BB619096527A8C475B3D8DB28AF8543A00EC3480DFF1E2CDA9F9
85B523B879007AA5D0CE58D21B18631006617F6F769EB947F924EA5161EC2C0488B63ED7993BA8EF
4E552FA32FC3F1BDB19923902BCBBE5DDABB824126E08459CA6CFA0267E5294A98C632569791E6
0EF659AEE9518CDF08D87833690C1B79183ED127E53360CD86514859A28B5494F51AA4882419A25A
2D01A5F47AA27301E79A5370CCB3E197F

3.2.3.3. IFFT

In DVB-T2 systems there are six different transmission modes which are 1K, 2K, 4K, 8K, 16K and 32K. Transmission mode is also named as FFT size.

A DVB-T2 transmitted signal is organized in frames. Each frame has duration of T_F and consists of OFDM symbols. N_{T2} frames constitute one super frame. Each symbol is constituted by a set of K_{total} carriers and has duration of T_S. A carrier is composed of two parts which are useful part with duration T_U and guard interval with duration Δ. Some important OFDM parameters are given in table 3.19.

Table 3.19. OFDM parameters
(Source: ETSI EN 302 755 2011)

Parameters	**1K**	**2K**	**4K**	**8K**	**16K**	**32K**
K_{total}	853	1705	3409	6817	13633	27265
K_{min}	0	0	0	0	0	0
K_{max}	852	1704	3408	6816	13632	27265
T_U in µs	112	224	448	896	1792	3584
Carrier Spacing $1/T_U$ (Hz)	8929	4464	2232	1116	558	279
Spacing between carriers K_{min} and K_{max}	7,61 MHz	7,61 MHz	7,61 MHz	7,61 MHz	7,61 MHz	7,61 MHz

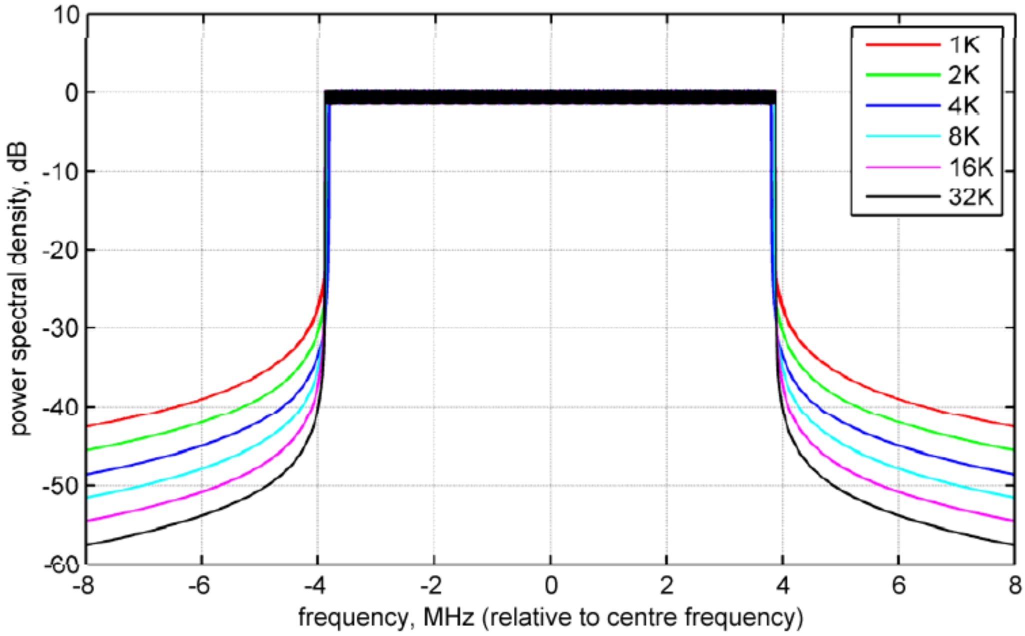


Figure 3.26. Theoretical DVB-T2 signal spectrum
(Source: ETSI EN 302 755 2011)

The emitted signal of DVB-T2 when PAPR reduction is not used is given in the equation below.

$$s(t) = Re\left\{e^{j2\pi f_c t}\sum_{m=0}^{\infty}\left[p_1(t-mT_F)\ldots\right.\right.$$
$$\left.\left.+\frac{5}{\sqrt{27\times K_{total}}}\sum_{l=0}^{L_F-1}\sum_{k=0}^{K_{max}} c_{m,l,k}\times\psi_{m,l,k}(t)\right]\right\} \tag{3.18}$$

Where

$$\psi_{m,l,k}(t) = \begin{cases} e^{j2\pi\frac{k'}{T_U}(t-\Delta-T_{p1}-l\times T_S-m\times T_F)} & , TT+lT_S \le t \le TT+(l+1)T_S \\ 0 & , \quad else \end{cases} \tag{3.19}$$

Where:

k	→	The carrier number
l	→	The OFDM symbol number
m	→	The T2 transmission frame number

K_{Total} → The number of transmitted carriers

L_F → Number of OFDM Symbols per frame

T_S → The symbol duration

T_U → The inverse of the carrier spacing

Δ → The duration of the guard interval

f_c → The central frequency of the RF signal

k' → The carrier index relative to the center frequency, $k' = k - (K_{max} + K_{min})/2$

$TP1$ → The P1 symbol duration

TF → The duration of a frame

TT → The duration of frames and P1 symbols, $TT = mT_F + T_{P1}$

$p1(t)$ → The P1 waveform

3.2.3.4. Guard Interval Insertion

DVB-T2 systems have seven guard interval fractions. For each combination of FFT size and guard interval fractions, the absolute guard interval fractions are given in table 3.21 expressed in multiples of the elementary period T which is also given in table 3.20.

Table 3.20. Elementary Period as a Function of Bandwidth
(Source: ETSI EN 302 755 2011)

Bandwidth	**1,7 MHz**	**5MHz**	**6MHz**	**7MHz**	**8MHz**	**10MHz**
Elementary period T	71/131 μs	7/40 μs	7/48 μs	1/8 μs	7/64 μs	7/80 μs

Table 3.21. Duration of Guard interval in terms of elementary period T
(Source: ETSI EN 302 755 2011)

FFT Size	Guard Interval fraction (Δ/T_U)						
	1/128	**1/32**	**1/16**	**19/256**	**1/8**	**19/128**	**¼**
32K	256T	1024T	2048T	2432T	4096T	4864T	NA
16K	128T	512T	1024T	1216T	2048T	2432T	4096T
8K	64T	256T	512T	608T	1024T	1216T	2048T
4K	NA	128T	256T	NA	512T	NA	1024T
2K	NA	64T	128T	NA	256T	NA	512T
1K	NA	NA	64T	NA	128T	NA	256T

Guard interval usage depends on the usage of PAPR reduction. If PAPR reduction is used, the guard intervals shall be inserted following PAPR reduction.

CHAPTER 4

MULTIPATH CHANNEL PROFILES

DVB organization has developed many channel profiles to obtain reasonable results in off-line computer simulations and real time simulations. Some information is given in different DVB- standards such as DVB-T, DVB-T2, DVB-H and etc.

Some of the channels which are used in this study's simulations are developed and defined by European Cooperation in Science and Technology (COST) and is a part of COST207 project which is finished and published in 1989 in Luxemburg.

COST is an intergovernmental framework for European Cooperation in Science and Technology, allowing the coordination of nationally-funded research on a European level. COST has a very specific mission and goal. It contributes to reducing the fragmentation in European research investments and opening the European Research Area (ERA) to cooperation worldwide (COST Organization n.d.).

4.1. Channel Models

In this study, for both of the systems (DVB-T and DVB-T2) they are going to be used seven different multipath channels which are divided into three there groups such as fixed, portable and mobile. These seven channels are;

- Additive White Gaussian Noise (AWGN) Channel
- Ricean Channel
- Simple 2 Path Channel, 3 dB Echo
- Portable Outdoor Channel (PO)
- Portable Indoor Channel (PI)
- Typical Urban Channel (TU6)
- Rural Area Channel (RA6)

The information about these seven channels and some specific properties such as power-delay profiles, of them will be examined in this chapter. Also channel modeling characteristics will take place in further sections.

4.1.1. AWGN Channel Profile

In this type of channel models, just white Gaussian noise is added to the transmitted signal. It is thought that there will be just one path which is given in table 4.1.

Table 4.1. AWGN Channel Model

Path Number	Attenuation	Delay (µs)	Phase (radians)
1	1	0	0

4.1.2. Ricean Channel

Ricean channel is described both in DVB-T standard (ETSI EN 300 744 2009) and DVB-T2 standard (ETSI EN 302 755 2011) to describe the fixed, outdoor rooftop-antenna reception conditions. There is no Doppler effect and also this channel has 21 taps. This model is defined by where $y(t)$ and $x(t)$ is output and input signal of the channel respectively;

$$y(t) = \frac{\rho_0 x(t) + \sum_{i=1}^{N} \rho_i e^{-j\theta_i} x(t-\tau_i)}{\sqrt{\sum_{i=0}^{N} \rho_i^2}} \tag{4.1}$$

Where

- $\rho_0 x(t)$ represents LOS (Line of Sight) ray
- N is the number of echoes and is equal to 20
- θ_i is the phase shift from scattering of the ith path (Table 4.2)
- ρ_i is the attenuation of the ith path (Table 4.2)
- τ_i is the relative delay of the ith path (Table 4.2)

The Ricean factor K, is given as;

$$K = \frac{\rho_0^2}{\sum_{i=1}^{N} \rho_i^2} \tag{4.2}$$

In DVB simulations, K is chosen as 10 dB and in this case, attenuation factor of the LOS path shall be calculated as;

$$\rho_0 = \sqrt{10.\sum_{i=1}^{N} \rho_i^2} \tag{4.3}$$

According to the values which is given in table 4.2, power delay profile of Ricean channel is illustrated in Figure 4.1.

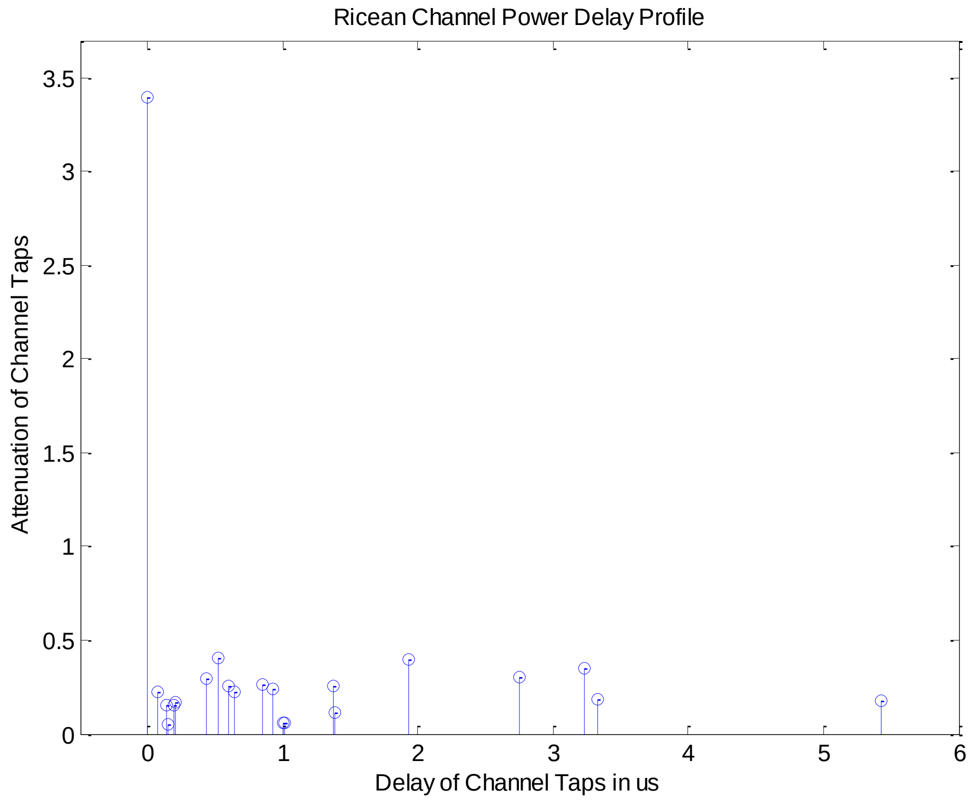


Figure 4.1. Ricean Channel Power Delay Profile

Table 4.2. Attenuation, Delay and Phase Values for Ricean Channel
(Source: ETSI EN 302 755 2011)

Path Number	**Attenuation**	**Delay (μs)**	**Phase (radians)**
1	0.057662	1.003019	4.855121
2	0.176809	5.422091	3.419109
3	0.407809	0.518650	5.864470
4	0.303585	2.751772	2.215894
5	0.258782	0.602895	3.758058
6	0.061831	1.016585	5.430202
7	0.150340	0.143556	3.952093
8	0.051534	0.153832	1.093586
9	0.185074	3.324866	5.775198
10	0.400967	1.935570	0.154459
11	0.295723	0.429948	5.928383
12	0.350825	3.228872	3.053023
13	0.262909	0.848831	0.628578
14	0.225894	0.073883	2.128544
15	0.170996	0.203952	1.099463
16	0.149723	0.194207	3.462951
17	0.240140	0.924450	3.664773
18	0.116587	1.381320	2.833799
19	0.221155	0.640512	3.334290
20	0.259730	1.368671	0.393889

4.1.3. Simple 2 Path Channel, 3 dB Echo

This channel profile is described in DVB-T2 standard (ETSI A133 2010). It only includes 2 paths. In this study, a different version is used. Original version has 0 dB echoes for both paths. The corresponding paths are defined by their delay, phase, frequency shift and attenuation values in table 4.3.

Table 4.3. 3 dB Echo Profile

Path number	Attenuation	Delay (μs)	Phase (rad)	Frequency Shift (Hz)
1	1.0000	0	0	0
2	0.7079	0.9Δ	0	0

The parameter '*Δ*' denotes the guard interval duration in μs.

According to the values which are given in table 4.3, power delay profile of simple 2-path channel, 3 dB echo is illustrated in Figure 4.2.

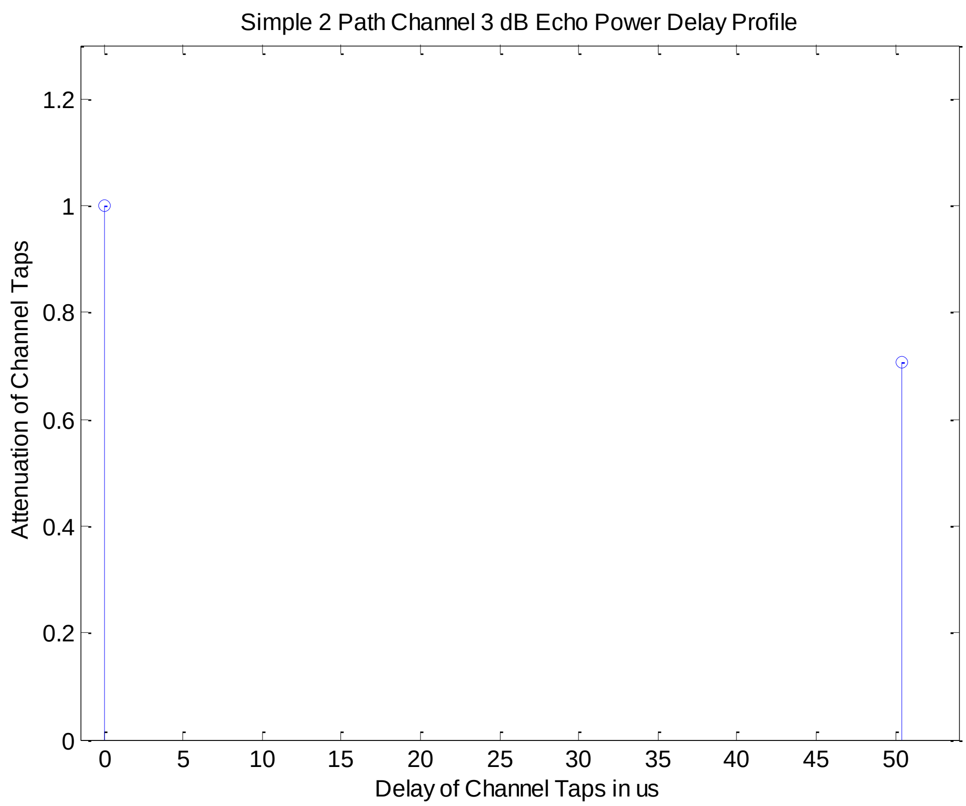


Figure 4.2. Simple 2-path Channel 3 dB Echo Power Delay Profile for ¼ Guard Interval in 2K Mode

4.1.4. Portable Indoor and Outdoor Channel

Portable indoor (PI) and Portable outdoor (PO) channel profiles are described in DVB-H (ETSI TR 102 377 2001) standard. They have been developed by the Wing TV project to describe the slowly moving hand held reception indoors and outdoors. Definitions about PI and PO are given in table 4.4. The Doppler frequency of these channel are chosen as 1.69 Hz which is corresponding 3km/h velocity at 666 MHz carrier frequency.

