INTEGRATION OF MIMO SUPPORT IN A DVB-T2 SIMULATOR

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ABSTRACT

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This thesis examines the benefits of using multi-antenna transmission in terrestrial digital video broadcasting, especially in the DVB-T2 and DVB-NGH standards. The thesis extends an existing DVB-T2 simulator with a platform for running MIMO simulations. The platform is constructed in a manner that will allow it to be easily adapted to future needs.

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Marcus Hellberg

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ABBREVIATIONS

ARQ Automatic Repeat Request

AWGN Additive White Gaussian Noise

B21C Broadcast for the 21th Century

BCH Bose-Chaudhuri-Hocquenghem code

BER Bit Error Rate

BICM Bit Interleaved Coding and Modulation

CP Continuous Pilot

CNR Carrier-to-Noise Ratio

DVB Digital Video Broadcasting

DVB-T2 Second generation terrestrial Digital Video Broadcasting

DVB-NGH Next generation handheld Digital Video Broadcasting

FEC Forward Error Correction Coding

FEF Future Extension Frame

FFT Fast Fourier Transform

ISI Inter-Symbol Interference

LDPC Low Density Parity Check

LLR Log-Likelihood Ratio

MIMO Multiple Input Multiple Output

MISO Multiple Input Single Output

OFDM Orthogonal Frequency Division Multiplexing

PAPR Peak-to-Average-Power Ratio

PLP Physical Layer Pipe

QAM Quadrature Amplitude Modulation

QPSK Quadrature Phase-shift Keying

SFN Single-Frequency Network

SP Scattered Pilot

SNR Signal to Noise Ratio

STBC Space-Time Block Code

ÅAU Åbo Akademi University

NOTATION

α Noise standard deviation

c^* Complex conjugate of c

E_s Symbol energy

f_c Carrier wave center frequency

$\mathbf{H}$ Channel transfer matrix

$\mathbf{H}^*$ Complex conjugate transpose of matrix $\mathbf{H}$

$\mathbf{n}$ Noise vector

$\mathbf{r}$ Received symbol vector

$\mathbf{s}$ Sent signal vector

T_c Coherence time of channel

T_d Delay spread

W Signal bandwidth

W_c Coherence bandwidth

CHAPTER ONE

INTRODUCTION

1.1 Motivation

The increasing consumer and industry demand for high definition video content and more reliable transmissions has led to a search of transmission methods that can satisfy these demands. One such technology is multiple-input multiple-output, or MIMO, transmission. MIMO transmission involves the use of several antennas for both transmitting and receiving signals. MIMO systems can deliver both higher data throughput and greater robustness by taking advantage of the additional signal paths between a transmitter and a receiver.

The goal of this thesis is to build a platform for conducting simulations of MIMO transmissions in a DVB-T2 (second generation terrestrial Digital Video Broadcast standard) environment. The completed simulator will be able to conduct simulations with several different multi-antenna configurations.

The DVB-T2 standard is aimed to be backwards compatible with current antenna structures and therefore does not include any transmission models that require multiple antennas at the receiver. It does, however, include a multi-antenna scheme that utilizes two transmitting antennas. The Next Generation Handheld DVB standard (DVB-NGH) will most likely be built upon the DVB-T2 standard and is looking at using MIMO transmission as a solution to commercial requirements that state a need for a 50 percent increase in capacity over the current generation system.

There are still many unanswered questions regarding exactly which techniques will be used in the upcoming standards. It is therefore important that the MIMO platform that is being built in this thesis is as flexible as possible. To achieve this, the platform should allow easy expansion of functionality, both in form of new transmission schemes and receiver types.

1.2 Thesis structure

This thesis will begin with an introduction of some basic concepts of wireless transmission in chapter 2 to give the reader an understanding of how using multiple antennas can help to achieve reliable and higher throughput transmission systems. Chapter 3 will discuss the different advantages of MIMO transmissions compared to single antenna transmissions. The chapter will also introduce the MIMO transmission techniques that will be used later in the simulator implementation.

Following that, chapter 4 will lead the discussion to Digital Video Broadcasting. The chapter will introduce the DVB Project that is behind the DVB-T2 and DVB-NGH standards as well as the Broadcast for the 21st Century project, to which this thesis contributes. After introducing the DVB standards, the thesis will continue in chapter 5 with a description of the Åbo Akademi University DVB-T2 simulator that is used as a base for the work in this thesis.

Chapter 6 introduces the work done to implement a platform for conducting MIMO simulations. The chapter also examines simulation results to ensure that the newly constructed extension to the simulator is working as desired.

Finally, the results of the work done in the thesis will be reviewed along with recommendations on further work in chapter 8

CHAPTER
TWO

WIRELESS TRANSMISSION

This chapter introduces some fundamental concepts of wireless communication that are needed to explain how DVB-T2 works and what kinds of advantages multiple antenna transmission can offer over single antenna transmission. All wireless transmissions are ultimately transformed into an analog signal, even if they are processed digitally. This chapter thus begins with describing how modulation is used to transform a digital representation of a signal into an analog signal suitable for transmission over air. After examining modulation, the chapter continues by looking at some of the issues that a transmitted signal is subject to along with measures that can be used to counter these issues. Finally, the chapter gives a short introduction to the concept of channel models, mathematical models that mimic the effect of transfer on a signal.

2.1 Modulation

Modulation is a technique of modifying a waveform with another signal. In digital modulation, a carrier wave is modified according to a bit sequence to produce an analog signal that can be sent over the air. This section will show an example of a digital modulation technique called Quadrature Phase Shift Keying that modifies the phase of a carrier signal based on a binary sequence.

The key concept of modulation that is necessary for understanding how DVB-T2 transmissions work is *constellation points*. The constellation points, shown as gray circles in figure 2.1, are used to convey one or more bits. Higher order modulations, like 16 Quadrature Amplitude Modulation (QAM) shown in figure 2.4(a), can transmit more bits per constellation point. The disadvantage of having more constellation points is that they are closer together. As signals are subjected to both phase and amplitude distortions during a transmission, a received constellation point will not be received at exactly the same point. The closer together the points are, the more difficult it is to determine with certainty the correct sent point.

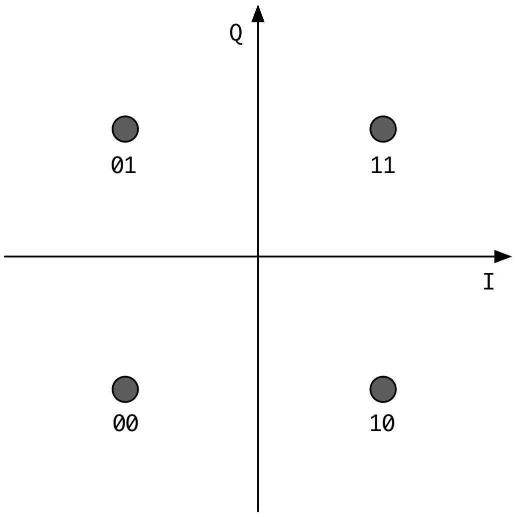


Figure 2.1: Quadrature Phase Shift Keying with Gray-coding.

Quadrature Phase-Shift Keying (QPSK), also known as 4-QAM, is the lowest order modulation in use in DVB-T2 transmissions. QPSK has four constellation points, each designated a two-bit sequence. The bits are *Gray-coded*, that is, they are positioned so that two adjacent constellation points differ in only one bit. Gray coding has the advantage that even if a constellation point is incorrectly identified, it will only differ with one bit and will thus be easy to correct with an error correction code.

The constellation points in QPSK are given by [2]:

$$s_i(t) = \sqrt{\frac{2E_s}{T}} cos \left(2\pi f_c t + (2i-1)\frac{\pi}{4})\right), \qquad i = 1,2,3,4 \tag{2.1}$$

Where E_s signifies the energy of the symbol, or constellation point. f_c is the carrier wave center frequency and T the symbol time. This gives the points the following phases: $\frac{\pi}{4}$, $\frac{3\pi}{4}$, $\frac{5\pi}{4}$ and $\frac{7\pi}{4}$.

The in-phase component of the signal (`I` in figure 2.1) is given by Equation 2.2 and the quadrature component (`Q`) by Equation 2.3.

$$\phi_1(t) = \sqrt{\frac{2}{T}} cos(2\pi f_c t) \tag{2.2}$$

$$\phi_2(t) = \sqrt{\frac{2}{T}} sin(2\pi f_c t) \tag{2.3}$$

The four constellation points can then be represented by

$$\left(\pm\sqrt{\frac{E_s}{2}}, \pm\sqrt{\frac{E_s}{2}}\right) \tag{2.4}$$

where E_s denotes the symbol energy. The factor $\frac{1}{2}$ simply means that transmit power is evenly divided between the two carrier waves. By representing constellation points in this way, they can be easily managed using complex numbers.

All other modulation schemes used in DVB-T2 transmissions (16-QAM, 64-QAM and 256-QAM) share the same basic principles as QPSK, but add an amplitude shift along with a phase shift. The signal of a M-ary QAM is given by[2]:

$$s_i(t) = \sqrt{\frac{E_s}{T}} a_i cos(2\pi f_c t) + \sqrt{\frac{E_s}{T}} b_i cos(2\pi f_c t), \qquad 0 < t < T \tag{2.5}$$

where $\{a_i, b_i\}$ is an element from the L×L matrix:

$$\begin{bmatrix} (-L+1, L-1) & (-L+3, L-1) & \dots & (L-1, L-1) \\ (-L+1, L-3) & (-L+3, L-3) & \dots & (L-1, L-3) \\ \vdots & \vdots & & \dots \\ (-L+1, -L+1) & (-L+3, -L+1) & \dots & (L-1, -L+1) \end{bmatrix} \tag{2.6}$$

where $L = \sqrt{M}$.