Table 4.4. Definitions of PI and PO Channels

Path Number	**PI**		**PO**		**Doppler Spectrum**	**Fd (Hz)**	**STD Norm.**
	Delay (µs)	**Power (dB)**	**Delay (µs)**	**Power (dB)**			
1	0.0	0.0	0.0	0.0	Classical	1.69	0.08
2	0.1	-6.4	0.2	-1.5	Classical	1.69	0.08
3	0.2	-10.4	0.6	-3.8	Classical	1.69	0.08
4	0.4	-13.0	1.0	-7.3	Classical	1.69	0.08
5	0.6	-13.3	1.4	-9.8	Classical	1.69	0.08
6	0.8	-13.7	1.8	-13.3	Classical	1.69	0.08
7	1.0	-16.2	2.3	-15.9	Classical	1.69	0.08
8	1.6	-15.2	3.4	-20.6	Classical	1.69	0.08
9	8.1	-14.9	4.5	-19.0	Classical	1.69	0.08
10	8.8	-16.2	5.0	-17.7	Classical	1.69	0.08
11	9.0	-11.1	5.3	-18.9	Classical	1.69	0.08
12	9.2	-11.2	5.7	-19.3	Classical	1.69	0.08

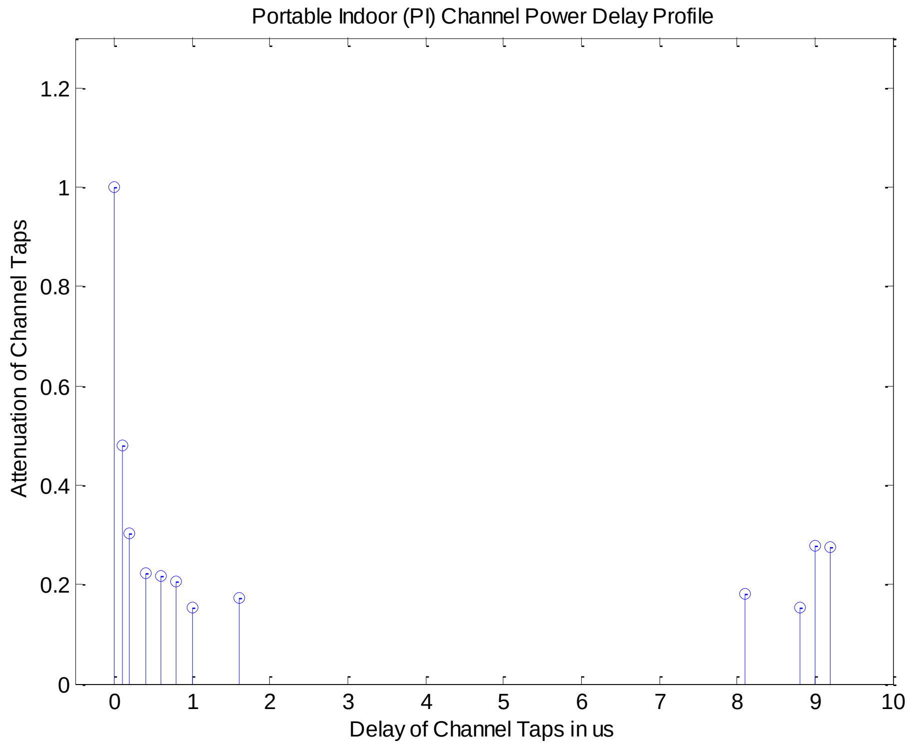


Figure 4.3. Portable Indoor (PI) Channel Power Delay Profile

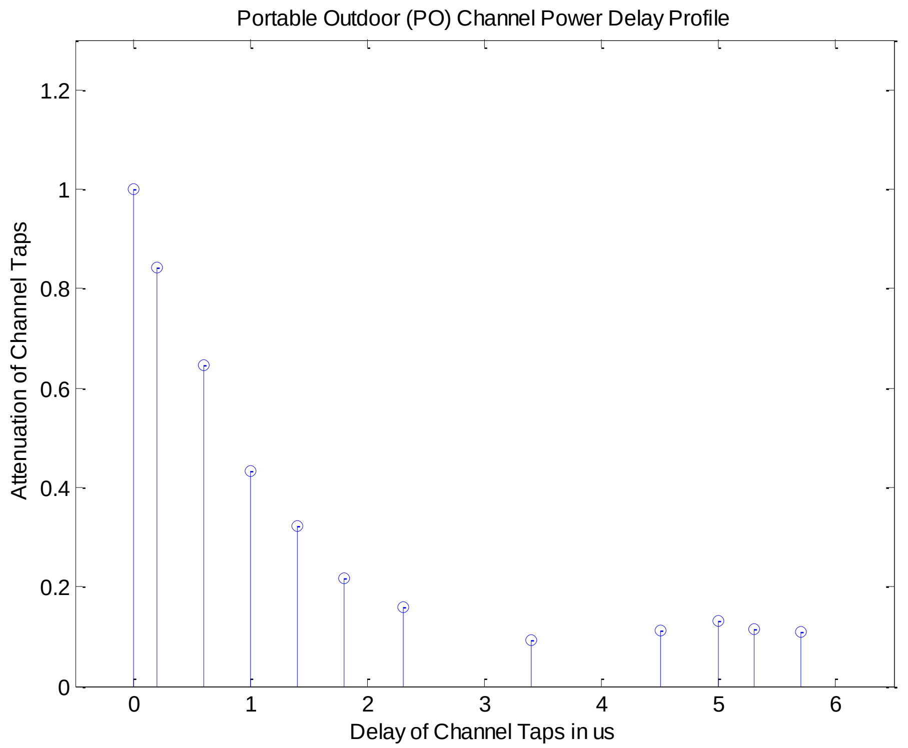


Figure 4.4. Portable Outdoor (PO) Channel Power Delay Profile

4.1.5. Typical Urban Channel

The Typical Urban (TU6) channel profiles are described in DVB-T2 standard (ETSI A133 2010). It was originally defined by COST207 as describing a typical urban profile and has 6 paths. These paths have wide dispersion in delay and relatively strong power. GSM and DAB services have also used this channel in their tests. The parameters of this channel are given in table 4.5.

Table 4.5. Typical Urban (TU6) Channel Profile
(Source: ETSI A133 2010)

Path Number	Delay (µs)	Power (dB)	Doppler Spectrum
1	0.0	-3	Classical
2	0.2	0	Classical
3	0.5	-2	Classical
4	1.6	-6	Classical
5	2.3	-8	Classical
6	5.0	-10	Classical

Where the Classical Doppler Spectrum is $K(f; f_D) = \frac{1}{\sqrt{1-\left(\frac{f}{f_D}\right)^2}}$

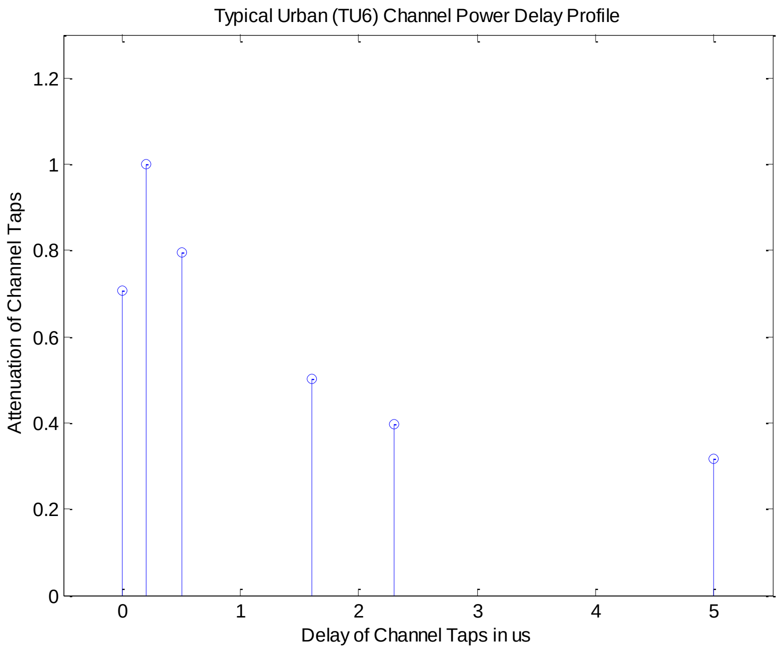


Figure 4.5. Typical Urban (TU6) Channel Power Delay Profile

4.1.6. Rural Area Channel

The Typical Rural Area (RA6) channel profiles are described in ETSI TR 101 290 document (ETSI TR 101 290 2001). It was originally defined by COST207 as describing the terrestrial propagation in a rural area and has 6 paths. These paths have relatively short delay and small power. GSM and DAB services have also used this channel in their tests. The parameters of this channel are given in table 4.6.

Table 4.6. Typical Rural Area (RA6) Channel Profile
(Source: ETSI TR 101 290 2001)

Path Number	Delay (µs)	Power (dB)	Doppler Spectrum
1	0.0	0	Classical
2	0.1	-4	Classical
3	0.2	-8	Classical
4	0.3	-12	Classical
5	0.4	-16	Classical
6	0.5	-20	Classical

The Classical Doppler Spectrum is described in section 4.1.5.

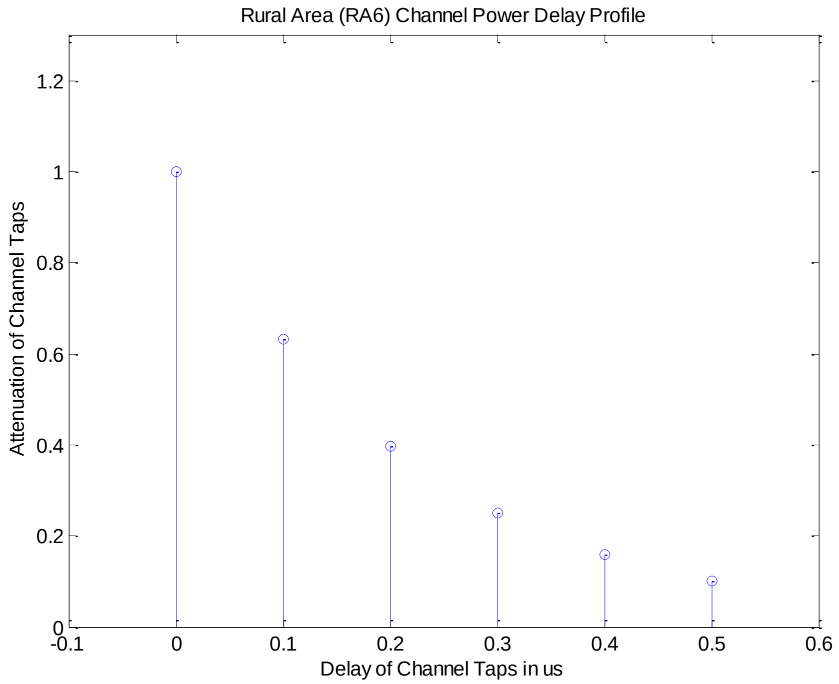


Figure 4.6. Rural Area (RA6) Channel Power Delay Profile

4.2. Simulation of Multipath Fading Channels

There are many methods which are used to simulate multipath fading channels accurately such as Filtered Gaussian Channel, Jakes' Model, etc. Since it is desirable to assess the system performance over all ranges of expected channel conditions, controls of the channel characteristics are essential. For this reason, channel simulators are of interest that is derived from theoretical principles (Stüber 1997).

In this study, Jakes' Model is used as channel simulator and main principles of this method will be explained in next sub-section.

4.2.1. Jakes' Method

Jakes has suggested a very effective channel simulator. The description of this method begins with assumptions of stationarity and equal strength multipath components. In this case, the received complex low-pass envelope is (Stüber 1997);

$$r(t) = \sum_{n=1}^{N} e^{-j(\hat{\phi}_n + 2\pi f_m t \cos\theta_n)}, \tag{4.4}$$

Where

$$\hat{\phi}_n = 2\pi(f_c + f_m)\tau_n. \tag{4.5}$$

Suppose that an isotropic scattering channel is modeled. Then the N components are uniformly distributed in angle (Stüber 1997),

$$\theta_n = \frac{2\pi n}{N},\ n = 1, 2, \ldots, N\,. \tag{4.6}$$

Then equation 4.4 can be rearranged in the form (Stüber 1997)

$$\boldsymbol{r(t)} = \sum_{n=1}^{\frac{N}{2}-1} \left[e^{-j(\hat{\phi}_{-n} + 2\pi f_m t \cos\theta_n)} + e^{j(\hat{\phi}_n + 2\pi f_m t \cos\theta_n)} \right] \ldots + e^{-j(\hat{\phi}_{-N} + 2\pi f_m t)} + e^{j(\hat{\phi}_N + 2\pi f_m t)} \tag{4.7}$$

$$r(t) = \sqrt{2}\sum_{n=1}^{\mathrm{M}} \left[e^{-j(\hat{\phi}_{-n}+2\pi f_m t\cos\theta_n)} + e^{j(\hat{\phi}_n+2\pi f_m t\cos\theta_n)}\right]\ldots + e^{-j(\hat{\phi}_{-N}+2\pi f_m t)} + e^{j(\hat{\phi}_N+2\pi f_m t)} \tag{4.8}$$

Where

$$M = \frac{1}{2}\left(\frac{N}{2} - 1\right). \tag{4.9}$$

After obtaining this, by using some trigonometric identities and further algebra, equation 4.8 can be expressed as (Stüber 1997)

$$r(t) = \sqrt{2}\left\{\begin{aligned}&\left[2\sum_{n=1}^{M}\cos\beta_n\cos 2\pi f_n t + \sqrt{2}\cos\alpha\cos 2\pi f_m t\right] \ldots \\ &+j\left[2\sum_{n=1}^{M}\sin\beta_n\cos 2\pi f_n t + \sqrt{2}\sin\alpha\cos 2\pi f_m t\right]\end{aligned}\right\} \tag{4.10}$$

Where,

$$\alpha = \frac{\hat{\phi}_N - \hat{\phi}_{-N}}{2} \tag{4.11}$$

is an arbitrary phase. From the above development, the Rayleigh fading simulator shown in Figure 4.7 can be constructed. With this simulator, M low-frequency oscillators with frequencies $f_n = f_m cos\left(\frac{2\pi n}{N}\right)$, n = 1, 2… M, where $M = \frac{1}{2}\left(\frac{N}{2} - 1\right)$, and with one oscillator at frequency f_m are used to generate waveforms that are added together to produce $r_I(t)$ and $r_Q(t)$. It follows from the Figure 4.7 that (Stüber 1997)

$$r_I(t) = 2\sum_{n=1}^{M}\cos\beta_n\cos 2\pi f_n t + \sqrt{2}\cos\alpha\cos 2\pi f_m t \tag{4.12}$$

$$r_Q(t) = 2\sum_{n=1}^{M}\sin\beta_n\cos 2\pi f_n t + \sqrt{2}\sin\alpha\cos 2\pi f_m t\ . \tag{4.13}$$

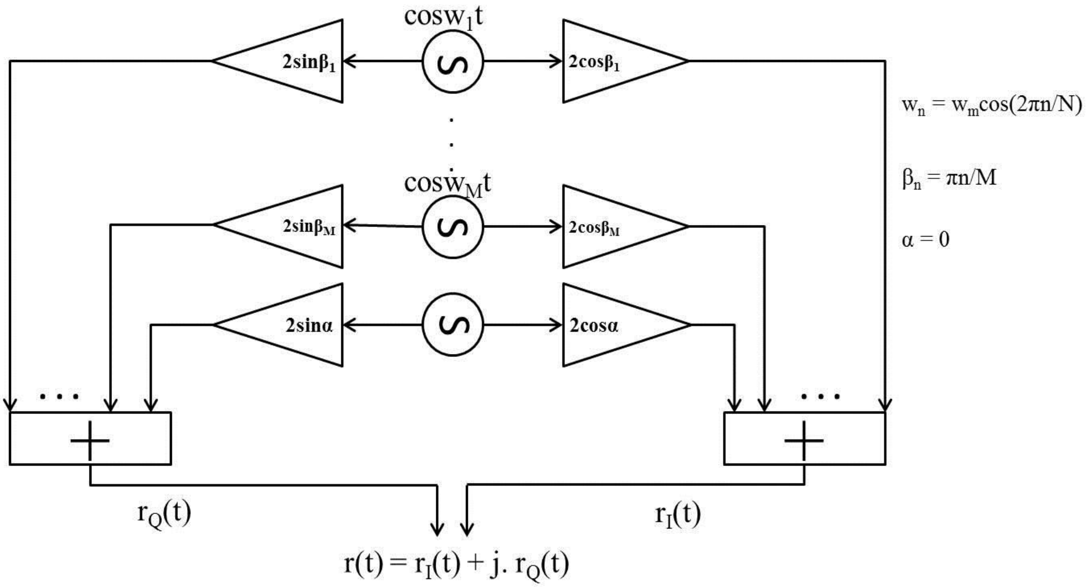


Figure 4.7. Jakes' Rayleigh fading simulator that generates a faded envelope by using a number of low frequencies oscillators (Source: Stüber 1997).

CHAPTER 5

SIMULATED END-TO-END SYSTEM STRUCTURES

DVB-T and DVB-T2 systems have specific transmitter implementations according to their standards (ETSI EN 300 744 2009) and (ETSI EN 302 755 2011). These transmitter structures are explained briefly in chapter 3.

The main problem arises for these standards when trying to implement a receiver. Because there is no specific configuration for both systems and they are available for adding some extra blocks or reversely removing some parts.

For this purpose, to show the way to the designers of DVB systems, DVB organization published documents with name “Implementation Guideline” for all their systems such as DVB-T, DVB-T2, DVB-S2 and etc. (ETSI EN 300 744 2009) (ETSI EN 302 755 2011) (ETSI EN 302 307 2009) In these documents, there is not a specific configuration about receiver, there are ideas and some alternative designs about the systems.

In this study, two different end-to-end systems are designed according to the principles in standards and these systems are implemented by using the technical computing program Matlab®.

When implementing the systems, in the name of simplicity, just the main parts of the systems are selected as the core systems.

In this chapter, implemented end-to-end system structures will be explained and given some extra information about how they are simulated on computer.

5.1. DVB-T System

The main blocks of DVB-T transmitter are explained in chapter 3. In this sub-section, simulated transmitter and receiver structures of DVB-T and object oriented coded Matlab® instructions will be explained. The simulated end-to-end DVB-T system block diagram is illustrated in Figure 5.1.

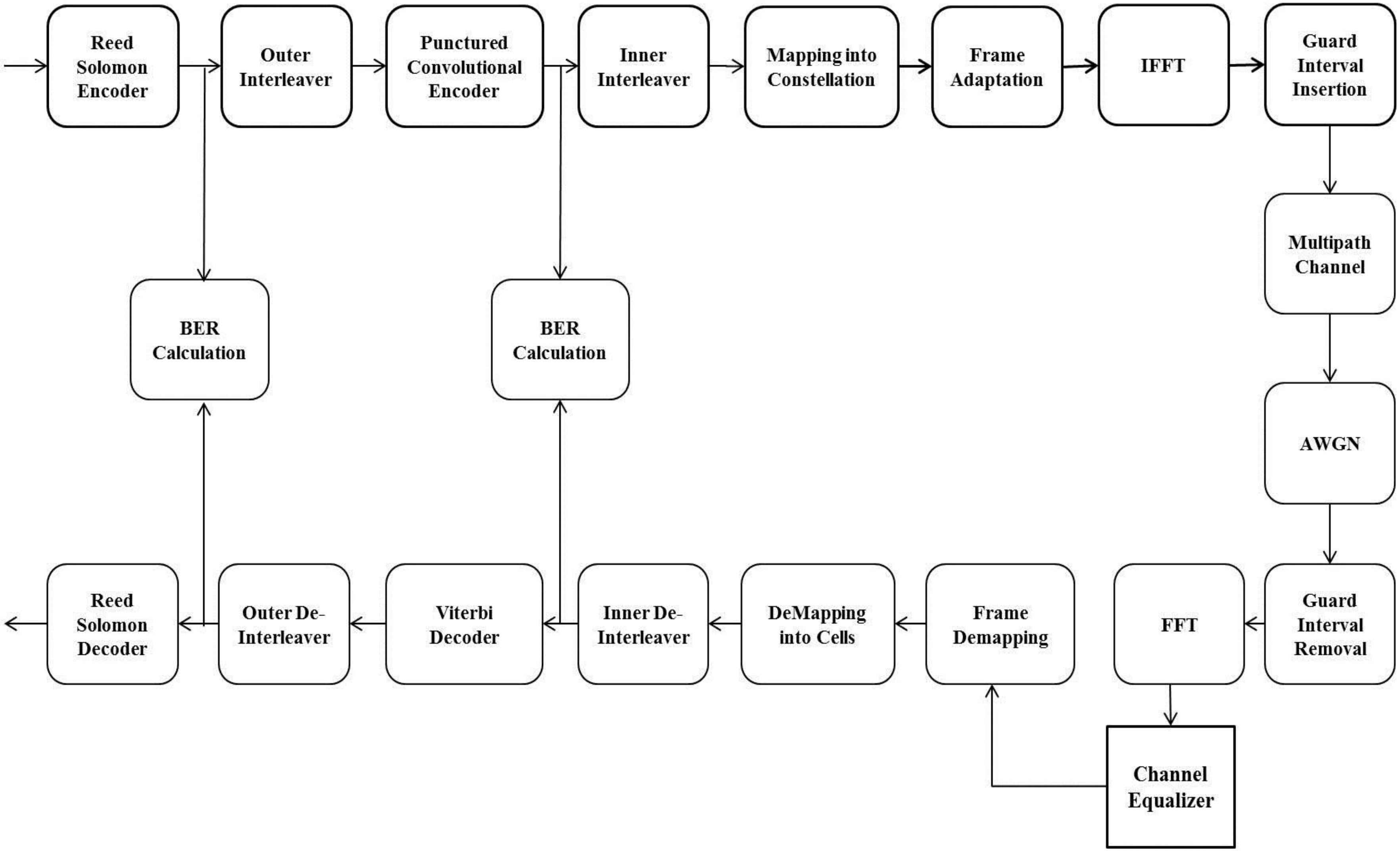


Figure 5.1. DVB-T Simulated End-to-End System Block Diagram

5.1.1. Outer Encoder/Decoder

Encoder block of DVB-T system is implemented by constructing a class whose name is “OKY_DVBT_RS_Enc”. This class has some properties and member functions with its original constructor function. When creating an OKY_DVBT_RS_Enc class object, constructor is automatically called and creates an empty vector whose name is “RS_Coded_Data”. The encoding part is happening when “process” function is called.

The codification procedure of input data which is coded in function “process” is explained below;

- The hexadecimal input is divided into parts whose length is equal to shortened uncoded length of encoder which is 188.
- Zeros of length 51 bytes is prepended to every part to obtain original uncoded message length of 239.
- By using Matlab built-in function “gf” data vector is converted into Galois Fields.
- By using Matlab built-in function “rsenc”, these Galois Fields are encoded and the encoded data with length 255 is obtained.
- Prepended zeros removed and 204 bytes encoded data is obtained at the output of the function.

This procedure is applied every subpart with length 188 bytes, so at the output it’s obtained an integer number of Reed-Solomon packets with length 204 bytes.

At the decoder part, a class whose name is “OKY_RS_Decoder” is constructed. The codification procedure is applied in reverse order in this class. To decode the Galois Fields, Matlab built-in function “rsdec” is used.

The list of used Matlab built-in function in this process is below;

- hex2dec()
- dec2hex()
- reshape()
- size()

5.1.2. Outer Interleaver/Deinterleaver

Outer Interleaving stage of DVB-T system is implemented by constructing a class whose name is “OKY_DVBT_Outer_Interleaver”. This class has some properties and member functions with its original constructor function. When creating an OKY_DVBT_Outer_Interleaver class object, constructor is automatically called and creates an empty vector whose name is “Outer_Interleaver_out”. This class is also has a member function named “process” to succeed interleaving procedure. This procedure is;

- The input for the systems is an integer number of RS-coded data with length 204 bytes.
- A matrix with size of 12x17 is constructed.
- Every 204 byte input data, written serially to this matrix column-wise.
- After written process, the output data is read from this matrix row-wise.

The De-Interleaver procedure is implemented by constructing a class whose name is “OKY_DVBT_Outer_DeInterleaver”. In this class, interleaver process is applied in reverse order.

5.1.3. Inner Encoder/Decoder

Inner Encoder stage of DVB-T system is implemented by constructing a class whose name is “OKY_DVBT_Conv_Enc”. This class has some properties and member functions with its original constructor function.

When creating an OKY_DVBT_Conv_Enc class object, constructor is automatically called and creates an empty vector whose name is “Conv_Coded_Data”, puncturing patterns changes according to code rate value and generator polynomials of mother convolutional encoder in octal form.

This class is also has a member function named “process” to succeed the encoding procedure. This procedure is;

- Because this process is a bit-wise process, first of all, the input hexadecimal data is converted into bits by using “hex2bit” function which is created when designing this class.

- After obtaining a vector that consists of bits, by using Matlab built-in function “poly2trellis” trellis pattern of encoder object is obtained. This function uses generator polynomials and constraint length of encoder when creates trellis patterns.
- By using this obtained trellis pattern and puncturing pattern as its inputs, Matlab’s built-in function “convenc” creates punctured and encoded data, as its output.

At decoder side of the system, the same procedures are applied in reverse order. A class whose name is “OKY_Viterbi_Decoder2” is constructed. By using the same trellis pattern, Matlab built-in function “vitdec” is used to decode the data. In this study, in the name of simplicity, “Hard-Decision Decoding” concepts are used.

5.1.4. Inner Interleaver/Deinterleaver

Inner Interleaver stage of DVB-T system is implemented by constructing a class whose name is “OKY_DVBT_Inner_Interleaver”. This class has some properties and member functions with its original constructor function. Demultiplexing of coded bits into sub-streams is also succeeded in this class.

When creating an OKY_DVBT_Inner_Interleaver class object, constructor is automatically called and creates an empty vector whose name is “Inner_Int_out”. Demultiplexing indexes changes according to modulation type and sub-stream numbers.

This class is also has a member function named “II_process” to succeed interleaving procedure. This procedure is;

- First of all, the permutation functions, $H_e(w), R_i', R_i and\ H(q)$ which are used in both Bit-wise and Symbol interleaving processes obtained according to the algorithms which are given in standard’s page from 18 to 21 in section 4.3.4.
- The input data is demultiplexed into v sub-streams according to the demultiplexing patterns which are defined in constructor.
- By using permutation function $H_e(w)$, and demultiplexed data, Bit-Wise Interleaving is applied.

- By using other permutation functions $R'_i, R_i and\ H(q)$, Symbol interleaving process is applied

At the Deinterleaver side, this two interleaving parts are applied in reverse order in a class whose name is “OKY_DVBT_Inner_DeInterleaver2” by using “IdeI_process” member function of this class. The list of used Matlab built-in function in this process is below;

- strcmp()
- xor()
- mod()
- sum()
- floor()
- log2()

5.2. DVB-T2 System

The main blocks of DVB-T2 transmitter are explained in 3 groups in chapter 3. In this subsection, simulated transmitter and receiver structures of DVB-T2 and object oriented coded Matlab® instructions will be explained. The simulated end-to-end DVB-T2 system block diagram is illustrated in Figure 5.2.

5.2.1. BCH Encoding/Decoding

In DVB-T2 systems, BCH Encoder is used as outer encoder whose main principles are explained in chapter 3. In this study, a class whose name is “OKY_DVBT2_BCH_Enc2” is created for encoding process. When this class' constructor is called, all the encoding processes are applied in it. So encoding procedure is;

- The applied BCH code is the same for all the code rates and frame type.
- First of all, zeros are prepended to the input data to obtain coded data length of 65535 bits.

- By using zero added data length and 65535, Matlab's built-in class structured function "fec.bchenc" is constructed an object with properties of BCH encoding.
- By using Matlab function "encode" encoding process is succeed and added zeros are removed from BCH encoded data.

Decoder side is the same with other blocks. The encoding process is applied in reverse order in a class whose name is "OKY_DVBT2_BCH_Decoder" with specified Matlab functions "fec.bchdec" and "decode".

5.2.2. LDPC Encoding/Decoding

In DVB-T2 systems, LDPC Encoder is used as inner encoder whose main principles are explained in chapter 3. A class whose name is "OKY_DVBT2_LDPC_Enc2" is created for encoding process. When this class's constructor is called, all the encoding processes are applied in it. So the encoding procedure is;

- In Matlab, there is a built-in function named "dvbs2ldpc" which is designed for specifically DVB-S2 LDPC encoding process. By using this function whose input is code rate value, the parity-check matrix of LDPC code is obtained. This parity-check matrix is a sparse logical matrix.
- By using parity-check matrix as input of Matlab built-in structured class function "fec.ldpcenc" an encoder object is obtained.
- The LDPC output is obtained by using Matlab's "encode" function.

Decoder side is the same with other blocks. The encoding process is applied in reverse order in a class whose name is "OKY_DVBT2_LDPC_Decoder" with specified Matlab functions "fec.ldpcdec" and "decode". For the decoder input either Hard-Decision or Soft-Decision outputs of Demapping block can be used.

5.2.3. Cell-Time Interleaver/Deinterleaver

DVB-T2 systems have 2 cascaded interleaving blocks which are described in chapter 3. These blocks are Cell and Time interleaving blocks respectively.

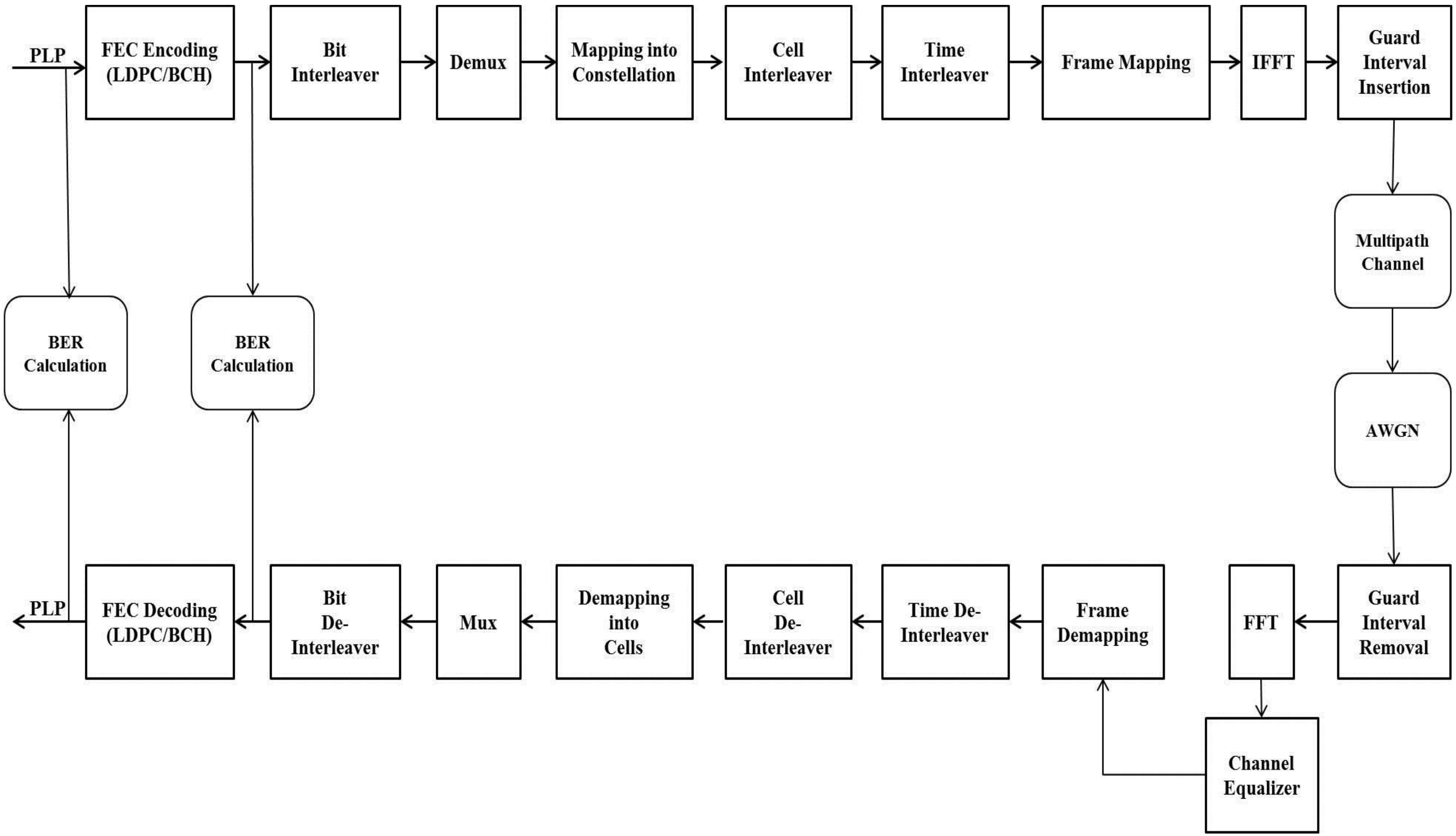


Figure 5.2. DVB-T2 Simulated End-to-End System Block Diagram

In simulations these blocks are implemented in a class whose name is “OKY_DVBT2_Interleaving”. This class has 6 member functions except its constructor. By using these 7 functions, both of the interleaving blocks are simulated. These functions are;

- OKY_DVBT2_Interleaving() → Important parameters which are used in all functions are set in this main function.
- Set_S(), Set_L0(), Set_Pr() → By using these functions, some important sequences and functions which are used in Cell Interleaving block are defined.
- CI_process() → Cell Interleaver procedure is applied in this function.
- TI_process() → Time interleaver procedure is applied in this function.
- process() → This function is used all the functions above to succeed Cascaded Interleaving process.

In receiver, Cell and Time Deinterleaving are succeeded by applying this procedure in reverse order. By doing this, “OKY_DVBT2_DeInterleaving” class is created and all the sub-functions run in this class.

5.3. Common Blocks

Some processes are same for the both system. In this sub-section, these common blocks will be explained.

5.3.1. Mapper/Demapper

Mapper blocks of DVB-T and DVB-T2 systems work with the same purpose. The main difference between them is DVB-T2 has extra 256QAM modulation type.

For the both system, Mapper is implemented by constructing classes whose names are “OKY_DVBT_Const_Mapping2” and “OKY_DVBT2_Mapping_Const2”. These classes have some properties and member functions with their original constructor functions.

When creating an OKY_DVBT_Const_Mapping2 class object, constructor is automatically called and creates an empty vector whose name is “Y_mapped” and mapping parameters. When creating an OKY_DVBT2_Mapping_Const2 class object, constructor creates an empty vector whose name is “Const_out” and mapping parameters

According to modulation type, by using Matlab built-in class structures’ function of “modem.qammod”, the simulation environment which is the same as the facts which are explained in chapter 3 is defined.

These classes also have a member function named “process” to succeed interleaving procedure. This procedure is;

- In constructor of the class, the modulating parameters are defined and according to these parameters, a modulation object of modem.qammod class is constructed.
- By using modulation object and inner interleaved data as inputs of Matlab’s built-in function “modulate”, mapping of input bits into output modulation symbol.
- Modulation symbols are normalized according to the values in table 3.5.

In receiver, Demapping procedures are the same for both systems except one difference. DVB-T system in this study is designed to work just for Hard-Decision data and the corresponding Demapper is designed according to this concept. In DVB-T2 system, decoders can use either Hard-Decision or Soft-Decision data. The simulations are run in the classes QAM_DeMapping2 and T2_QAM_DeMapping for the systems respectively DVB-T and DVB-T2 by the help of Matlab built-in functions “modem.qamdemod” and “demodulate”.