2.2 Interference

Wireless communication is susceptible to interference from the environment and other wireless communication. Figure 2.2 shows a typical situation when dealing with wireless transmission; the signal sent from the transmitter (TX) is received at the receiver (RX) via multiple paths, each with a different amplitude and phase distortion. Fading due to multi-path propagation is a problem in single antenna communication as there is a significant risk that a channel will experience severe drops in signal-to-noise ratio (SNR), known as *deep fades*. Different diversity techniques can be used to reduce the probability of a deep fade.

2.3 Fading

A wireless channel can be affected by several types of fading. A *slow fading channel* can be a result of a large object between the transmitter and the receiver that shadows the signal. A slow fading channel remains fairly constant over the period of the transmission. It is very difficult to compensate

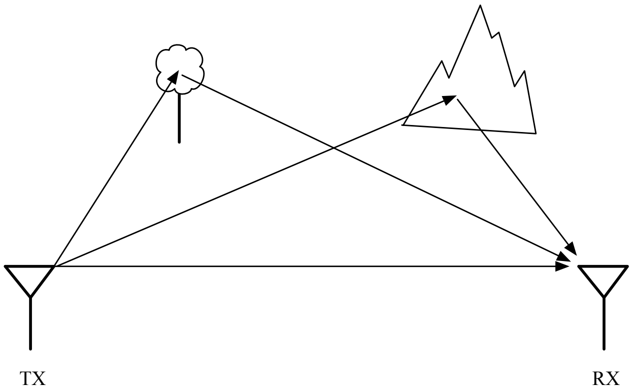


Figure 2.2: Schematic drawing showing different signal paths between a transmitter and a receiver.

for a deep fade in a slow fading channel as all data transmitted during the deep fade will be lost.

A *fast fading channel* varies significantly during the transmission period. These fluctuations can be more easily mitigated using the diversity techniques discussed in the following section.

The time during which a channel stays stable, or coherent, is called its coherence time, denoted T_c. Coherence time is closely related to Doppler spread(D_s), or the difference in Doppler shifts between signals received through different paths. Correspondingly, the frequency range for which a channel is considered coherent is called the coherence bandwidth and is denoted W_c [16]. With the help of these definitions, it is possible to give more formal definitions to the fading channels discussed in the previous paragraph.

A fast fading channel is characterized by having a delay requirement that is greater than the coherence time,

$$T_c \ll \text{delay requirement}$$

A slow fading channel is the opposite of this, a channel where the coherence time is greater than the delay requirement of the protocol.

$$T_c \gg \text{delay requirement}$$

A channel that has a higher coherence time than its delay spread, $T_d \ll T_c$, is called an under-spread channel. This is beneficial, as it enables the channel to be modeled as a time-invariant channel [16].

Besides being fast or slow fading, channels can be either flat fading or frequency-selective fading. A flat fading channel has a coherence bandwidth that is greater than the signal bandwidth, W.

$$W < W_c$$

A frequency-selective fading channel is conversely a channel for which the signal bandwidth is larger than the coherence bandwidth.

$$W > W_c$$

A channel with frequency-selective fading will affect different frequency components of the sent signal differently.

This section provided a brief introduction to the concepts of wireless communication that are most relevant for this thesis. Chapters 2 and 3 in "Fundamentals of Wireless Communication" by Tse and Viswanath [16] can be used for a more extensive overview of wireless communication.

2.4 Diversity techniques

There are several techniques that can be used to combat fading in a wireless channel. These techniques add diversity to the signal by spreading out the transmitted data in time, frequency or spatial dimensions to minimize the risk of data loss. This section will discuss four such techniques: temporal diversity, frequency diversity, spatial diversity and polarization diversity. Several of these techniques are typically used in parallel as diversity is vital for attaining a reliable wireless link [16].

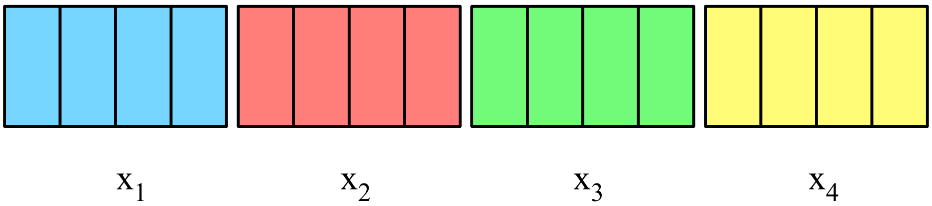
2.4.1 Time diversity

Time diversity is achieved by averaging out the fading effect of the channel over time. A common method for achieving time diversity is interleaving. When interleaving a signal, the coded symbols are sent out of order over a period that is longer than the coherence time of the channel. The basic assumption in time interleaving is that the channel will fade independently within different coherence periods. This provides the advantage that only a few symbols are incorrectly received, even if the channel is in deep fade for one symbol time.

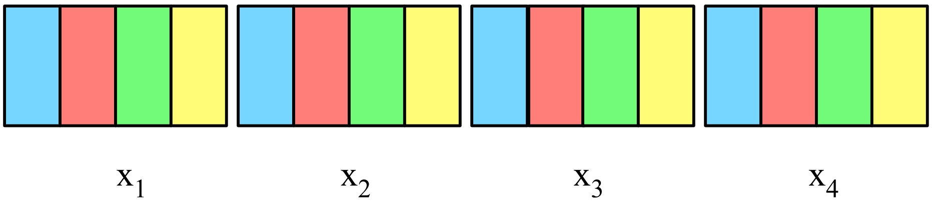
Figure 2.3 illustrates the basic principle of interleaving. x_1 through x_4 are the sent codewords, while the colored rectangles represent coded symbols. Wirelessly transmitted signals always contain error correction codes, which enable the receiver to reconstruct codeword symbols even if some of them are incorrectly received. Error correction is discussed in more detail in section 2.5.

Another way of achieving time diversity is using rotation code. Rotation code exploits more degrees of freedom in the channel than simple one-dimensional repetition and will therefore offer a *coding gain* in addition to diversity gain [16]. Rotation coding works by rotating the constellation points of the sent signal as shown in Figure 2.4. The benefit of rotating the constellation is that both the real (I) and imaginary (Q) axis will contain enough information to decipher which points have been received, as each point has an unique projection on the I and Q axes. [9]. Rotation coding in DVB-T2 uses cyclic Q-delay, which means that the imaginary part is cyclically delayed in relation to the real part.

Time diversity always involves sending symbols over several coherence periods. Because the signal is sent over a longer period, time diversity will inherently lead to time delays. This may not be acceptable in applications

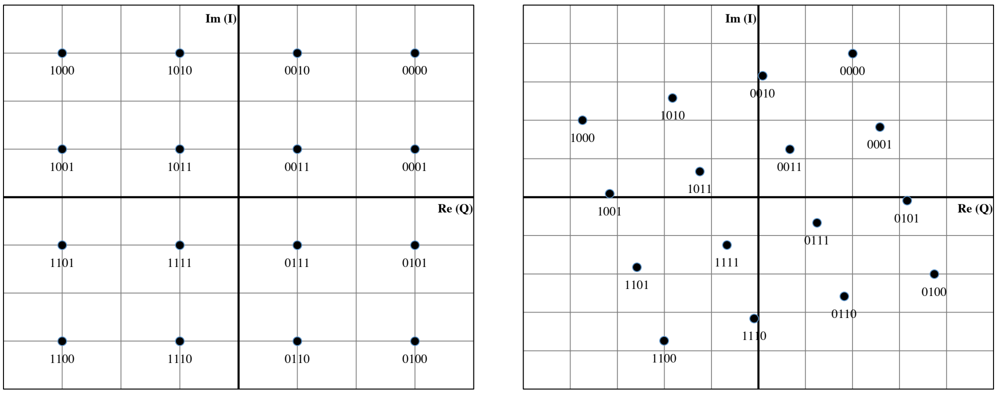


(a) Non-interleaved codewords.



(b) Interleaved codewords.

Figure 2.3: Time interleaving codewords.



(a) 16QAM constellation

(b) Rotated 16QAM constellation

Figure 2.4: Illustration of rotation using a 16QAM constellation.

that have strict delay constraints or if the coherence time of the channel is long. Another type of diversity, frequency diversity, can be used in these situations, provided that the coherence bandwidth W_c of the channel is larger than the signal bandwidth W [16].

2.4.2 Frequency diversity

In order to achieve frequency diversity, a signal is sent over a larger frequency span than the coherence bandwidth of the channel. This reduces the probability of all signal paths fading for the same frequency components.

A common and highly effective way to achieve frequency diversity and coding diversity is to use Orthogonal Frequency Division Multiplexing (OFDM). OFDM handles frequency selective fading by sending data over several orthogonal narrowband subcarriers [16]. These subcarriers are flat fading and therefore do not require any complex equalization filters at the receiver. Each of the subcarriers are modulated with a modulation scheme at a low symbol rate. The low symbol rate used for the subcarriers allows the use of longer guard intervals than a single carrier with a comparable symbol rate.

A guard interval is an interval between sent symbols that reduces intersymbol interference (ISI). The interval allows the interference from the reflections of the previously sent symbol to settle. Guard intervals will thus facilitate the demodulation of the received signal. In OFDM, a cyclic prefix (CP) is sent in the guard interval [2]. A cyclic prefix implies that the end of the sent symbol is copied prefixed to the symbol as shown in Figure 2.5. OFDM is used in DVB-T2 because it provides a resilient link even in severe channel conditions [8].