5.3.2. OFDM Modulation/Demodulation

OFDM is maybe the most important common ground of both systems. These concepts are explained deeply in chapter2 and transmitted signal structures for both systems are given chapter 3.

According to this information, it’s known that OFDM procedure can be obtained by applying Fast Fourier Transform (FFT) and Inverse FFT (IFFT) to the input signal with appropriate FFT length.

In simulations two different Matlab functions are used for this purpose. These functions are “ifft(x)” and “fft(x)”. Zeros added to the input data to obtain FFT length data. Outputs of these functions are multiplied and divided by a specific number to obtain the total signal energy is equal to 1.

5.3.3. AWGN Channel

AWGN is added to the transmitted signal according to the Signal to Noise Ratio (SNR) value. Matlab built in function “awgn” is used for this purpose. This function uses SNR value in dBs, transmitted data and AWGN option as its inputs. AWGN option is used as ‘measured’. This means that, function first of all measures the power of input data and according to this value and SNR value, then it calculates the noise variance. By using this calculated noise variance, functions create a normally distributed random number with zero mean and add this number to the symbol.

5.3.4. Multipath Channel

Multipath channel effect for both systems is applied with the same class whose name is “Multipath_Channel_Model”.

This class constructs complex channel impulse response from chosen channel’s power, delay, phase and Doppler frequency parameters by using the theory which is explained in chapter 4.

By performing fft of this complex impulse response, Frequency response of the chosen channel is obtained. This Frequency response is used to equalize the channel. (See 5.3.5)

Sample number representation of the tap delays can be calculated from the division of tap delays in seconds to the input sample period.

In this part, it’s generated a single fading coefficient with the “sum of sinusoids” concepts. Jakes model has 32 oscillators according to the design. So this generates 140 incident waves for each fading coefficients. (See 4.2.1)

5.3.5. Channel Estimation

There are many channel estimations techniques which can be used in DVB-T and DVB-T2 systems such as Least Squares (LS) Method, Minimum Mean Square Error (MMSE) Method and etc. but in the name of simplicity, in this study Perfect Channel Estimation concept is used.

One of the most important rules in theory says that "The convolution in time domain is equal to multiplication in frequency domain".

$$y(t) = x(t) \circledast h(t) + \mathrm{n(t)} \xleftrightarrow{Fourier\ Transform} Y(j\Omega) = X(j\Omega).H(j\Omega) + N(j\Omega) \quad (5.1)$$

Where y is received signal, x is transmitted signal, h is channel impulse response and n is the additive noise.

According to this rule, in perfect channel estimation, the channel equalized signal is obtained as the OFDM demodulated signal is divided directly by the FFT of channel impulse response.

CHAPTER 6

SIMULATION AND RESULTS

This chapter includes the main purpose of this study. Simulated system performance results will be given both on tables and on Figures. In this chapter, also a comparison between DVB-T and DVB-T2 will be performed according to the changing effects of seven different channels.

6.1. Simulation Properties & Interfaces

The DVB-T & DVB-T2 Simulation v1.0 offers a simulation of European Digital Terrestrial Television Broadcasting Standards by selecting their most important parameters such as code rate, modulation type etc. In the name of simplicity, the GUIs are designed to be user-friendly. There are three main interfaces. First one is Main Menu.

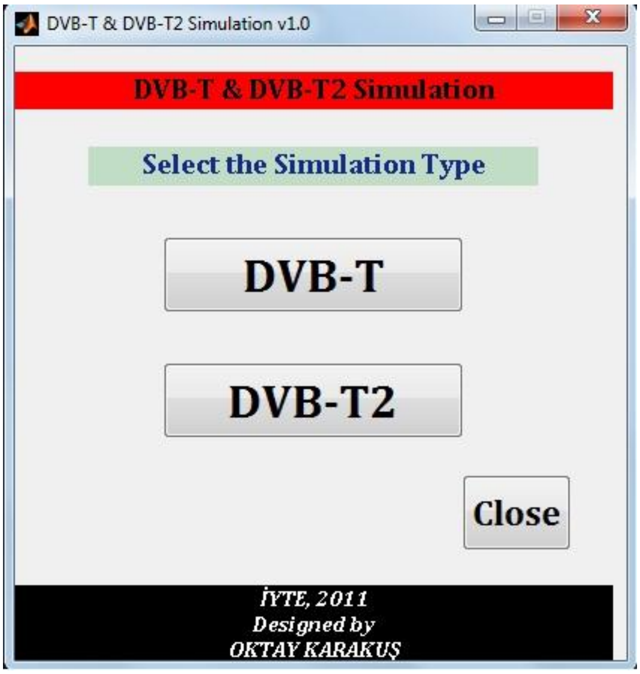


Figure 6.1. Simulation Main Menu

In addition to main menu, DVB-T and DVB-T2 main menus are designed and given in Figures 6.2 and 6.3.

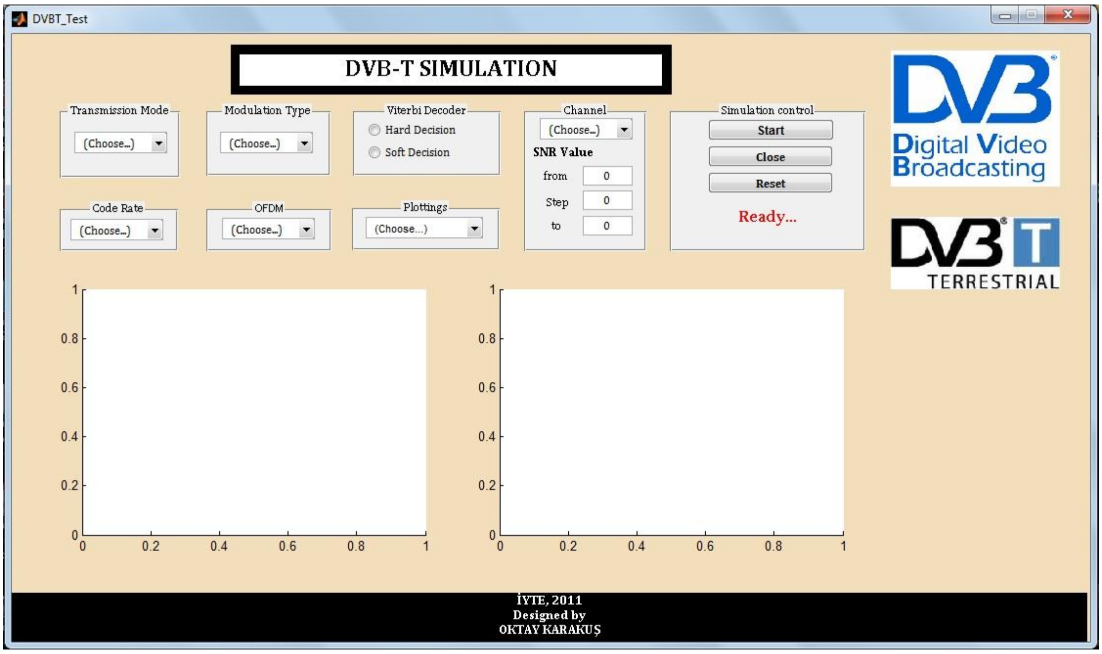


Figure 6.2. DVB-T Main Menu

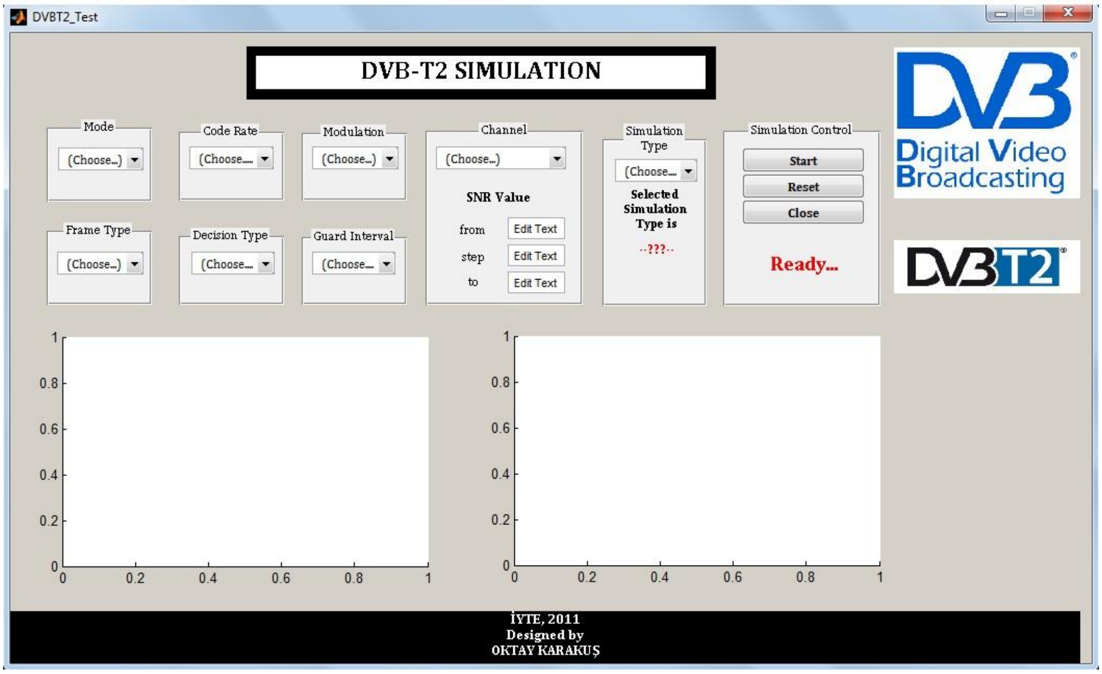


Figure 6.3. DVB-T2 Main Menu

By the help of main menu, user can select the desired simulation platform or can close the main menu window by clicking the Close Button.

In simulation sub-menus, user can select the important parameters of simulation and starts the simulation. There designed two different simulation options which are;

- BER vs. SNR
- Required C/N for Target BER

6.1.1. BER vs. SNR

This simulation option offers two Bit Error Rate vs. Signal-to-Noise Ratio (BER vs. SNR) curves for selected parameters. User can select parameters by using related parameter menus. After selecting parameters, by using simulation control buttons, simulation will be started. Close button closes simulation window and Reset button clears the graphic axes which are located in the window. There are two example screenshots for both systems in Figures 6.4 and 6.5.

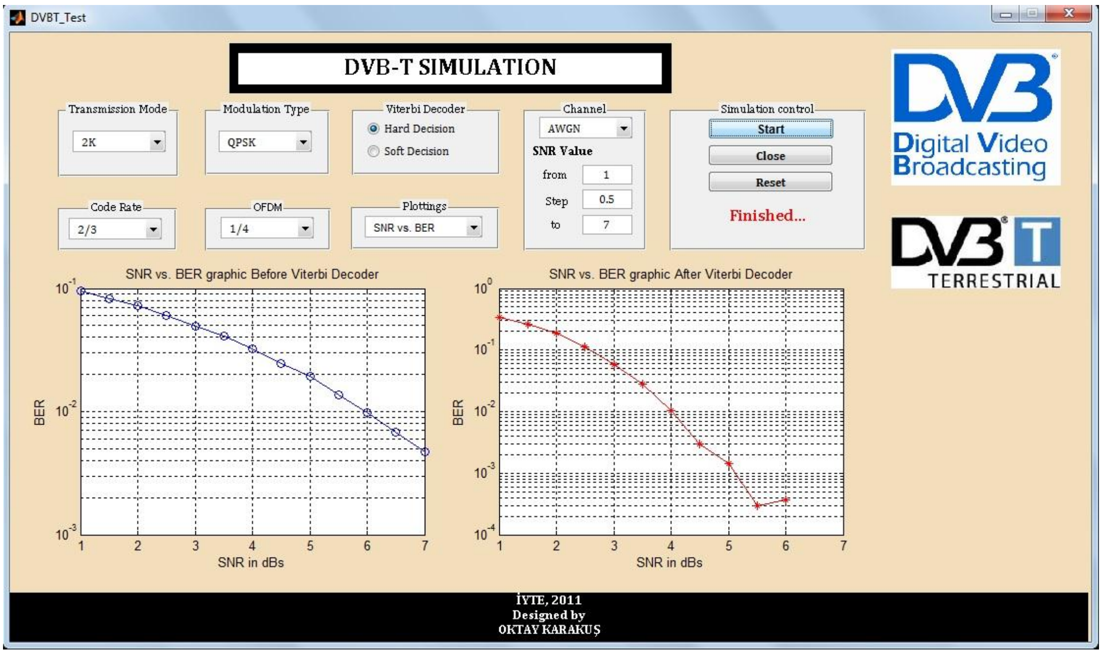


Figure 6.4. DVB-T Simulation Option 1

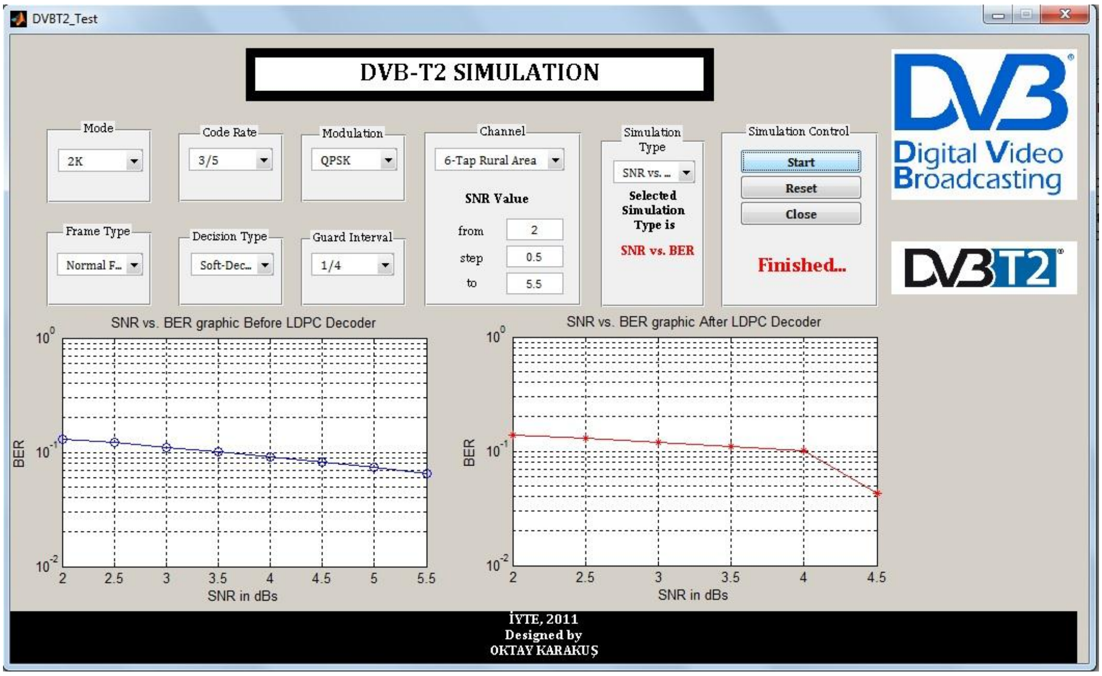


Figure 6.5. DVB-T2 Simulation Option 1

6.1.2. Required C/N for Target BER

This simulation option offers required C/N value in dBs for selected parameters of selected DVB system. The parameters of the simulation are selected by using the same interface which is given in Figure 6.2 and 6.3. In this simulation option just one of the two axes is used for plotting the transmitted signal spectrum. Another axis is not used for this option. Two examples for both systems are given in Figures 6.6 and 6.8.

The resulting C/N value in dBs is declared to the user with a dialog box appeared when the simulation finishes. In this dialog box, there are also selected important systems parameters which are Code Rate value of inner encoder, Modulation type and selected channel type for the environment. Two examples of these dialog boxes for both systems are given in Figure 6.7 and 6.9.

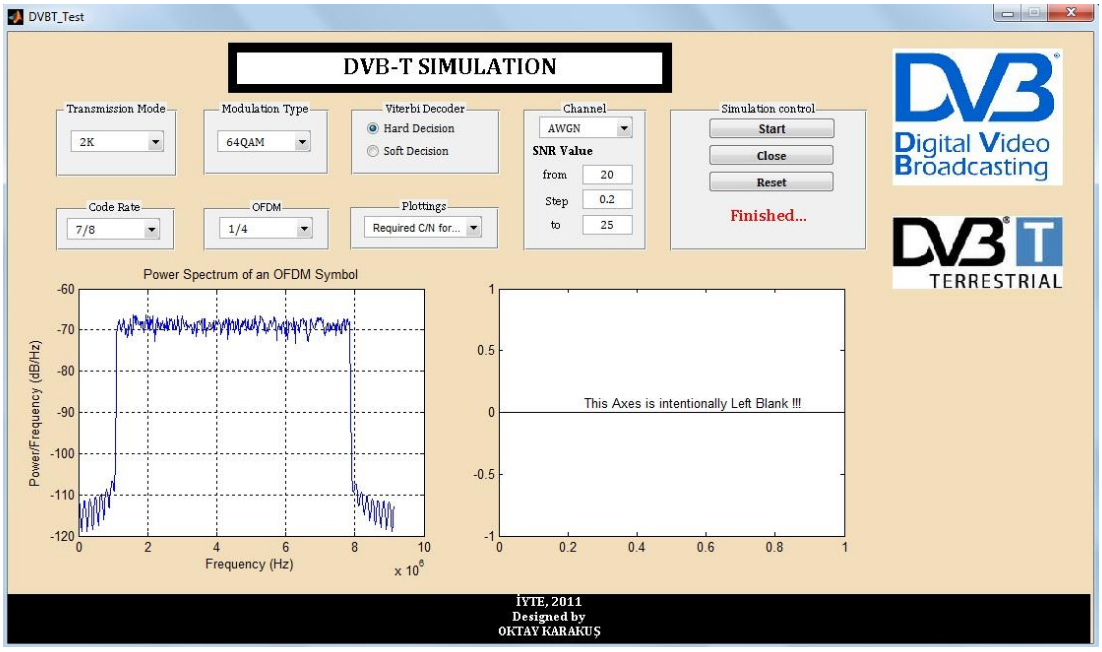


Figure 6.6. DVB-T Simulation Option 2

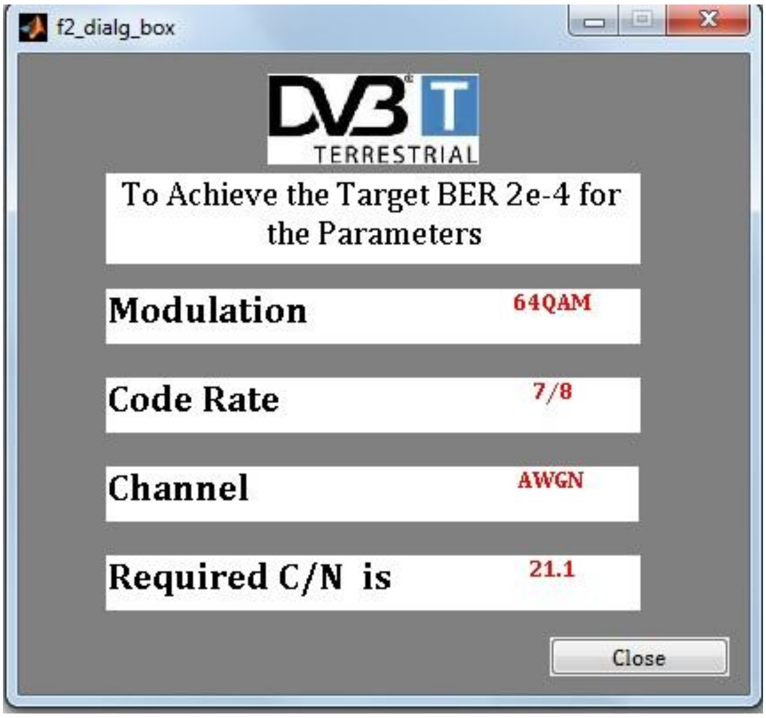


Figure 6.7. DVB-T Simulation Option 2 Dialog Box

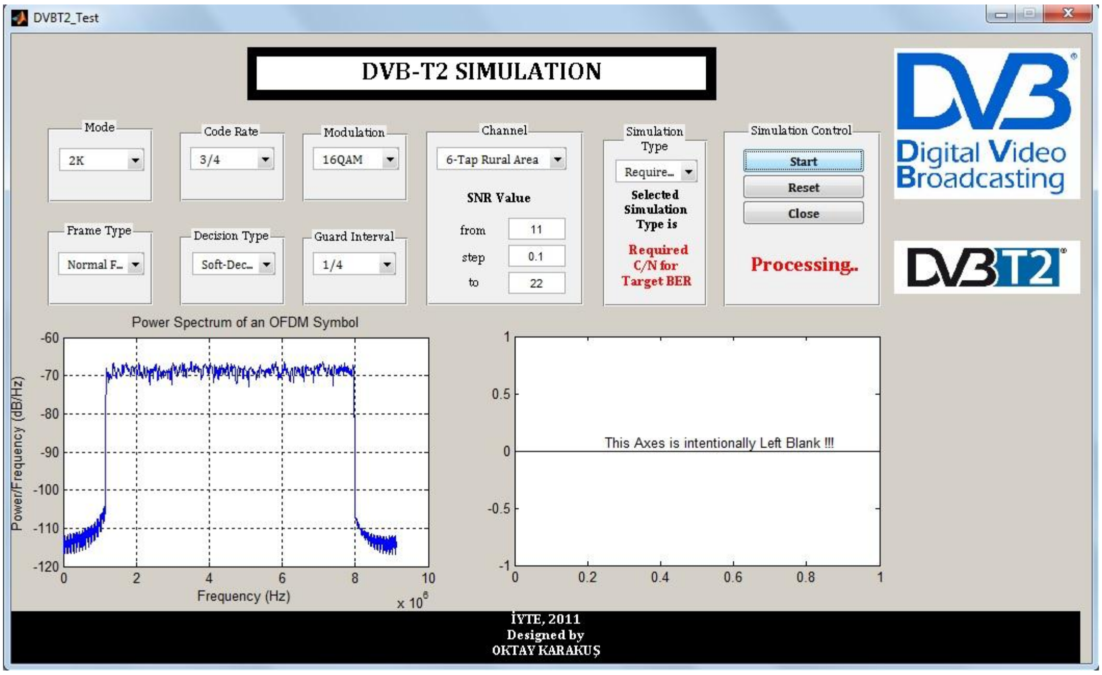


Figure 6.8. DVB-T Simulation Option 2

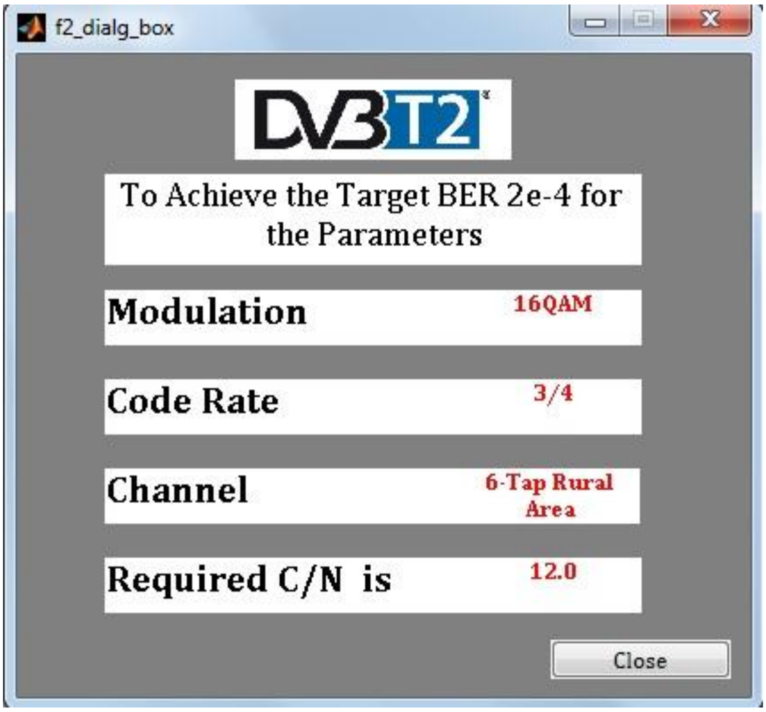


Figure 6.9. DVB-T Simulation Option 2

6.2. Log-Files

If simulation option 1 “BER vs. SNR” is selected, the related values of the simulation which are drawn into the both figures are written and saved in a text file. This log-file is named as “LogFile_DATE_TIME”. The formats for data and time are;

- Date Format → dd-mm-yyyy
- Time Format → hh-mm

An example log-file is given in Appendix A whose name is “LogFile_04-11-2011_17-02.txt”.

6.3. Simulation Environment

As indicated in the sections above, there are many different parameters of both systems. Some of these are common and some of these are distinct. In the name of simplicity, it’s created a simulation environment from these parameters. In this environment, some of the parameters are always taken the same and these parameters’ effects are not mentioned in this study. By changing some parameters, systems’ performance is simulated. There will be given this simulation environment below.

Common Parameters;

- Transmission Mode → 2K
- Transmission Type → SISO
- Channel Bandwidth → 8 MHz
- Channel Estimation → Perfect
- Synchronization → Perfect
- Guard Interval → ¼
- Channel Model → Jakes Model
- Jakes Model Oscillator Number → 32
- Doppler Frequency → 20 Hz
- Target BER after Inner Encoders → $2x10^{-4}$
- Target BER after Outer Encoders → 0

Specific DVB-T Parameters;

- Viterbi Decoder Traceback Length → 136

- Viterbi Decoder Decision Type → Hard Decision

Specific DVB-T2 Parameters;

- Frame Type/Length → Normal/64800 bits
- LDPC Decoder Decision Type → Hard Decision
- Unused Modulation Type → 256 QAM.

6.4. Comparison Results

DVB-T and DVB-T2 systems and simulation environment are explained in previous sections. As indicated in this study, main purpose is to measure the performance of both systems under the effects of different channel models. In this section the theoretical comparison and simulated comparison values will be given.

6.4.1. Theoretical Comparison

Before introducing the simulation results, as it's told in previous chapters, DVB-T and DVB-T2 use the same processes in some cases. But as might be expected, DVB-T2 has some additional features and new systems than DVB-T. DVB-T2 can offer a much higher data rate than DVB-T or a much more robust signal. For comparison, the last two rows of the table show the maximum data rate at a fixed C/N ratio and the required C/N ratio at a fixed useful data rate.

Table 6.1. DVB-T vs. DVB-T2
(Source: ETSI DVB Fact Sheet 2011)

	DVB-T	**DVB-T2 (new/improved options are bold)**
FEC	Convolutional Encoding + Reed-Solomon 1/2, 2/3, 3/4, 5/6, 7/8	LDPC + BCH Encoding 1/2, **3/5**, 2/3, 3/4, **4/5**, 5/6
Modulations	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 Modes	2K, 8K	**1K**, 2K, **4K**, 8K, **16K**, **32K**
Scattered Pilots	8% of Total	**1%**, **2%**, **4%**, 8% of Total
Continual Pilots	2.6% of Total	**0.35%** of Total
Typical Data Rate (UK)	24 MBits/s	**40 MBits/s**
Max. Data Rate (@20 dB C/N)	29MBits/2	**47.8 MBits/s**
Required C/N Ratio (@ 22MBits/s)	16.7 dB	**8.9 dB**

6.4.2. Simulation Results

6.4.2.1. BER vs. SNR Results

In this section, a comparison will be performed on SNR-BER curves whose values are found according to the simulation option one. These values are combined and plotted on a figure for each combination of parameters. Only the common values are used for Modulation Type and Code Rate. These common values are;

- Modulation → QPSK, 16QAM, 64QAM
- Code Rate → 1/2, 2/3, 3/4, 5/6

Twelve figures are selected for this comparison each simulated in one channel type which is selected randomly from the seven simulation channels and given in Figures from 6.10 to 6.21.