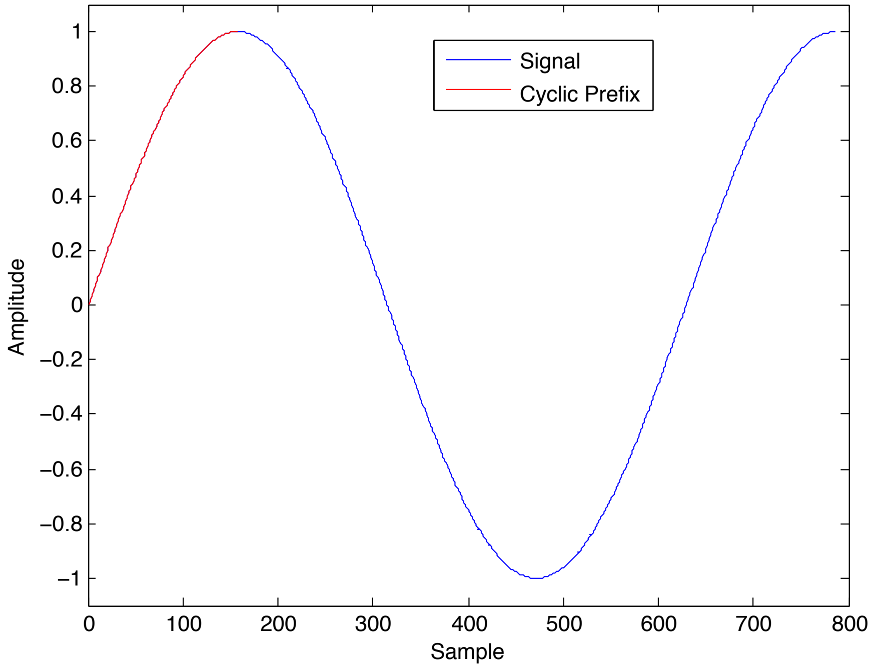


Figure 2.5: Illustration of cyclic prefix on sinusoidal signal.

2.4.3 Spatial diversity

The most interesting type of diversity for the purpose of this thesis is spatial diversity, or antenna diversity. Spatial diversity can be acquired by using several antennas that are spaced sufficiently far apart. Signals sent through spatially separated antennas will ideally have independently fading channels and can thus be independently resolved. There are three kinds of spatial diversity: receive diversity (SIMO), transmit diversity (MISO) and systems that use both types of diversity (MIMO). The advantages of spatial diversity will be examined in more detail in section 3.1 of the following chapter.

The current DVB-T2 specifications include a possibility for MISO transmission using a modified Alamouti scheme, which will be discussed further in section 3.2.

2.4.4 Polarization diversity

A final form of diversity that will be discussed in this chapter is polarization diversity. It is closely related to spatial diversity by the fact that it uses several antennas for signal transmission. The difference between spatial diversity and polarization diversity is that the antennas are transmitting with different polarizations instead of being spatially separated, as shown in figure 2.6.

Figure 2.6: Illustration of a dual polarized antenna setup.

The advantage of polarization diversity over spatial diversity is that the antennas do not need to be spatially separated. This enables the manufacturing of smaller devices, which is one reason that polarization diversity is considered for the upcoming DVB-NGH standard.

The signals from the polarized antennas will, like the signals from the spatially separated antennas, fade differently and can be detected independently due to their polarization. There is however a risk that the signal polarization is shifted during transmission. It can, however, be shown that even in worst case polarization mismatch scenario, half of the best-case signal power can be received [12].

As both spatial diversity and polarization diversity schemes send data from several antennas to several antennas, they can be examined together. This thesis will thus discuss the general case of MIMO transmissions. Both spatially separated and polarized antenna setups can be accommodated with the simulator shown in this thesis, provided that suitable channel models are used.

2.5 Error correction

Current DVB systems are broadcast systems and cannot thus send requests for retransmission of lost packets. To circumvent this problem, DVB uses forward error coding (FEC). As the name implies, FEC adds redundant data to the transmitted signal that can be used to correct errors that occur during transmission.

DVB-T2 uses two different forward error coding methods: low density parity check codes (LDPC) and Bose, Charudhuri, Hocquenghem codes (BCH) [8]. LDPC codes provide very robust error correction while allowing transfer rates close to the Shannon limit [13]. LDPC codes have a linear complexity and are therefore an attractive solution for sending data over an error-prone channel. BCH codes are used in conjunction with LDPC in DVB-T2 to remove an error floor present in LDPC codes (typically around 10^{-7}) to achieve the target bit error rate (BER) of 10^{-12} [8]. An error floor of a code occurs when the bit-error probability does not approach zero as fast for medium or high SNR as it does for low SNR.

The ratio of actual data to the length of a codeword is called *code rate*. A higher code rate allows more information to be transmitted, while a lower code rate will provide a higher error tolerance. DVB standards allow several different code rates to ensure that a balance between robustness and transfer rate can be found in varying channel conditions.

2.6 Channel models

In order to simulate a working DVB-T2 system, the propagation of the transmitted signal must be modeled. There are several channel models with varying degrees of complexity and realisticity. This section will describe two models that are used in this thesis: the additive white Gaussian noise channel model and Rayleigh channel model.

2.6.1 Additive white Gaussian noise

The additive white Gaussian noise (AWGN) model is the simplest channel model used in the Åbo Akademi University DVB-T2 simulator. It works by simply adding noise to the sent signal. AWGN assumes noise to be independent and identically distributed. A complex AWGN channel can be represented with:

$$r(t) = s(t) + n(t) \tag{2.7}$$

where $r(t)$ represents the received signal and $s(t)$ the transmitted signal at time t. The white Gaussian noise is denoted $n(t)$ and is $\mathcal{CN}(0, N_0)$, i.e. the noise is circularly symmetric and has a covariance matrix N_0. N_0 is the power spectral density of white Gaussian noise.

The AWGN channel model is a very simple model, but it works well as a base for comparing different transmission schemes and as a building block for other more complex channel models.

2.6.2 Rayleigh

The Rayleigh channel model is a multi-path channel model that does not include any line of sight between the transmitter and the receiver. The model contains many small signal scattering and reflecting elements in the environment and thus assumes that a given path's phase is uniformly distributed between 0 and 2π [16].

The fact that there are a large number of independent scattered and reflected paths with the given phase distortions allows each path gain to be modeled as a zero-mean Gaussian random variable

$$z = x + yi \tag{2.8}$$

The variance of the variable is given by

$$\sigma^2 = E(z^2) \tag{2.9}$$

The magnitude $|z^2|$ has a probability density function of [2]

$$p(z) = {\frac{z^2}{\sigma^2}}^{\frac{-z^2}{2\sigma^2}}, \qquad z \geq 0 \tag{2.10}$$

The Rayleigh fading channel model is a reasonable channel model for environments where there are many small reflectors. The implementation of a Rayleigh channel in the Åbo Akademi University simulator will be shown in section 6.3.

2.6.3 Channel estimation

To decode a received signal, the receiver must have an estimate of the effect that the channel has had on the sent signal. To accomplish this, a transmitter can send out a defined sequence of symbols, called *pilots*, at predefined intervals. This way, the receiver can compare the received signal to the actual received signal and deduce the effect of the channel. The receiver can then use this *channel estimate* during a period that is less than the coherence time of the channel.

The pilot sequence used in DVB-T2 will be presented in subsection 6.1.2.

CHAPTER

THREE

MULTIPLE INPUT MULTIPLE OUTPUT

Increasing industry and consumer demands have led to a need of new transmission techniques that can deliver higher spectral efficiency and better quality transmissions [3][17]. As an example, the next generation standard of the Digital Video Broadcasting for hand held devices (DVB-NGH) has a commercial requirement of at least 50 percent higher capacity for any given robustness level. To meet these increasing demands, the DVB-NGH project is examining the possibility of utilizing multiple input multiple output (MIMO) transmissions [7].

MIMO is a transmission technique that uses spatial diversity to deliver more robust performance and higher bandwidth utilization without the need for increased transmit power. MIMO offers several advantages over traditional single input single output (SISO) transmission. By employing several transmitting and receiving antennas, it is possible to achieve *diversity gain* and *multiplex gain* in the system. MIMO systems are capable of using multi-path fading effects that negatively affect other transmission systems to its advantage. To do this, MIMO systems use the signatures of the signal paths to separate signals that originate from different transmitting antennas.

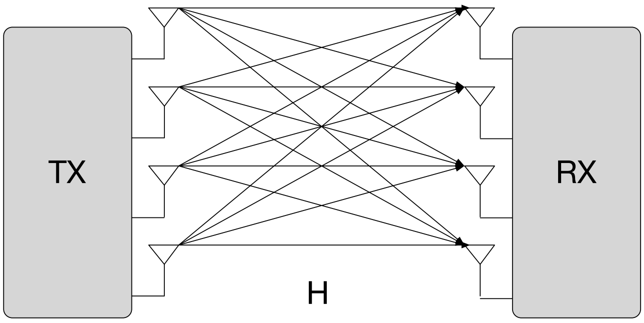


Figure 3.1: Schematic of a MIMO system with four transmitting antennas (TX), four receiving antennas (RX) and signals traveling through a channel (H).

Figure 3.1 shows a schematic of a MIMO transmission system with four transmit antennas and four receive antennas. The wireless channel, represented by **H**, is simulated with a channel matrix that defines signal distortions and correlations between antennas. As can be seen, there are several signal paths between the antennas. Ideally, then, these different paths can be taken advantage of to deliver more content or to increase redundancy in the transmission. In reality, there will be crosstalk between the antennas and measures need to be taken to separate the signals from each antenna.