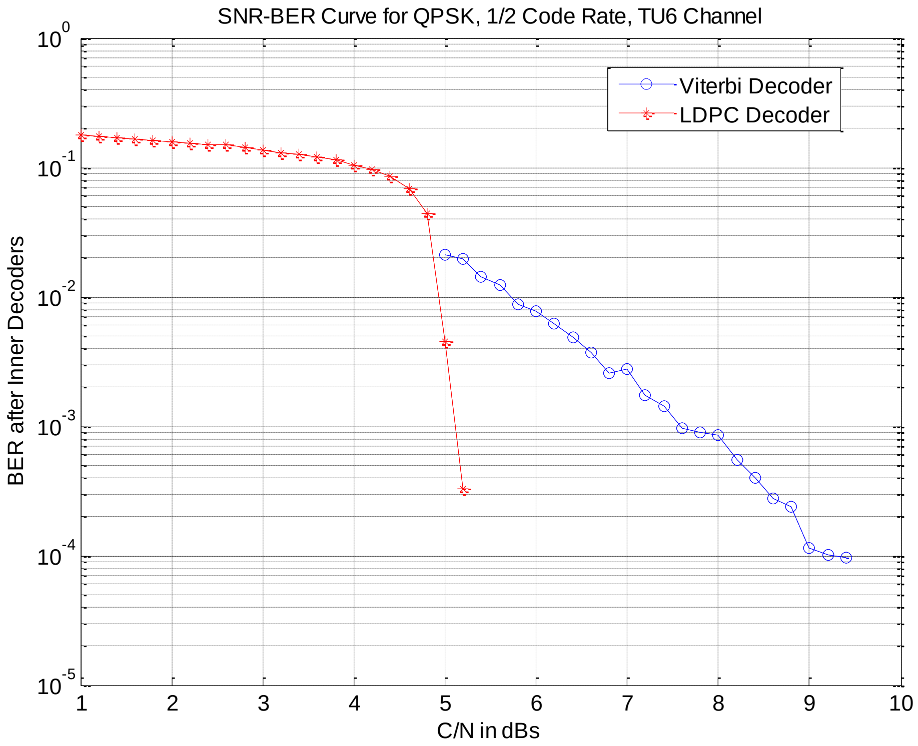


Figure 6.10. BER vs. SNR – 1

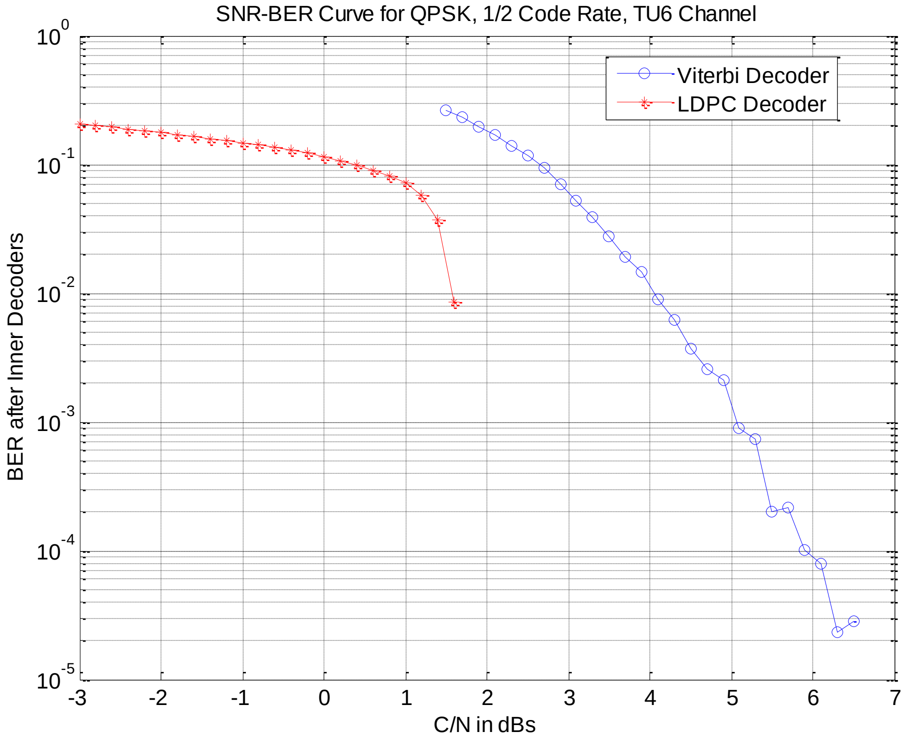


Figure 6.11. BER vs. SNR – 2

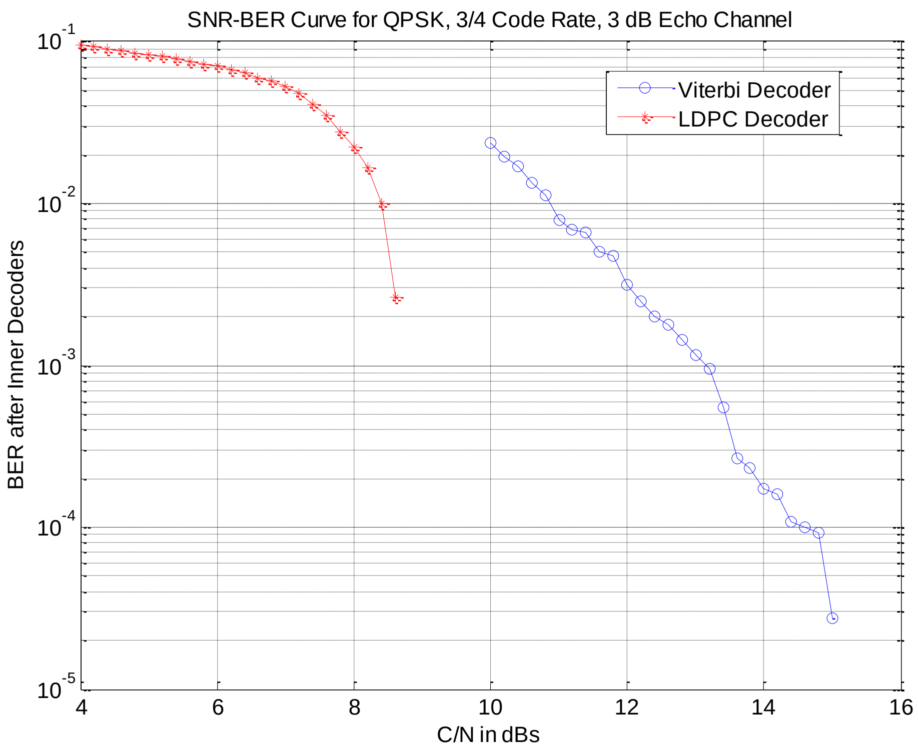


Figure 6.12. BER vs. SNR – 3

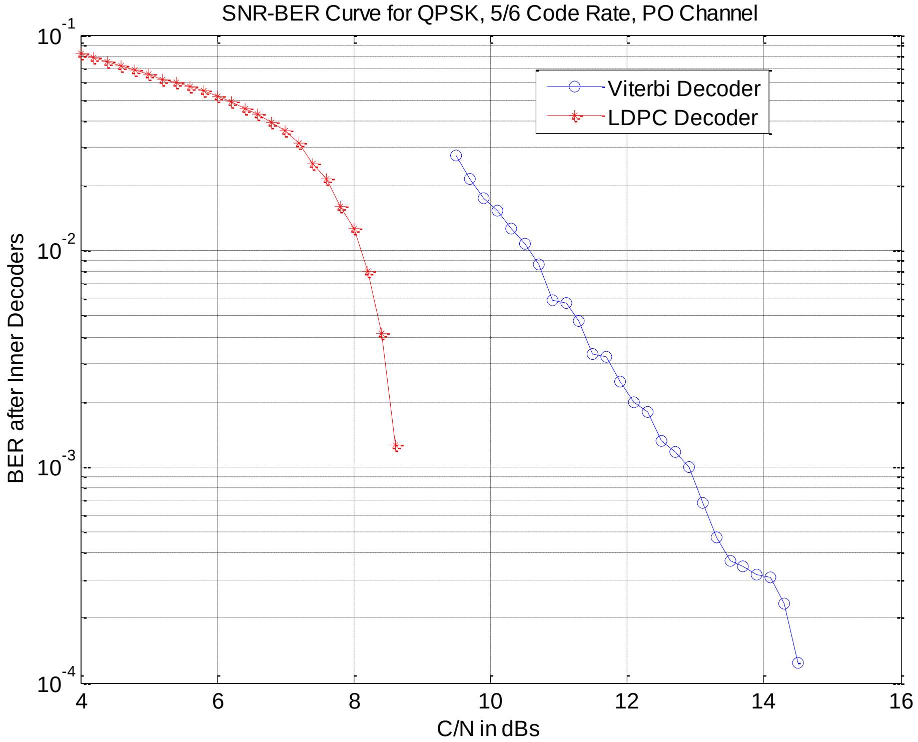


Figure 6.13. BER vs. SNR – 4

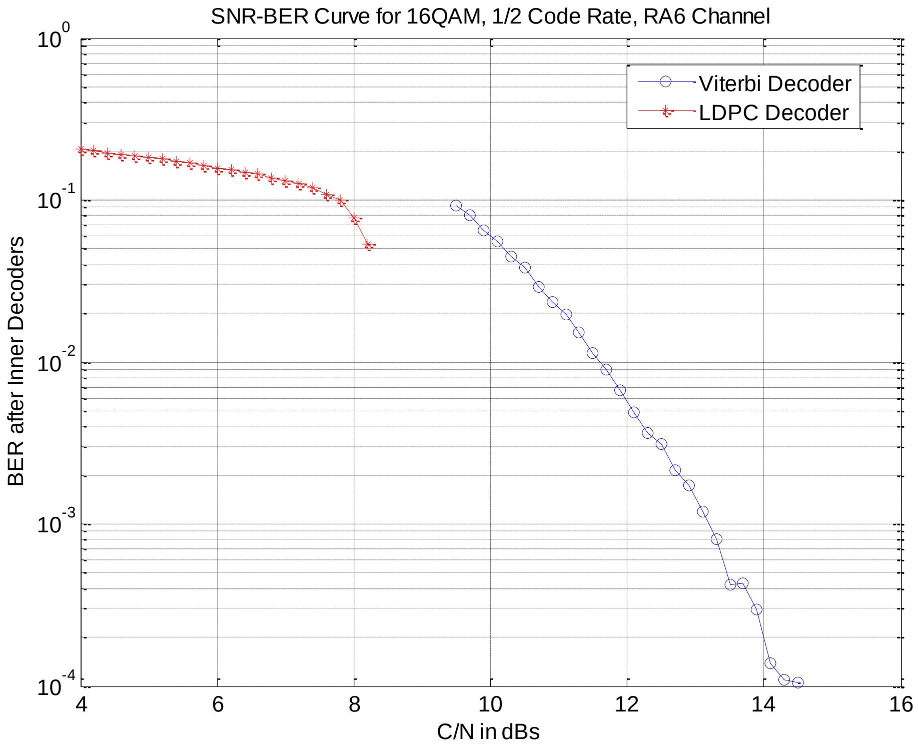


Figure 6.14. BER vs. SNR – 5

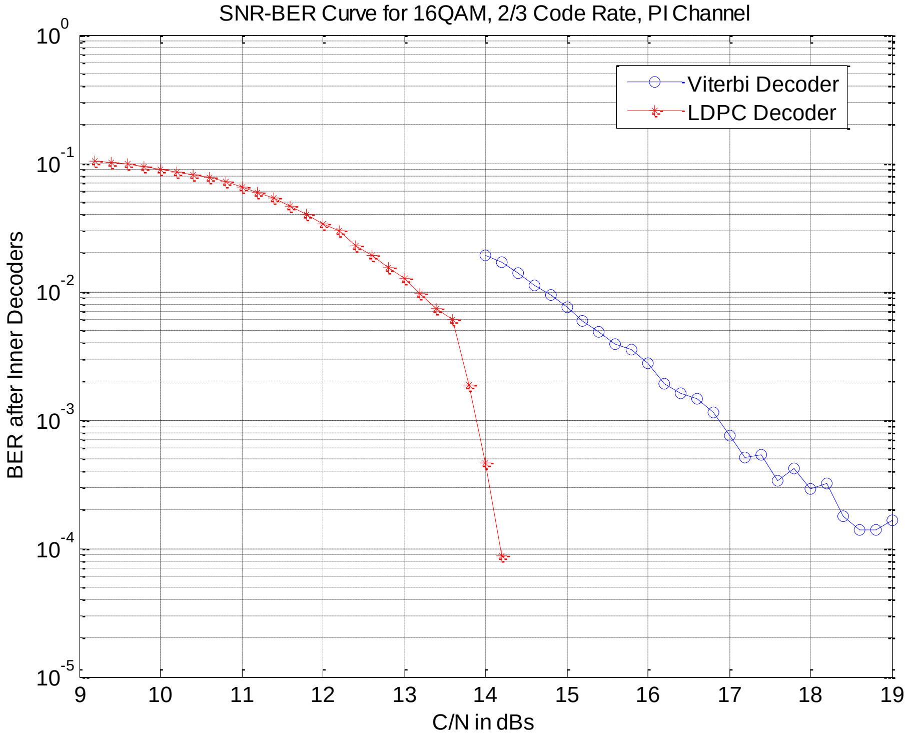


Figure 6.15. BER vs. SNR – 6

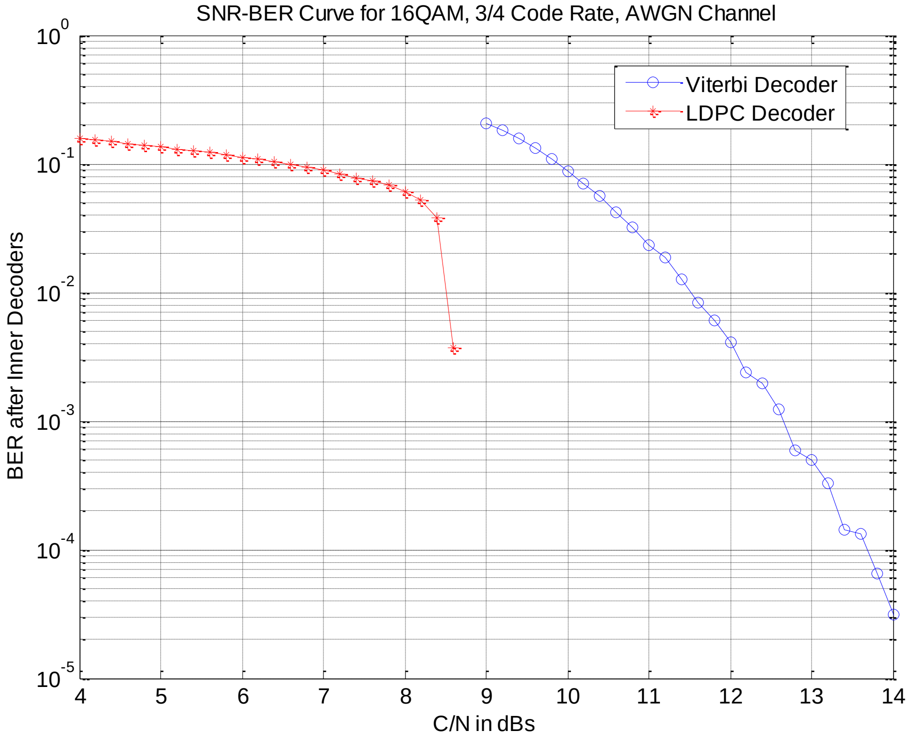


Figure 6.16. BER vs. SNR – 7

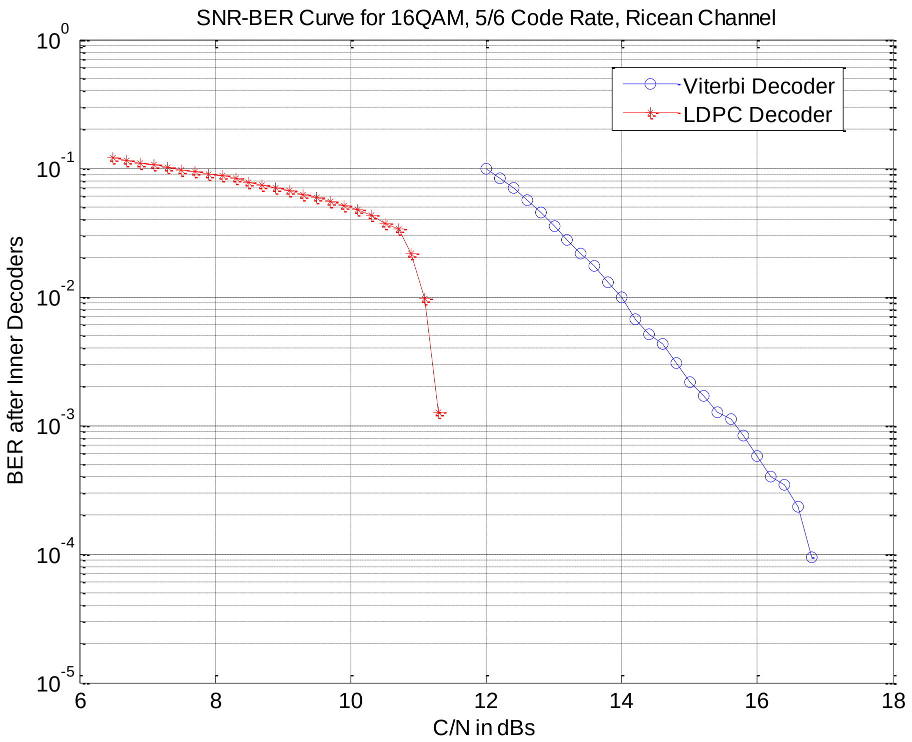


Figure 6.17. BER vs. SNR – 8

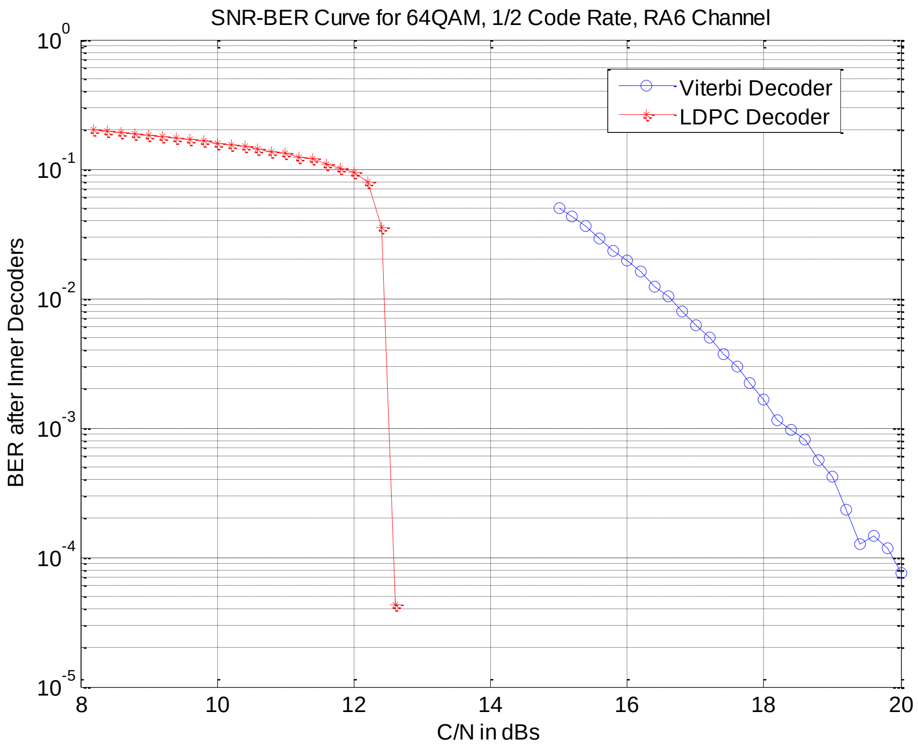


Figure 6.18. BER vs. SNR – 9

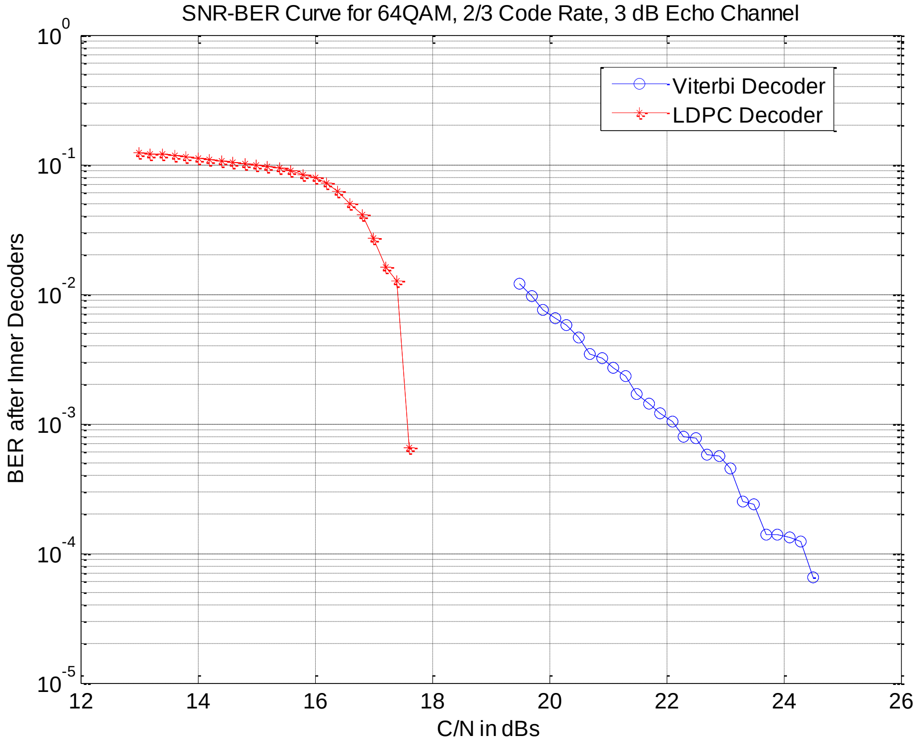


Figure 6.19. BER vs. SNR – 10

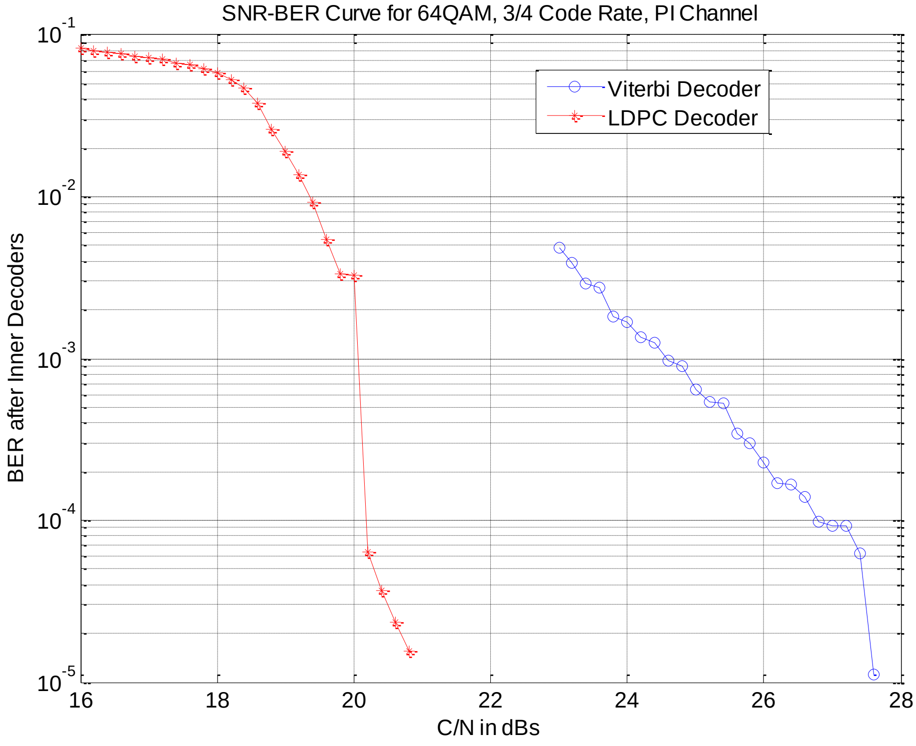


Figure 6.20. BER vs. SNR – 11

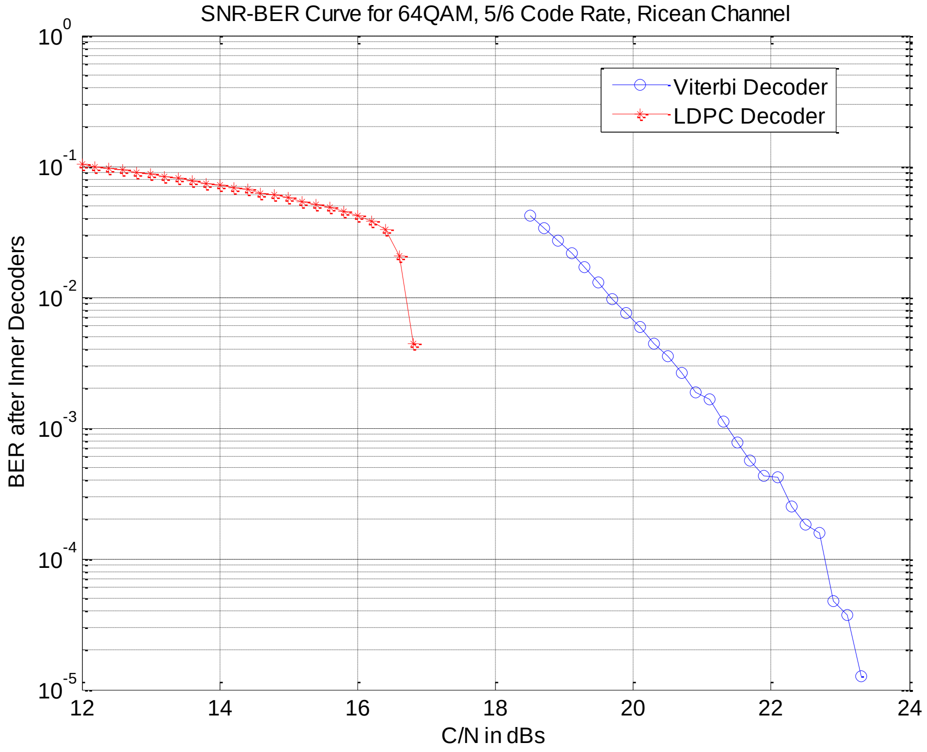


Figure 6.21. BER vs. SNR – 12

6.4.2.2. Required C/N Values Results

In this section, a comparison will be performed according to the required C/N values which are found according to the simulation option two for Target BER 2.10^{-4}. These values are combined and written on a table for each simulation channels.

In addition to the tables, also seven figures plotted for comparison. First four figures (Figure 6.22-6.25) give Required C/N values in figures. Other three figures (Figure 6.26-6.24) give comparison results for DVB-T's gain in dBs. Only the common values are used for Modulation Type and Code Rate. These common values are;

- Modulation → QPSK, 16QAM, 64QAM
- Code Rate → 1/2, 2/3, 3/4, 5/6

Seven different tables are drawn with simulated values are given in tables below.

Table 6.2. DVB-T vs. DVB-T2 under the effects of AWGN Channel

AWGN Channel Comparison in C/N dBs			
Modulation	**Code Rate**	**DVB-T**	**DVB-T2**
QPSK	**1/2**	*4.1*	*-0.4*
QPSK	**3/5**	---	*0.8*
QPSK	**2/3**	*5.7*	*1.7*
QPSK	**3/4**	*6.8*	*2.6*
QPSK	**4/5**	---	*3.3*
QPSK	**5/6**	*7.9*	*3.8*
QPSK	**7/8**	*8.1*	---
16QAM	**1/2**	*10.5*	*4.8*
16QAM	**3/5**	---	*6.2*
16QAM	**2/3**	*12.1*	*7.2*
16QAM	**3/4**	*13.3*	*8.5*
16QAM	**4/5**	---	*9.3*
16QAM	**5/6**	*14.7*	*10.0*
16QAM	**7/8**	*14.9*	---
64QAM	**1/2**	*15.9*	*9.4*
64QAM	**3/5**	---	*11.1*
64QAM	**2/3**	*17.8*	*12.3*
64QAM	**3/4**	*19.1*	*13.9*
64QAM	**4/5**	---	*14.9*
64QAM	**5/6**	*20.7*	*15.7*
64QAM	**7/8**	*21.1*	---

Table 6.3. DVB-T vs. DVB-T2 under the effects of Ricean Channel

20 Taps Ricean Channel Comparison in C/N dBs			
Modulation	**Code Rate**	**DVB-T**	**DVB-T2**
QPSK	**1/2**	*4.9*	*0.2*
QPSK	**3/5**	---	*1.5*
QPSK	**2/3**	*6.6*	*2.5*
QPSK	**3/4**	*7.9*	*3.6*
QPSK	**4/5**	---	*4.2*
QPSK	**5/6**	*9.7*	*4.9*
QPSK	**7/8**	*10.4*	---
16QAM	**1/2**	*11.2*	*5.4*
16QAM	**3/5**	---	*6.9*
16QAM	**2/3**	*13.2*	*8.1*
16QAM	**3/4**	*14.5*	*9.4*
16QAM	**4/5**	---	*10.1*
16QAM	**5/6**	*16.6*	*10.9*
16QAM	**7/8**	*17.3*	---
64QAM	**1/2**	*16.6*	*10.0*
64QAM	**3/5**	---	*11.9*
64QAM	**2/3**	*19.0*	*13.2*
64QAM	**3/4**	*20.6*	*14.8*
64QAM	**4/5**	---	*16.0*
64QAM	**5/6**	*22.3*	*16.6*
64QAM	**7/8**	*23.1*	---

Table 6.4. DVB-T vs. DVB-T2 under the effects of 3 dB Echo Channel

Simple 2Path, 3dB Echo Channel Comparison in C/N dBs			
Modulation	**Code Rate**	**DVB-T**	**DVB-T2**
QPSK	**1/2**	*8.9*	*4.5*
QPSK	**3/5**	---	*5.5*
QPSK	**2/3**	*12.8*	*7.4*
QPSK	**3/4**	*14.1*	*8.6*
QPSK	**4/5**	---	*9.6*
QPSK	**5/6**	*15.9*	*10.0*
QPSK	**7/8**	*16.8*	---
16QAM	**1/2**	*14.1*	*9.5*
16QAM	**3/5**	---	*11.1*
16QAM	**2/3**	*18.2*	*12.6*
16QAM	**3/4**	*20.2*	*13.9*
16QAM	**4/5**	---	*14.8*
16QAM	**5/6**	*23.3*	*15.7*
16QAM	**7/8**	*24.2*	---
64QAM	**1/2**	*19.4*	*13.8*
64QAM	**3/5**	---	*15.8*
64QAM	**2/3**	*23.7*	*17.4*
64QAM	**3/4**	*25.8*	*19.2*
64QAM	**4/5**	---	*20.4*
64QAM	**5/6**	*28.4*	*21.2*
64QAM	**7/8**	*29.6*	---

Table 6.5. DVB-T vs. DVB-T2 under the effects of PO Channel

12 Taps Portable Outdoor Channel Comparison in C/N dBs (F_d = 1.69 Hz)			
Modulation	**Code Rate**	**DVB-T**	**DVB-T2**
QPSK	**1/2**	*6.9*	*2.7*
QPSK	**3/5**	---	*4.0*
QPSK	**2/3**	*9.5*	*5.6*
QPSK	**3/4**	*11.5*	*6.5*
QPSK	**4/5**	---	*7.3*
QPSK	**5/6**	*14.0*	*8.4*
QPSK	**7/8**	*15.2*	---
16QAM	**1/2**	*13.2*	*7.7*
16QAM	**3/5**	---	*9.6*
16QAM	**2/3**	*15.8*	*11.1*
16QAM	**3/4**	*17.9*	*12.0*
16QAM	**4/5**	---	*13.0*
16QAM	**5/6**	*20.7*	*14.1*
16QAM	**7/8**	*22.0*	---
64QAM	**1/2**	*18.5*	*12.1*
64QAM	**3/5**	---	*14.2*
64QAM	**2/3**	*21.5*	*15.6*
64QAM	**3/4**	*23.6*	*17.5*
64QAM	**4/5**	---	*18.7*
64QAM	**5/6**	*26.1*	*19.5*
64QAM	**7/8**	*27.4*	---

Table 6.6. DVB-T vs. DVB-T2 under the effects of PI Channel

12 Taps Portable Indoor Channel Comparison in C/N dBs (F_d = 1.69 Hz)			
Modulation	**Code Rate**	**DVB-T**	**DVB-T2**
QPSK	**1/2**	*8,6*	*4,5*
QPSK	**3/5**	---	*5,8*
QPSK	**2/3**	*11,7*	*8,0*
QPSK	**3/4**	*14,3*	*9,4*
QPSK	**4/5**	---	*10,4*
QPSK	**5/6**	*17,6*	*11,2*
QPSK	**7/8**	*19,7*	---
16QAM	**1/2**	*14,7*	*10,0*
16QAM	**3/5**	---	*12,0*
16QAM	**2/3**	*18,1*	*13,6*
16QAM	**3/4**	*21,2*	*14,7*
16QAM	**4/5**	---	*15,4*
16QAM	**5/6**	*24,6*	*16,6*
16QAM	**7/8**	*26,4*	---
64QAM	**1/2**	*20,1*	*14,4*
64QAM	**3/5**	---	*16,4*
64QAM	**2/3**	*23,6*	*18,2*
64QAM	**3/4**	*26,4*	*19,7*
64QAM	**4/5**	---	*21,1*
64QAM	**5/6**	*30,1*	*22,0*
64QAM	**7/8**	*32,0*	---

Table 6.7. DVB-T vs. DVB-T2 under the effects of TU6 Channel

6 Taps Typical Urban Channel Comparison in C/N dBs (F_d = 20 Hz)			
Modulation	**Code Rate**	**DVB-T**	**DVB-T2**
QPSK	**1/2**	*9.1*	*5.4*
QPSK	**3/5**	---	*6.6*
QPSK	**2/3**	*12.5*	*8.8*
QPSK	**3/4**	*14.7*	*10.1*
QPSK	**4/5**	---	*10.7*
QPSK	**5/6**	*18.0*	*11.4*
QPSK	**7/8**	*19.2*	---
16QAM	**1/2**	*14.9*	*10.2*
16QAM	**3/5**	---	*12.3*
16QAM	**2/3**	*18.7*	*14.0*
16QAM	**3/4**	*21.2*	*15.2*
16QAM	**4/5**	---	*16.2*
16QAM	**5/6**	*24.2*	*17.0*
16QAM	**7/8**	*25.5*	---
64QAM	**1/2**	*19.9*	*14.9*
64QAM	**3/5**	---	*17.0*
64QAM	**2/3**	*23.7*	*18.7*
64QAM	**3/4**	*26.3*	*20.3*
64QAM	**4/5**	---	*21.7*
64QAM	**5/6**	*30.2*	*22.6*
64QAM	**7/8**	*31.3*	---

Table 6.8. DVB-T vs. DVB-T2 under the effects of RA6 Channel

6 Taps Rural Area Channel Comparison in C/N dBs (F_d = 20 Hz)			
Modulation	**Code Rate**	**DVB-T**	**DVB-T2**
QPSK	**1/2**	*7.6*	*3.0*
QPSK	**3/5**	---	*4.5*
QPSK	**2/3**	*9.7*	*5.3*
QPSK	**3/4**	*10.8*	*6.3*
QPSK	**4/5**	---	*6.9*
QPSK	**5/6**	*12.2*	*7.4*
QPSK	**7/8**	*12.5*	---
16QAM	**1/2**	*14.0*	*7.8*
16QAM	**3/5**	---	*9.4*
16QAM	**2/3**	*16.0*	*10.6*
16QAM	**3/4**	*17.3*	*12.0*
16QAM	**4/5**	---	*12.9*
16QAM	**5/6**	*19.1*	*13.6*
16QAM	**7/8**	*19.7*	---
64QAM	**1/2**	*19.3*	*12.6*
64QAM	**3/5**	---	*14.4*
64QAM	**2/3**	*21.6*	*15.7*
64QAM	**3/4**	*23.3*	*17.4*
64QAM	**4/5**	---	*18.6*
64QAM	**5/6**	*24.8*	*19.4*
64QAM	**7/8**	*25.3*	---