The chapter begins by discussing the types of gains that can be achieved with MIMO transmission technologies. Further, different methods for both transmission and reception are examined. Emphasis will be placed on aspects of MIMO that are most relevant for DVB-broadcasting, but the chapter will also describe features that help to illustrate the advantages of MIMO transmission over single antenna systems.

3.1 Gains

There are two types of gains that can be attained by using MIMO in wireless transmission: diversity gain and multiplexing gain. Diversity gain provides a more robust link by transmitting a signal over several channels with different characteristics. By using several independent channels for transmission, there is a significantly smaller risk that all channels will fade at the same instant. Multiplexing gain in turn is used to deliver higher throughput by sending data through several data pipes within the same frequency band, which leads to a higher bandwidth utilization [3].

There is a fundamental tradeoff between achieving diversity gain and multiplexing gain in MIMO systems. The implications of this tradeoff are explored in subsection 3.1.3.

3.1.1 Diversity gain

A system can be made more resilient to the effects from channels with small scale fading by increasing the level of diversity in the signal. As discussed in the previous chapter, there are several ways of increasing the diversity in a wireless broadcast system. Frequency and time diversity can be attained in both SISO systems and multiple antenna systems. This chapter will therefore focus on spatial diversity, as it is a diversity type that is unique to MIMO transmission.

There are two main types of spatial diversity: *transmit diversity* and *receive diversity*. Transmit diversity is gained when using several antennas at the transmitter. Similarly, receive diversity comes from having several receiving antennas. A transmission system with N_T transmit antennas and N_R receive antennas can maximally obtain $N_T N_R{}^{\text{th}}$ order diversity [17]. The diversity order determines the number of independent channels that can be separated. All the links need to fade independently in order for the system to achieve full diversity [3].

If the transmitter knows the channel, it can try to optimize the sent signal with a technique called beam forming to compensate for the channel fading. To achieve this, beam forming requires a feedback channel from the client that provides the transmitter with information about channel state. The open loop broadcast systems such as the DVB-T2 standard do not have a feedback channel, and cannot thus try to optimize the signal at the transmitter. The transmitter must instead use coding that will benefit

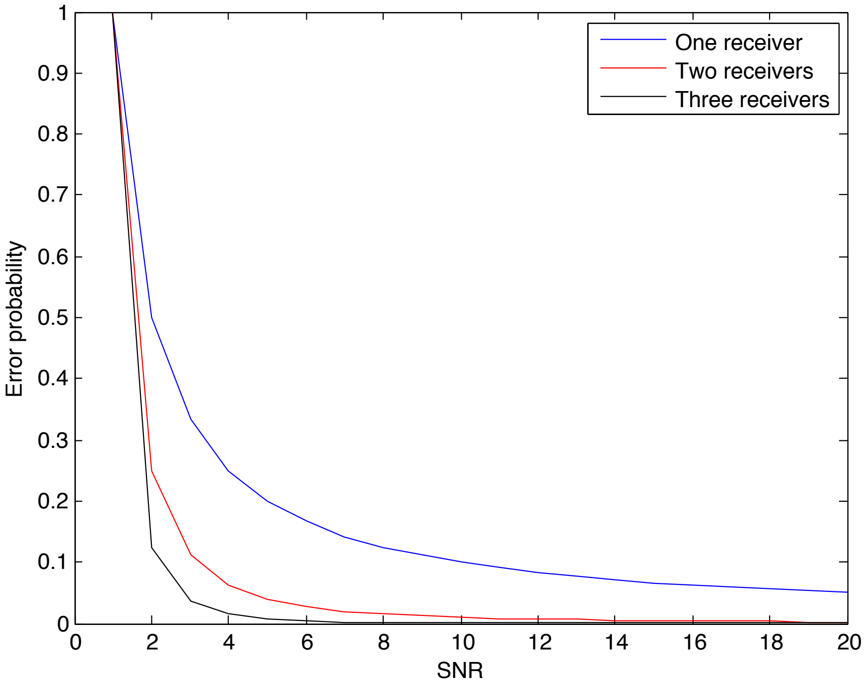


Figure 3.2: Decay of error probability at the receiver when using multiple receiver antennas.

all receivers. One such coding is the Alamouti scheme, which is used in DVB-T2 and will be described in section 3.2.

Having multiple antennas at the receiver side of the system and combining the inputs from the antennas constructively will provide *array gain*. In best-case conditions, a setup with two receiving antennas will get twice the received power compared to a single-antenna setup. Using n receive antennas, the average error probability will decay like $1/\mathsf{SNR}^n$ [17]. For a SISO system, the corresponding rate is SNR^{-1}, which clearly demonstrates the advantage of having multiple receiving antennas (Figure 3.2).

Both receive and transmit diversity are designed to counter the effects of fading. In MIMO transmission, this fading effect can be exploited to gain more degrees of freedom from the wireless channel [17]. By exploiting these degrees of freedom, it is possible to achieve the other type of gain in MIMO systems, multiplexing gain.

3.1.2 Multiplexing gain

Instead of offering a more robust link, multiplexing allows more data to be transmitted in the same frequency band. In essence, multiplexing gain is achieved through sending multiple, independent, parallel signals to the receiver [3]. These signals travel through different *spatial channels*. This capacity increase does not require any additional transmit power or bandwidth compared to SISO transmission [3].

In order for the receiver to be able to separate the transmitted signals, it is crucial that the signals have traveled through different paths and thus have differing spatial signatures [3]. The number of degrees of freedom in a MIMO system is given by $\min\{N_T, N_R\}$, i.e., it is limited by the lesser number of antennas either at the transmitting side or the receiving side.

3.1.3 Diversity-multiplexing gain tradeoff

Lizhong Zheng and David Tse have demonstrated that there is a fundamental tradeoff between the amount of diversity and multiplexing gain that can be achieved in a MIMO system. Both types of gain can be achieved in a system, but having higher multiplexing gain leads to less diversity in the system [17].

Figure 3.3 shows an example of the relation of multiplexing gain to the amount of diversity gain for a 2×2 MIMO system. The first number in the parenthesis is the spatial multiplexing gain, and the second is the diversity gain [17].

3.2 Alamouti space-time block code

The Alamouti Space-Time Block Coding (STBC) is a transmit diversity scheme developed by Siavash Alamouti. He argued that the only way of

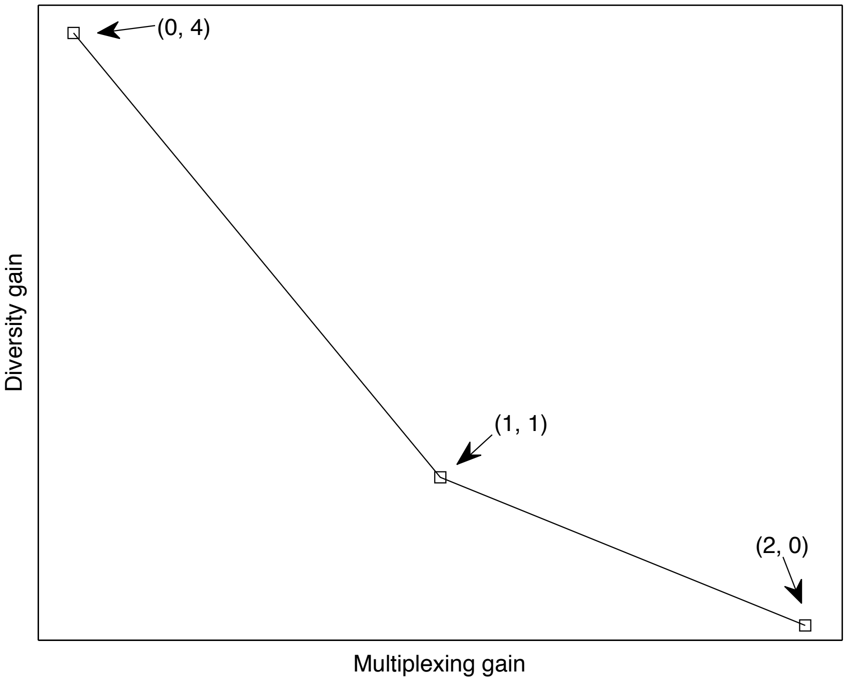


Figure 3.3: Diversity-multiplexing tradeoff.

Table 3.1: Encoding and transmission from two transmitters using the Alamouti scheme

Time	TX_0	TX_1
t_0	s_0	s_1
t_1	$-s_1*$	s_0*

achieving the requirements of next generation wireless systems in a cost effective way was to increase the transmitter complexity. This allows client devices to be smaller and only require one antenna [1].

In the Alamouti scheme, the signal is processed in blocks that are sent to different transmit antennas. The Alamouti scheme is a very attractive transmission scheme since it achieves full-rate transmission while maintaining a linear complexity for both transmitter and receiver [1].

The basic coding principle is shown in Table 3.1. In the first time slot, transmitter 0 (TX_0) sends out s_0 and transmitter 1 (TX_1) sends out s_1. In the second time slot, TX_0 sends out $-s_1*$ and TX_1 s_0*. Here, $*$ denotes the complex conjugate. The Alamouti scheme is a full-rate transmission scheme as one unique symbol is transmitted in each time slot.