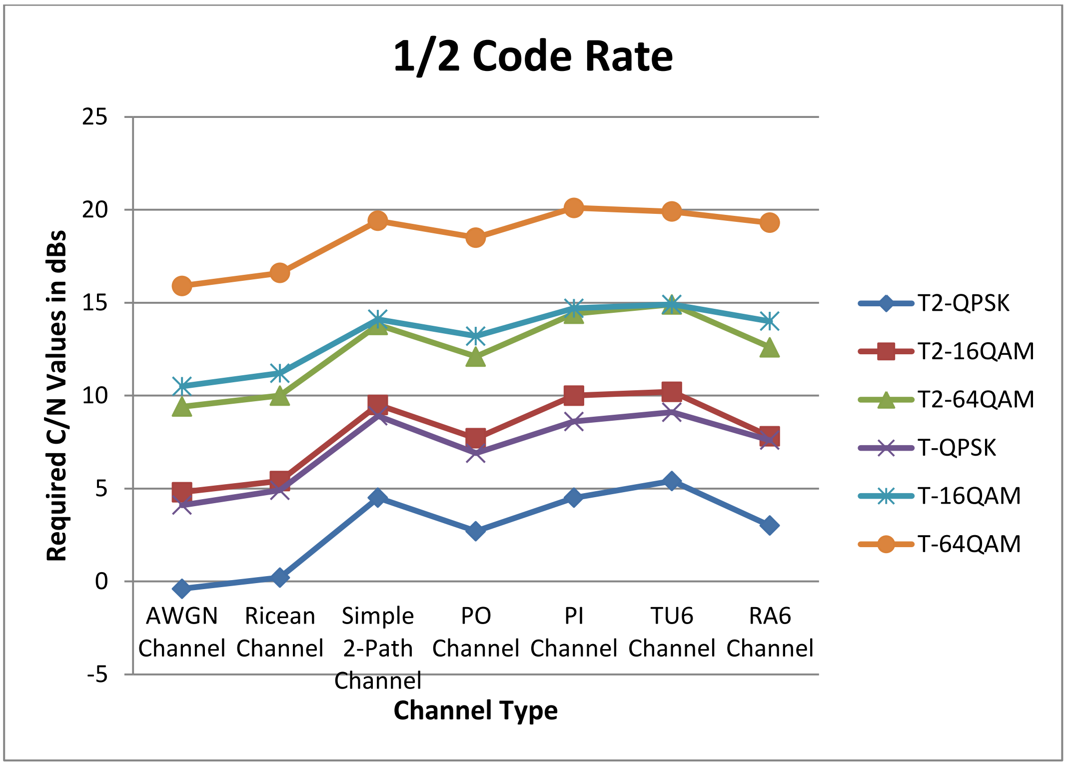


Figure 6.22. Required C/N Values for 1/2 Code Rate

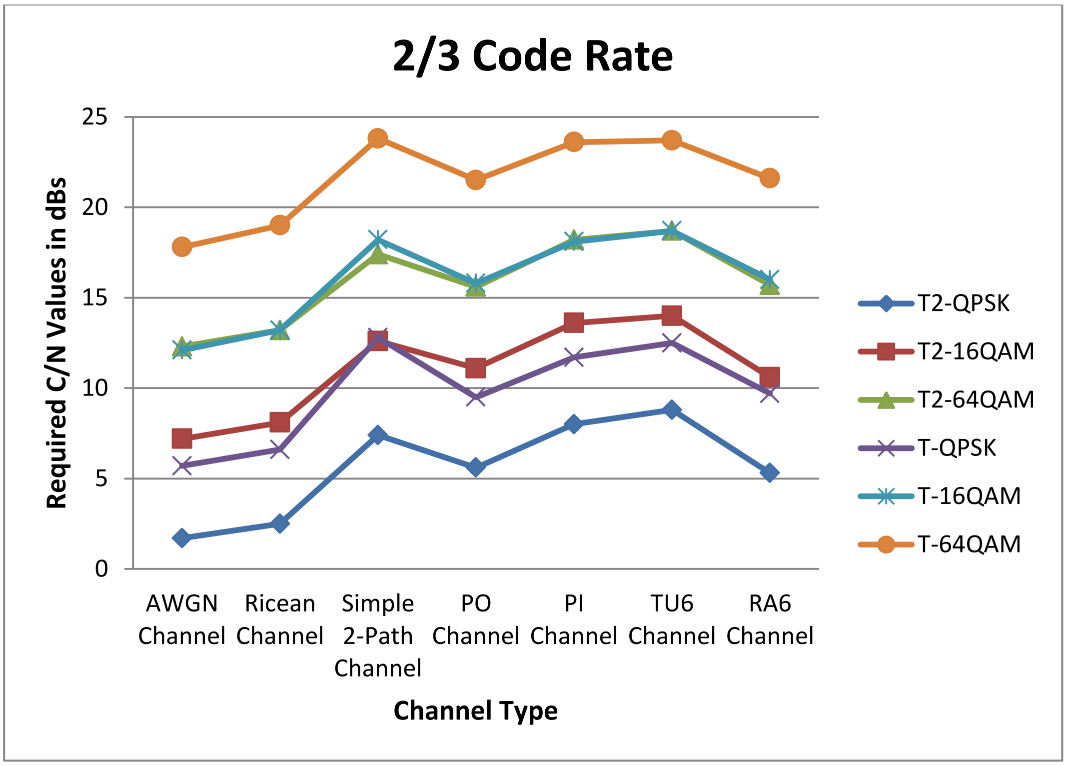


Figure 6.23. Required C/N Values for 2/3 Code Rate

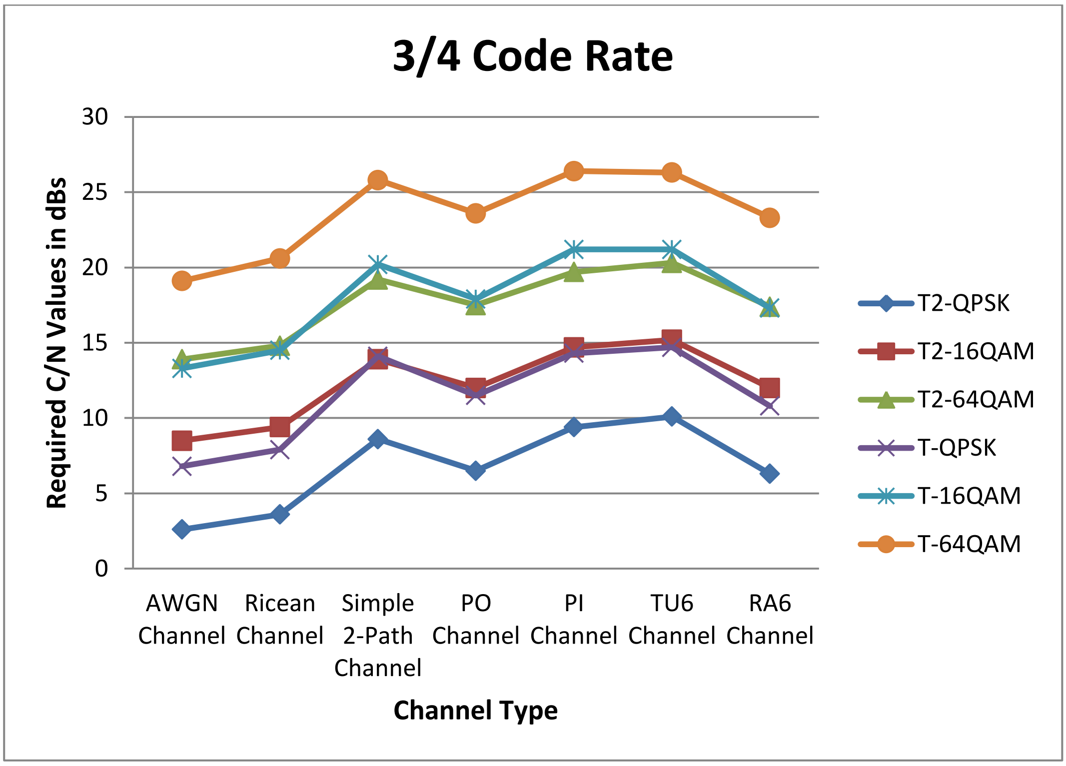


Figure 6.24. Required C/N Values for 3/4 Code Rate

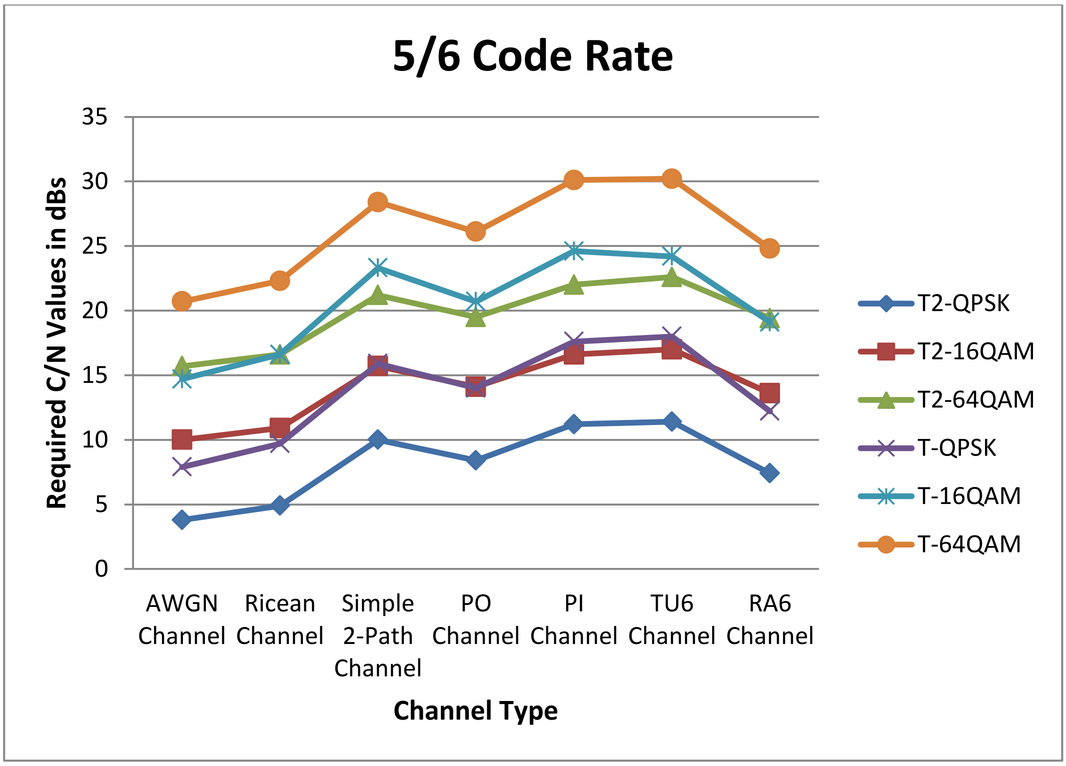


Figure 6.25. Required C/N Values for 5/6 Code Rate

These four figures are defined as the graphical representations of tables given in this section. With these figures, DVB-T2's great performance can be easily seen. So on next three figures this success of DVB-T2 will be shown according to Gain values in dBs.

Also in these figures a channel comparison can be applied according to the reference channel profile "AWGN Channel".

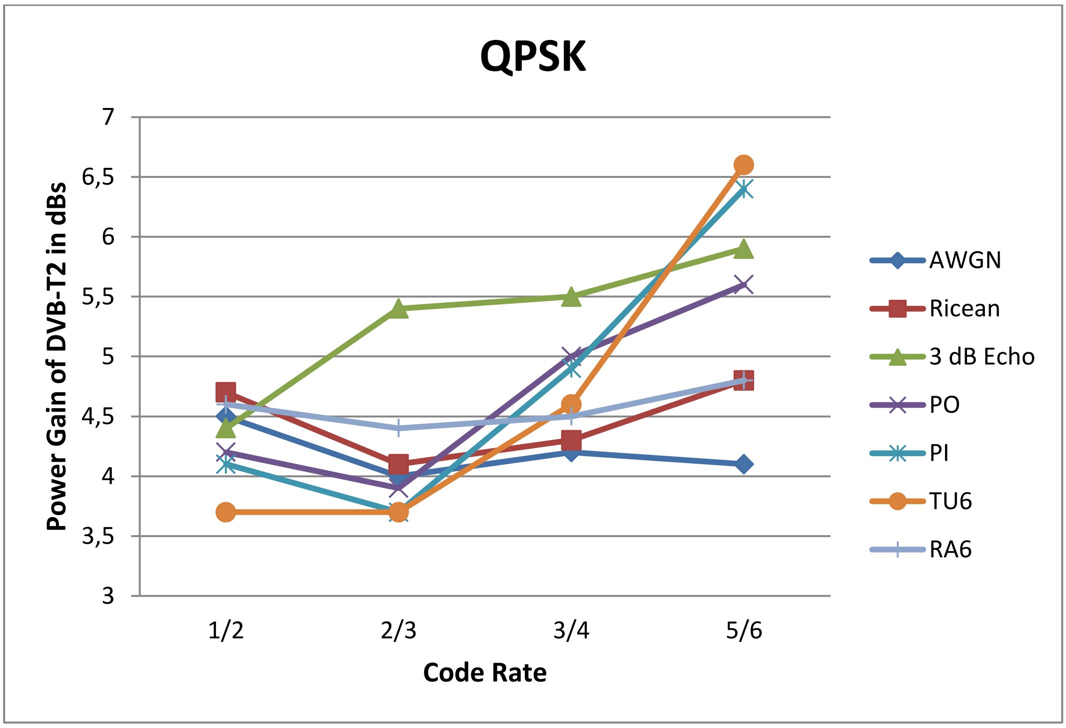


Figure 6.26. Gain values of DVB-T2 in dBs for QPSK Modulation

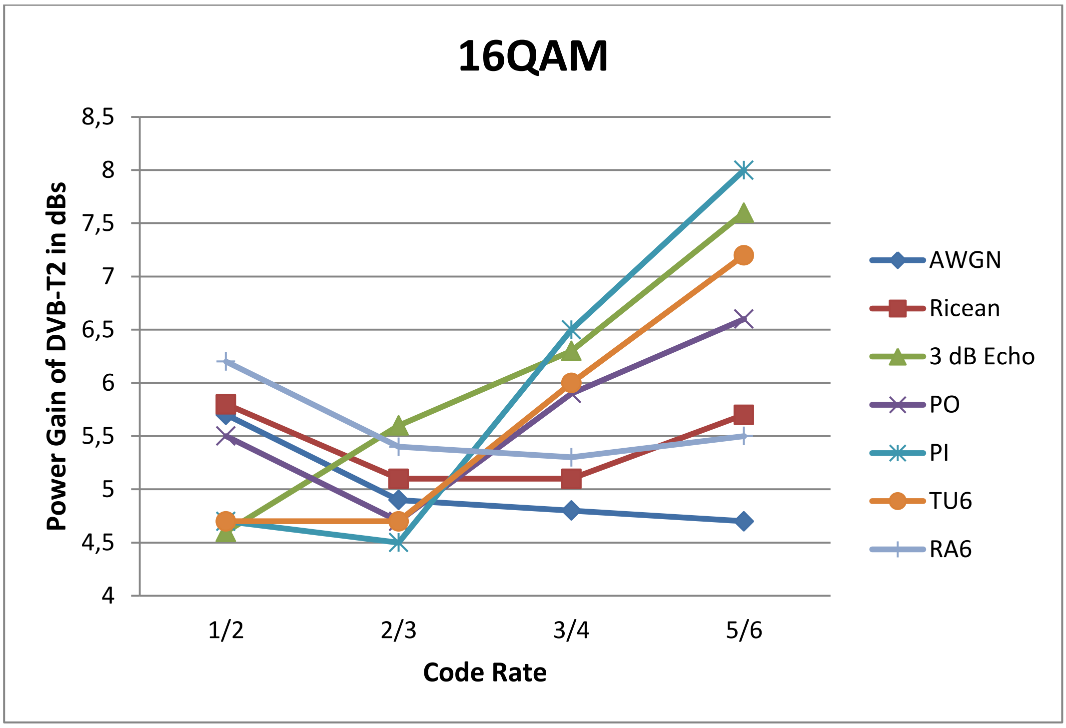


Figure 6.27. Gain values of DVB-T2 in dBs for 16QAM Modulation

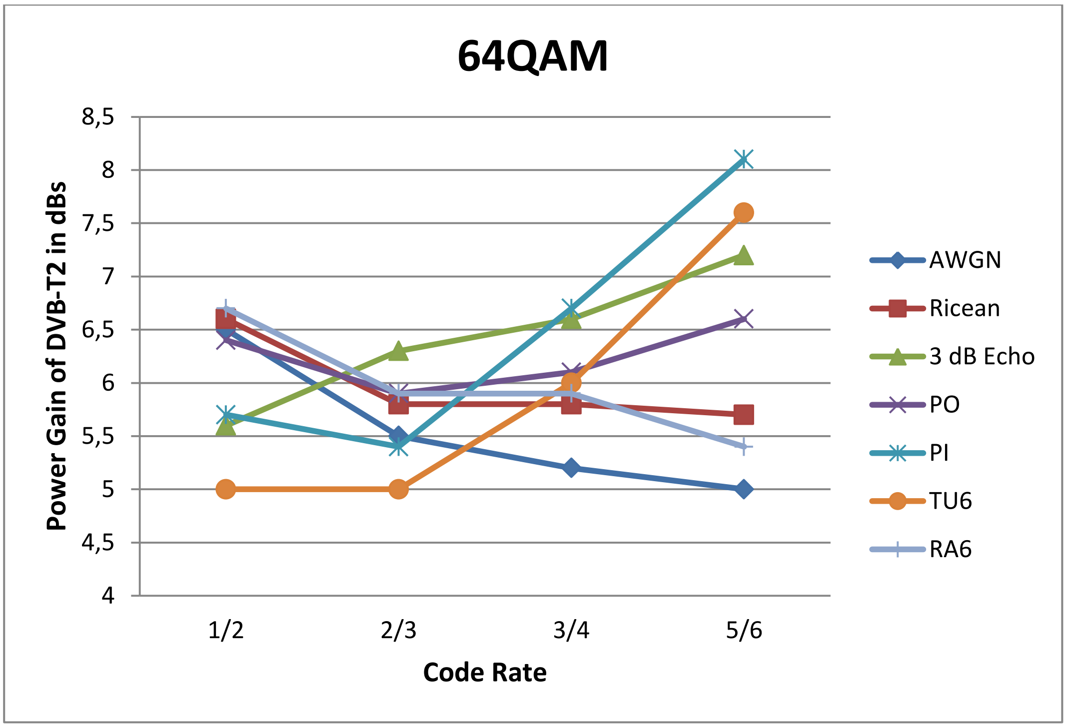


Figure 6.28. Gain values of DVB-T2 in dBs for 64QAM Modulation

CHAPTER 7

CONCLUSIONS

In this thesis, we studied on European Digital Terrestrial Television Broadcasting standards which are DVB-T and DVB-T2, and their receiver performance under the strong multipath interference of seven different channels. We expected to achieve better performance results as expected in DVB-T2 systems because of its better design and more accurate error correcting structures.

In chapter 6, comparison values are given in two different forms which are figures and tables. Shortly, it can be said that these two forms both show the same result. DVB-T2 system performance is better than DVB-T at every combination of parameters and channels. If C/N is slightly decreased, for example, to 0.5 dB, the LDPC bit error rate will be much greater. This is consistent with typical steep performance curves of LDPC codes.

As expected, systems need higher values of C/N in dBs by increasing order of Modulation and Code Rate. These results are seen in all the comparison figures. Increasing the core rate decreases performance because the less redundant information by coded blocks, making the system more sensitive to the errors and channel fading. Modulation increasing decreases performance because the reduction of the decision areas corresponding to each symbol when modulation order is increased causes that at the same noise levels, the symbol error rate is worse.

Another aim of this thesis is to measure the performance of the systems under different types of channel effects. At the beginning, simulated seven channels are classified into three groups. These groups are;

- Fixed → 20-tap Ricean and 3db Echo
- Portable → PI and PO
- Mobile → TU6 and RA6

AWGN channel is used as the reference channel and did not classify into these groups. As the result of the simulation for the both systems, 20-tap Ricean channel is the best channel and its required C/N values are very close to the AWGN Channel.

Mobile channel TU6 and Portable channel PI are the worst channels according to their required C/N values as expected. Despite the bad effects of this channel, the DVB-T2 was able to achieve better results in 3 to 9 dBs than DVB-T.

As future work;

- Simulated Core system structures can be expanded and a full simulation can be simulated.
- Channel Estimation Methods can be studied.
- Synchronization of time and frequency can be studied.
- By adding some new features and elaborating some blocks, fully mobile versions of DVB-T and DVB-T2 can be simulated. These mobile versions are DVB-H and DVB-T2 Lite respectively.
- Mobility affect can be increased and system performance can be compared under the effect of high Doppler spread.
- Stronger mobile channels which are described in COST207 document (COST Organization n.d.), HT12 (12-tap Hilly Terrain) and BU12 (12-tap Bad Urban) channel can be added simulated channel models.
- With a new type of structure that can be used instead of the TS packets, a new and unique transmission media can be created.
- LDPC Encoding/Decoding block can be deeply studied by using different decoding algorithms.
- LDPC decoder performance can be measured under the effects of “Non-Gaussian Noise”.
- DVB-T system performance with LDPC Encoder as its inner encoder instead of Punctured Convolutional Encoder.
- MISO (Defined in Standards) or MIMO (New Idea) concepts can be applied and studied.

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APPENDIX A

LOG-FILE EXAMPLE

```
DVB-T SIMULATION LOG FILE

-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*

Date:  04-11-2011

Time: 17:02

-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*

SIMULATION PARAMETERS;

** Transmission Mode: 2K

** Modulation: QPSK

** Code Rate: 2/3

** Guard Interval: 1/4

** Channel: AWGN

** Decision Type: Hard-Decision

-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*

SIMULATION RESULTS;

SNR      BER              BER              BER
in       Before           After            After
dBs      Viterbi          Viterbi          RS
---      -------          -------          -------

1.0      9.499e-002       3.342e-001       3.338e-001

1.5      8.260e-002       2.607e-001       2.607e-001

2.0      7.254e-002       1.908e-001       1.894e-001

2.5      6.024e-002       1.119e-001       1.119e-001

3.0      4.931e-002       5.901e-002       5.904e-002

3.5      4.099e-002       2.807e-002       2.439e-002

4.0      3.250e-002       1.056e-002       5.336e-003
```

4.5	2.470e-002	3.030e-003	8.669e-004
5.0	1.931e-002	1.418e-003	2.104e-004
5.5	1.369e-002	2.945e-004	0.000e+000
6.0	9.838e-003	3.720e-004	0.000e+000
6.5	6.805e-003	0.000e+000	0.000e+000
7.0	4.671e-003	0.000e+000	0.000e+000

SIMULATION RESULTS;

SNR in dBs	NumofErr Before Viterbi	NumofErr After Viterbi	NumofErr After RS
1.0	18384	43123	39666
1.5	15987	33631	30973
2.0	14039	24618	22498
2.5	11658	14439	13294
3.0	9544	7614	7015
3.5	7933	3622	2898
4.0	6290	1363	634
4.5	4781	391	103
5.0	3737	183	25
5.5	2650	38	0
6.0	1904	48	0
6.5	1317	0	0
7.0	904	0	0

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