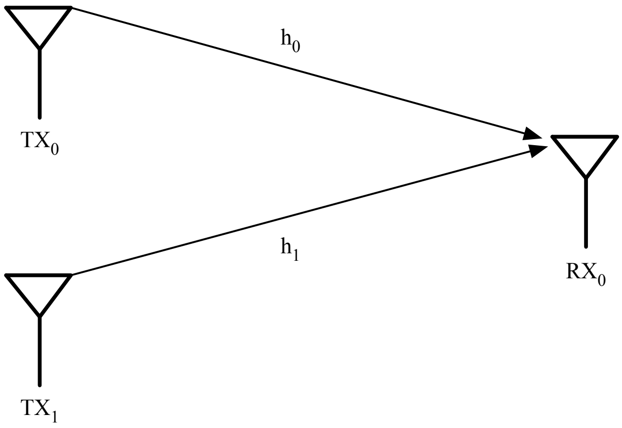


Figure 3.4: Illustration of Alamouti scheme with two transmit antennas and one receive antenna.

The signals travel through two channels, h_0 and h_1, to the receiver. The two signals must have a correlation of less than 0.7 and roughly equal transmit powers in order for the scheme to provide diversity gain [1]. An example of a transmission using Alamouti coding is shown in figure 3.4.

A slightly modified version of the Alamouti scheme is included in the DVB-T2 standard as an option and its implementation will be shown in chapter 6.

3.3 Receiver architectures

The task of a MIMO receiver is to separate the signals sent from the transmitting antennas using the signals' spatial signatures. Each receiving antenna will receive a combination of the sent signals and needs to decorrelate the signals to find the original signal. This section outlines four receiver architectures with varying computational complexities and characteristics.

3.3.1 Zero-Forcing receiver

A zero-forcing (ZF) receiver, also known as a linear decorrelator, is a simple receiver architecture that uses knowledge of the channel matrix to estimate the sent signal. The zero-forcing receiver calculates the estimated signal, $\hat{s}$, as

$$\hat{s} = \mathbf{H}^{\dagger}\mathbf{r} \tag{3.1}$$

where $\mathbf{H}^{\dagger}$ is defined by

$$\mathbf{H}^{\dagger} = (\mathbf{H}^{*}\mathbf{H})^{-1}\mathbf{H}^{*} \tag{3.2}$$

$\mathbf{H}^{*}$ denotes the complex conjugate transpose of $\mathbf{H}$ and $\mathbf{r}$ is the received signal. If $\mathbf{H}$ is square and invertible $\mathbf{H}^{\dagger} = \mathbf{H}^{-1}$.

The advantage of a zero-forcing receiver is that it will produce a perfect separation of the sent signals. However, a zero-forcing receiver will enhance noise significantly at low signal to noise ratio conditions and is thus best suited for use in high SNR conditions [3].

3.3.2 Minimum mean-square error receiver

A minimum mean-square error (MMSE) receiver takes another approach to separating the co-channel signals. Instead of aiming at perfect signal separation, it tries to minimize the impact of noise and co-channel interference in the received signal [3]. The signal estimation $\hat{s}$ is calculated according to

$$\hat{s} = (\mathbf{H}^{*}\mathbf{H} + \alpha^{2}\mathbf{I})^{-1}\mathbf{H}^{*}\mathbf{r} \tag{3.3}$$

where α is noise standard deviation [9].

A MMSE receiver is less sensitive to noise, but will also have reduced signal separation quality. In high SNR conditions where $\alpha^{2} \approx 0$, the MMSE receiver will converge to a ZF receiver [3].

3.3.3 V-BLAST receiver

The Vertical Bell Labs Space-Time Architecture (V-BLAST) increases the computational complexity of the receiver compared to ZF and MMSE receivers, but delivers improved signal separation and noise tolerance. The V-BLAST receiver works by iteratively selecting the strongest of the detected signals and removing it from the received signal, until all signals have been detected [11]. When the receiver has detected all the individual signals, it can reconstruct the sent bit stream.

3.3.4 Maximum likelihood receiver

The last receiver that will be discussed in this chapter is the Maximum likelihood (ML) receiver. The ML-receiver has the best error rate performance of the four receivers in this chapter, but is also the most computationally complex of them. The maximum-likelihood estimation of $\hat{s}$ is calculated

$$\hat{\mathbf{s}} = \arg\min_{s} ||\mathbf{r} - \mathbf{H}\mathbf{s}||^2. \tag{3.4}$$

The ML-receiver calculates the minimum over all possible codeword vectors s, which leads to an exponential growth of computational complexity with a growing number of transmit antennas [3]. Figure 3.5 shows the growth of computational complexity using the highest order modulation in DVB-T2, 256QAM.

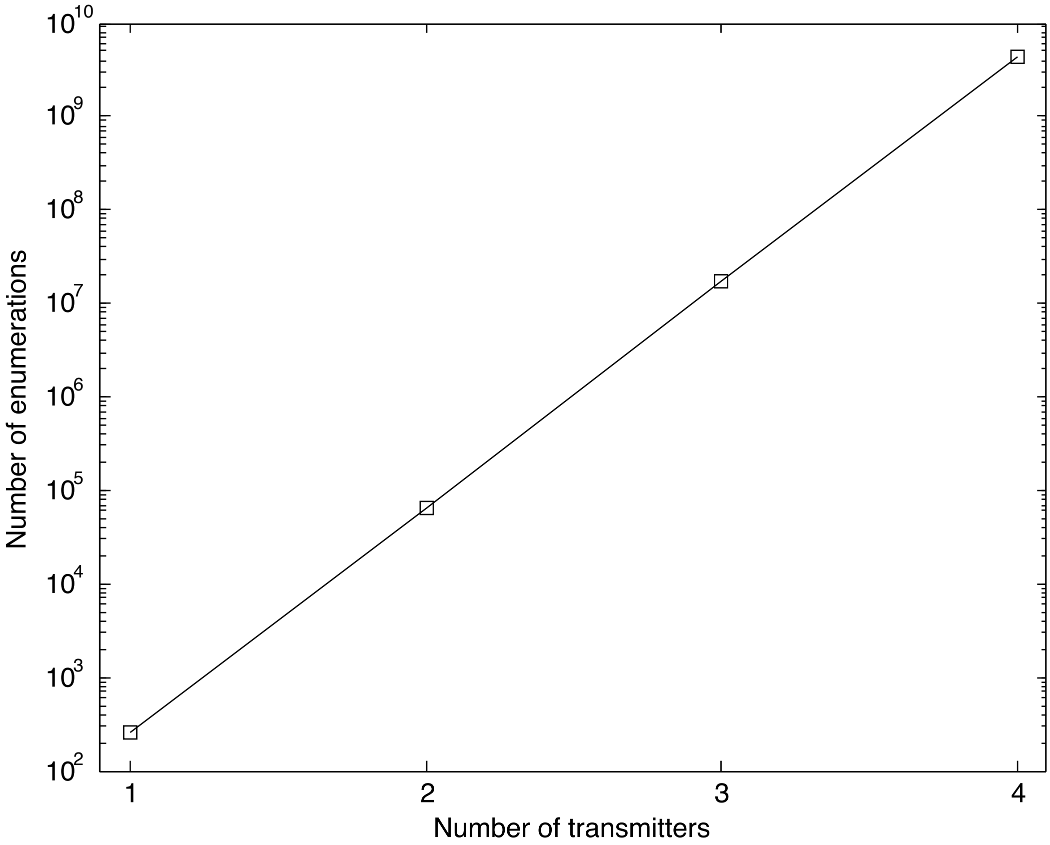


Figure 3.5: Computational complexity for a Maximum Likelihood receiver using 256QAM modulation.

CHAPTER

FOUR

DIGITAL VIDEO BROADCASTING

This chapter will introduce the Digital Video Broadcasting and Broadcast for the 21st Century projects and describe their relation to the work in this thesis. The main focus of this chapter will be on introducing the 2nd Generation Terrestrial television (DVB-T2) standard. The chapter will begin by outlining the key steps and technologies used in DVB-T2 broadcasting. Finally, the upcoming DVB-NGH standard and its implications on the work in this thesis are discussed.

4.1 DVB Project

The Digital Video Broadcasting (DVB) Project is a consortium comprising over 270 member organizations in more than 35 countries [10]. The primary function of the DVB Project is to design interoperable standards for video broadcasting. The specifications developed by the DVB Project are then standardized by a standardization organization such as the European Telecommunications Standards Institute (ETSI) [10].

In 1991, a number of European broadcasters, manufacturers and regulatory bodies formed the European Launching Group (ELG) [10]. The aim of this group was to oversee the development of digital television standards in a way that would benefit all members. The members of ELG signed a Memorandum of Understanding which stated that all members agree to license their technologies to the other members on fair, reasonable and nondiscriminatory terms [10].

The Digital Video Broadcasting Project is composed of several modules with different purposes. The four modules that constitute the DVB Project are the Commercial Module, the Technical Module, the Intellectual Property Rights Module and the Promotions & Communications Module. All modules are governed by a Steering Board and a General Assembly. The modules can be further divided into working groups that handle more specific tasks related to the work of the module. The structure of the DVB organization is illustrated in Figure 4.1.

The first step in creating a new DVB standard is that the Commercial Module draws up a Commercial Requirements document that states all market needs. The task of the Technical Module is then to create a specification that meets all implementable commercial requirements. The specification is then approved as a final specification by the Steering Board and later standardized by a standardization organization like ETSI. This process ensures that the specifications produced by DVB are market-driven and implementable [10].

The DVB Project has produced standards for terrestrial (DVB-T), cable (DVB-C), satellite (DVB-S) and handheld (DVB-H) television broadcasting as well as several other supporting standards. The different standards are all adapted to their specific operating environments. Despite the different operating requirements for different transmission systems, the DVB Project strives to keep the standards coherent. When possible, the DVB Project reuses solutions developed in one standard in other standards to improve the interoperability between standards and decrease the effort needed to develop receivers for different standards [5].

Increased demand for high definition television (HDTV) has prompted the

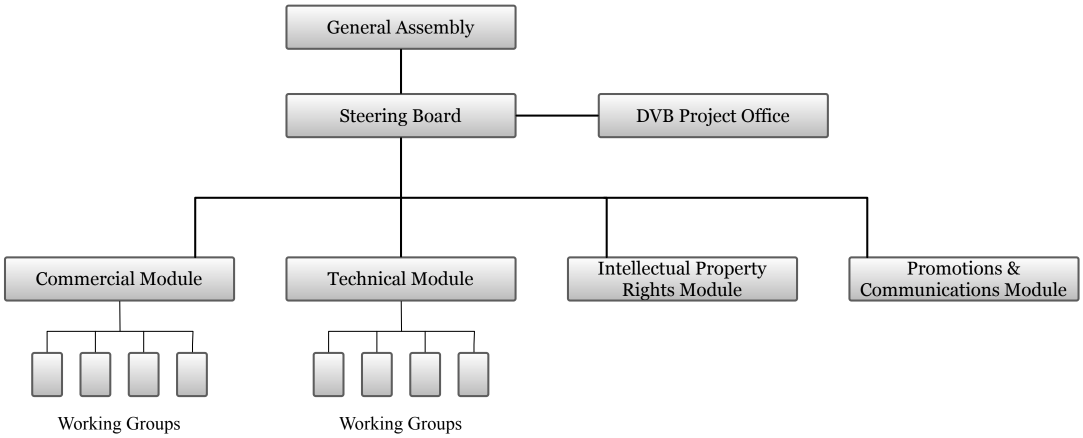


Figure 4.1: Structure of the DVB organization [10].

DVB Project to develop a second generation of standards for television broadcasting. The first standard to be completed was the 2nd Generation Satellite (DVB-S2) standard that was published as an ETSI standard in 2005. The knowledge gained from developing the second generation satellite standard was used as a base in the development of the DVB-T2 standard. The DVB-T2 specification builds upon the former DVB-T standard and expands it with more options for modulation and error detection. DVB-T2 uses the same error correction codes (LDPC and BCH) and system-layer architecture as DVB-S2.

4.2 Broadcast for the 21st Century

The Cooperation for a sustained European Leadership in Telecommunication (CELTIC) launched a project called Broadcast for the 21st Century (B21C) in 2007. The project superseded another CELTIC project called Wing TV which had done validation work on the DVB-H standard through simulations and field trials.

B21C comprises 35 partners, most of whom are also members of DVB. The project works in close coordination with DVB, helping to simulate and validate specifications.

B21C has three main purposes. The first task is to continue the validation process of DVB-H done in the Wing TV project. The project will also validate and optimize work done for the DVB-SH standard for hybrid satellite and terrestrial video broadcasting. Finally, B21C will participate in the designing of the DVB-T2 standard and running simulations to verify functionality [4]. The B21C project is scheduled to end in December 2009.

4.3 Åbo Akademi University DigiTV Group

The Åbo Akademi University (ÅAU) DigiTV group was formed in 2004 and joined the WingTV project in 2005. The WingTV project was awarded the CELTIC Excellence Award in 2008 for its valuable outputs.

The DigiTV group joined B21C alongside Tampere University of Technology and Turku University, two Finnish universities ÅAU had already cooperated with in the Wing TV project. Together, the three universities have worked on building a complete simulation chain for transmitting and receiving DVB-T2 transmissions. The initial task of Åbo Akademi University was to develop the Bit Interleaved Coding and Modulation (BICM) block shown in Figure 5.1, while the rest of the simulator was to be developed by Tampere University of Technology and Turku University.

In the effort to broaden Åbo Akademi University's knowledge on video broadcasting and enable the university to run simulations independently, a decision to implement a complete simulation chain was made. The simulator developed by ÅAU shares interfaces with a simulator used by Nokia so that the simulators may be compared to each other to verify their functionality.

4.4 DVB-T2

The DVB-T standard was published in 1997 and is already in use in over 35 countries, making it the most widely used digital terrestrial television system in the world [6]. Even though DVB-T is a flexible system allowing broadcasters to choose between different video codecs and transmission parameters to suit their needs, the need of a more robust system with a higher capacity has arisen. Several countries that have adopted DVB-T have ceased analog transmissions, freeing UHF and VHF frequencies for new applications [5].

DVB-T and DVB-T2 both target fixed and portable devices. Although not initially intended, DVB-T proved to work well even for mobile reception [6], and was later also used as a basis for the DVB handheld standard.

4.4.1 Commercial requirements

The commercial requirements document for the DVB-T2 standard was created in coordination with equipment manufacturers and broadcasters and included several enhancements over DVB-T. The commercial requirements document worked as a base for the standard creation process and ensured that the standard would adhere to the industry's needs.

The commercial requirements stated that existing antenna systems should be capable of receiving DVB-T2 transmissions [9]. This requirement ruled out the possibility for inclusion of MIMO into DVB-T2 as additional receiving antennas would be required. The standard did, however, leave open a possibility for future extension with MIMO capability by using Future Extension Frames.

The requirements further stated that a 30% increase in capacity over DVB-T should be achieved under the same constraints. The performance of DVB-T2 in single frequency networks should also be better than DVB-T.

Broadcasters that have been using DVB-T added a request to the commercial requirements for methods that would reduce peak to average power to make transmission cheaper. Greater flexibility in the choosing of bandwidth and frequency are also deemed necessary for the new standard. DVB-T2 also needed to support service specific robustness levels so that both fixed and portable devices could be targeted.

4.4.2 Design principles

When designing DVB-T2, the DVB Project aimed to create a coherent set of standards [5]. This meant that previous work done in DVB-T and other second generation systems such as DVB-S2 should be used as a base. A coherent family of standards helps equipment manufacturers create devices for the different standards by keeping modifications to a minimum.

To make DVB-T2 as flexible as possible for future extension needs, it was decided to include Future Extension Frames (FEF) into the specification. Current receivers do not use these frames yet, but they could in the future be used for example to implement MIMO transmissions in further revisions of the specification [8].

4.4.3 Benefits of DVB-T2 over DVB-T

Table 4.1 lists additions and changes made to the specification from DVB-T to DVB-T2. The largest capacity gains are derived from using 256QAM modulation in conjunction with a larger FFT size and shorter guard intervals. DVB-T2 offers a possibility of significantly lower overhead from pilot signals.

Using the new options, DVB-T2 offers theoretically a close to 50% gain in capacity compared to the DVB-T mode currently in use in the United Kingdom. Even higher gains, up to 67%, can be achieved in single frequency networks [9].

4.4.4 Overview of specification

Like DVB-T, DVB-T2 uses an OFDM modulated signal to deliver robust transmissions. The largest improvements over DVB-T are the new forward error-correcting codes and added choices for modulation, FFT size and pilot patterns. With a larger selection of parameters, it is easier for broadcasters

Table 4.1: A comparison between the DVB-T and DVB-T2 standards [5].

	DVB-T	**DVB-T2**
FEC	Convolutional coding + Reed Solomon	**LDPC + BCH**
Code Rate	1/2, 2/3, 3/4, 5/6, 7/8	1/2, **3/5**, 2/3, 3/4, **4/5**, 5/6
Modes	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM, **256QAM**
Guard Interval	1/4, 1/8, 1/16, 1/32	1/4, **19/256**, 1/8, **19/128**, 1/16, 1/32, **1/128**
FFT Size	2k, 8k	**1k**, 2k, **4k**, 8k, **16k**, **32k**
Scattered Pilots	8% of total	1%, 2%, 4% or 8% of total
Continual Pilots	2.6% of total	0.35% of total

to choose values that give a sufficiently robust signal with the minimal amount of overhead for any given environment.

DVB-T2 enables lower power consumption for receivers as receivers can choose to only decode one particular program instead of an entire multiplex of programs [14]. Each program can be sent through its own physical layer pipe (PLP) with its own modulation, coding and time interleaving [9]. This enables DVB-T2 to also deliver a specific level of robustness per service. Together with a new frame structure that allows for faster channel scanning and acquisition, DVB-T2 aims to deliver an enhanced user experience.

DVB-T2 also allows for increased robustness levels over DVB-T by incorporating constellation rotation, as described in subsection 2.4.1. As requested by the commercial requirements, DVB-T2 includes two methods for reducing peak to average power ratio to make transmitters cheaper.

Although the commercial requirements prohibited the inclusion of MIMO into the DVB-T2 specification, the specification includes a modified Alamouti MISO transmission scheme [5]. The modified structure and implementation of this scheme is described further in section 3.2.

4.5 DVB-NGH

Digital Video Broadcasting for the next generation handheld devices (DVB-NGH) is an evolution of the previous handheld standard, DVB-H. DVB-H was built with DVB-T as a base and was intended for linear broadcasting services. The requirements for multimedia content consumption have changed significantly since the introduction of DVB-H, which has sparked the need for a new standard capable of satisfying these needs [7].

DVB-NGH will facilitate the use of video on demand services, social content and location aware services [7]. It will target portable and mobile devices and leverage the advances made in second generation DVB standards like DVB-T2.

4.5.1 Commercial requirements

Like all DVB standards, DVB-NGH will build on top of previous standards and strive to make the transition from one standard to another easy. As DVB-NGH will be an evolution of DVB-H, the commercial requirements state that DVB-NGH devices should be capable of receiving DVB-H signals. The networks should also be able to reuse existing DVB-H network structures [7].

DVB-NGH is planned to be a complement to telecommunication networks such as third generation mobile (3G) and Long Term Evolution (LTE). Transmissions should incorporate a possibility for a back-channel, enabling two-way communication between client and transmitter. This capability can be used for example to send messages. DVB-NGH clients shall be location aware so that they can deliver content that is specific to the client's position [7].

DVB-NGH should be flexible enough to accommodate different types of media such as television, radio and video on demand. The requirements also specify that start-up and channel swapping times shall be significantly lower than those in DVB-H devices to enable users to enjoy the services during short periods of time, for example when waiting for a bus. To make receivers more attractive to the consumer, power consumption must be lowered compared to DVB-H devices so users can enjoy content for longer periods of time.

The final and most significant upgrade from the DVB-H specification is that DVB-NGH is required to increase capacity at any given robustness level by at least 50 percent compared to DVB-H. This will allow transmission of high-definition video as well as make it possible to send future television standards, such as three-dimensional video [7].

4.5.2 Future development

The DVB Project expects DVB-NGH to be standardized in 2011, with client devices available two years later [7]. The commercial requirements document was completed in June 2009, allowing the technical module to start working on the specification.

The Technical Module is looking into using MIMO for achieving the required 50 percent capacity increase. MIMO with polarized antennas have been the focus of the research as size constraints are strict on mobile devices.

The work in this thesis will serve as a study into the possible gains from using MIMO in DVB-NGH as the standard will be based largely on DVB-T2.

CHAPTER FIVE

DVB-T2 SIMULATOR

This chapter will introduce the Åbo Akademi University DVB-T2 simulator used as a base for the MIMO simulation support. The chapter begins with some background information on the simulator along with used design principles. After that, the chapter describes the simulator structure and different blocks of the simulator are presented to give an overview of how the simulator processes data.

5.1 Introduction

The Åbo Akademi University DVB-T2 simulator has been developed as a part of a collaboration between Turku University, Tampere University of Technology and Nokia. The simulator initially comprised only the Bit-Interleaved Coding and Modulation blocks of the simulation chain.

A desire to expand Åbo Akademi University's knowledge of digital broadcasting and allowing the university to perform entire simulations independently led to a decision to expand the simulator to cover the entire simulation chain [14].

The Åbo Akademi University simulator is written in the C programming language, allowing it to run efficiently on standard desktop computers. The main function of the simulator is to perform bit-error rate (BER) estimations, which allows for a simplified simulator design. Design considerations and requirements are presented in the following section.

5.2 Simulator features

The Åbo Akademi University simulator is built as a part of the Broadcast for the 21st Century project (B21C). As such, it was important to use standardized parameters and inputs as described in B21C documentation [14].

The simulator takes baseband frames as input and produces an OFDM modulated signal as output. The simulator can be used either for transmission or reception separately, or be chained together for a complete simulation. The user can choose the starting block and end block if only a specific part of the simulator is tested.

The simulator supports Input Mode B, which enables the use of longer time interleaving over several T2 frames [9]. Even though Input Mode B supports multiple PLPs, it was chosen to only simulate one single PLP to keep the simulator design simple. The single PLP is of type 2. The simulator has support for both shortened and extended interleaving of time interleaver blocks into T2 frames.

The simulator does not currently support Level 1 and 2 (L1 and L2) signaling or in-band signaling. The simulator will not either use P1 and P2 pilot symbols or frame closing symbols. The data that would normally be carried in L1 are read from a data structure instead. These features have been omitted because they do not affect the bit-error rate estimations that this simulator focuses on.

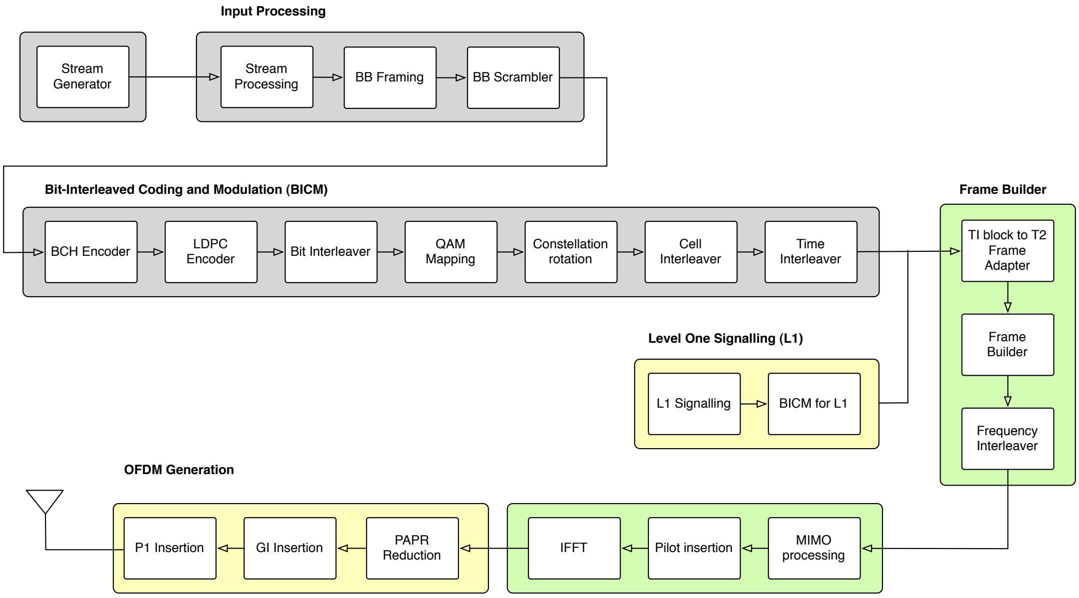


Figure 5.1: Block diagram of the DVB-T2 transmitter.

5.3 Simulator interfaces

Figure 5.1 shows a block diagram of the Åbo Akademi University DVB-T2 simulator. The gray blocks signify blocks that existed prior to the work in this thesis. The green blocks are new for this thesis and the yellow blocks are still unfinished. The blocks follow the interfaces defined by the DVB-T2 Verification and Validation Group [15] with an additional frame adapter inserted before the frame builder.

The simulator interfaces are implemented as data files so that simulation data may be easily shared between different applications such as Matlab and System Studio. The data file format is shown in Appendix A. A data file can be saved and loaded between each simulator block to simplify testing of specific parts of the simulator. All simulation data and parameters are kept in memory during a normal simulation run to speed up simulation. When using more than one antenna, the size of the data block in the file will be $N_{TX} \times$ blocksize on the transmitter side and $N_{RX} \times$ blocksize on the receiver side. The data from each antenna are appended to the data of the previous antenna (Figure 5.2). Blocks processing multi-antenna data can

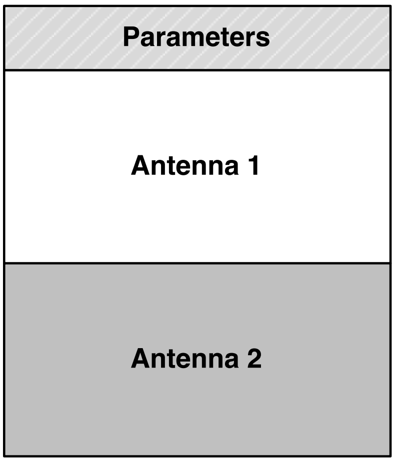


Figure 5.2: Data structure when using two antennas.

then access the data for different antennas by splitting the input based on system parameters for number of transmitters or receivers.

5.4 Program structure

Each block in the Åbo Akademi University DVB-T2 simulator is in a separate C-file and implements at least five functions:

```
int dvbt2_blockname_init(DVBT2_SYS *sys);

int dvbt2_blockname_destroy();

int dvbt2_blockname_e(DVBT2_SYS *sys,
    DVBT2_DATA *in, DVBT2_DATA *out);

int dvbt2_blockname_d(DVBT2_SYS *sys,
    DVBT2_DATA *in, DVBT2_DATA *out);

int dvbt2_blockname_test(DVBT2_SYS *sys);
```

All functions receive a `DVBT2_SYS` structure holding simulation parameters defined in the simulation data file. The `init` and `destroy` methods are called from the main simulator file prior to and after each simulation. The purpose of these functions is to set up all data that the block needs to work and de-allocate all used memory once finished.

The `dvbt2_blockname_e`, or encode function, is called on when simulating the transmission of DVB-T2 signals. The encode function receives pointers to incoming and outgoing data structures. On the receiving side of the simulator, the `dvbt2_blockname_d` function performs the inverse of the encoding function. The Frame Builder has two inputs and outputs for handling input from both the Frame Adapter and L1 signaling.

The `DVBT2_DATA` structure holds information of the type of data being sent, the amount of data, as well as a pointer to the data itself. The data structure holds the type and size of the block so that the data, that are stored as a void pointer, can be correctly read. The choice of a void pointer for sending data allows all blocks to use the same data structure, even though they handle different data types.

The final function is a test function that runs both the encode and decode functions with test data to ensure that the block can indeed restore the data that it produces. The test function is called from a main test program that runs through the tests defined in all blocks with different parameter combinations.

5.5 Completed blocks

This section will describe the functionality of the simulator blocks that were completed prior to the work done in this thesis. The functionality of the new blocks will be described in the following chapter along with implementation details.

Baseband frame scrambler

The first block in the Åbo Akademi University simulator is a Baseband (BB) frame scrambler. The task of the scrambler is to randomize the frame with a pseudo random binary sequence.

Forward Error Correcting

The second block in the simulator is the first block that belongs to the Bit-interleaved Coding and Modulation (BICM) subsystem. The Forward Error Correcting (FEC) takes an baseband frame and applies a BCH outer coding and LDPC inner coding to the data, producing a FEC frame.

Bit interleaver

The error protection level is not uniform for all bits of the FEC block. The bit interleaver writes an LDPC block column by column and reads it row by row to even out the error protection level in the frame [9].

Symbol mapping

The following block in the simulator maps a FEC frame into a FEC block consisting of modulated constellation points.

Constellation rotation

The following step rotates the constellation points, as shown in Figure 2.4. Rotating the constellation gives increased modulation diversity, as both I and Q axes contain the necessary information to determine a constellation point.

Cell interleaver

The cell interleaver spreads the cells of a FEC codeword uniformly so that channel distortion and interference will be distributed in an uncorrelated manner at the receiver [9].

Time interleaver

The time interleaver is an optional block that works in three different ways:

1. It can map one time interleaver block directly onto one interleaver frame and T2 frame.
2. It can map one time interleaver block onto one interleaver frame which is split up over several T2 frames. This increases time diversity and is suitable for lower bit-rate services.
3. It can map several time interleaver blocks onto one interleaver frame which is mapped onto a T2 frame. This results in a higher bit-rate for a PLP.

This chapter described the DVB-T2 bit-interleaved coding and modulation (BICM) simulator that is used as a base for adding MIMO simulation functionality. The following chapter will look at the modifications that are needed to the existing simulator and describe what work was done for adding MIMO support to the simulator.

CHAPTER
SIX

INTEGRATION OF MIMO SUPPORT IN THE DVB-T2 SIMULATOR

This chapter describes the work done to implement a MIMO simulation platform in the existing Åbo Akademi University DVB-T2 simulator. The aim of the platform is to be flexible, as the exact MIMO transmission schemes that will be used in future DVB standards are not yet decided upon.

The chapter begins by describing work done on a few prerequisite blocks that in themselves are not MIMO related, but are needed to simulate a complete DVB-T2 system. Following that, the chapter describes how the MIMO platform was implemented. Finally, an implementation of a Rayleigh fading channel capable of simulating multi-antenna transmissions is presented.

6.1 Prerequisite blocks

Before implementing MIMO support, the existing BICM simulator needed to be extended with functionality to build T2 frames and insert pilot symbols. A Fast Fourier Transform block was also needed to transform the signal to time domain in the transmitter and back to frequency domain in the receiver.

6.1.1 Frame builder

The frame builder in the Åbo Akademi simulator consists of two parts: a time interleaver (TI) block to T2 frame adapter and a frame constructor. This block, like all blocks, receives a `DVBT2_SYS` struct that contains all the system parameters set in the data file (shown in Appendix A).

The frame adapter is an intermediary block that adapts time interleaver blocks in one of three ways into a format that the frame constructor can use. The first option is a one-to-one mapping of TI blocks to T2 frames. This is signaled by setting the parameters `TIME_IL_TYPE` to `0` and `TIME_IL_LENGTH` to `1`. In this case, the frame adapter will simply copy the input block to the output block and return.

The second case is that one TI block is split up and mapped to several T2 frames. This mode is activated by setting `TIME_IL_TYPE` to `1` and `TIME_IL_LENGTH` to a value greater than one. The value of `TIME_IL_LENGTH` will determine the amount of T2 frames a TI block will be divided into. If the TI block size is not evenly divisible by the amount of T2 frames, an error is returned. The frame adapter will buffer the TI block and return parts of it the `TIME_IL_LENGTH` next times it is called. When the buffer is exhausted, the frame adapter will reset and wait for a new TI block.

The third and last case is that several TI blocks are assembled into a single T2 frame. This mode is signaled by setting `TIME_IL_TYPE` to `0` and `TIME_IL_LENGTH` to a value greater than one. Here, the value of

`TIME_IL_LENGTH` is used to determine how many TI blocks will be inserted into a frame. The frame adapter will buffer incoming TI blocks until it has `TIME_IL_LENGTH` blocks in its buffer. The buffer is then passed on to the frame constructor and the frame adapter reset.

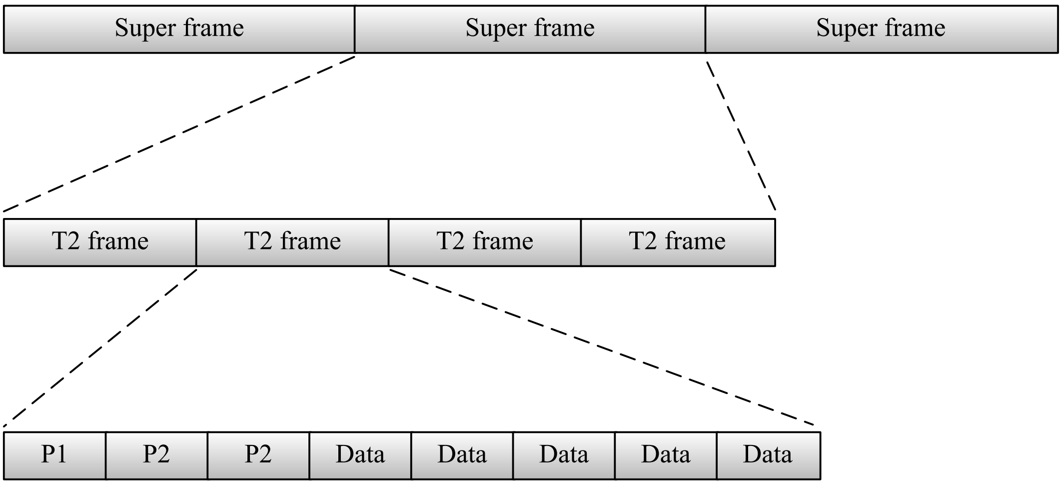


Figure 6.1: T2 frame structure [8].

Figure 6.1 shows the basic frame structure used in the DVB-T2 standard. The largest frame type in the DVB-T2 standard is a super frame. A super frame contains at least two T2 frames and may also carry future extension frames (FEF) [8]. The main task of the frame constructor is to construct a T2 frame from the output generated by the frame adapter. Normally, a T2 frame comprises a P1 pilot symbol, a variable amount of P2 pilot symbols along with data symbols and an optional frame closing symbol. In order to simplify the design, the simulator used in this thesis only uses data symbols in the T2 frames, substituting additional data symbols for all pilot and frame closing symbols. All the data that is normally carried in L1 and L2 signaling is read from the simulation parameters.

Since the data from the time interleaver is split up into correctly sized blocks by the frame adapter, the only task remaining for the frame constructor is to place the data into the data symbols and pad the rest of the frame with dummy cells. The frame adapter starts by checking whether sub slicing is to be used or not. The use of sub-slicing is signaled with the parameter `SUB_SLICES_PER_FRAME`. A value of one indicates that no sub-slicing is used, any other value indicates the number of sub-slices to be used. The data size must be evenly divisible with the number of sub-slices, otherwise an error is raised. The frame constructor determines the sub-slice length by dividing the input length of the block received form the frame adapter with the number of sub-slices. It then copies that amount of data evenly spaced into the entire frame. Figure 6.2 illustrates sub-slicing with a single physical layer pipe that is sliced into two sub-slices.

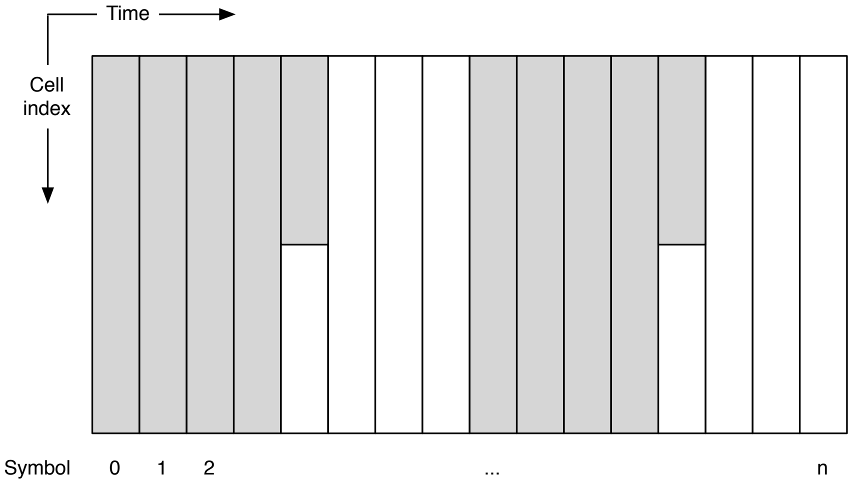


Figure 6.2: Illustration of a T2 frame using sub slicing.

All symbols that are not used to carry PLP data are filled with dummy data defined as:

$$\begin{aligned} \mathrm{Re}_{dummy} &= 2\left(\frac{1}{2} - b_{BSj}\right) \\ \mathrm{Im}_{dummy} &= 0, \end{aligned}$$

where b_{BSj} is the j^{th} bit given by the pseudo-random binary sequence (PRBS) shift register with the polynomial $1 + X^{14} + X^{15}$ and initialized with the bit-sequence 100101010000000 [8].

6.1.2 Pilot insertion

Once a frame is constructed, the simulator continues by inserting pilot carriers into the frame. These pilots are used by the receiver to calculate channel estimates.

There are three types of pilots used in DVB-T2: edge pilots, continual pilots and scattered pilots. Edge pilots are inserted as the first and last carrier in a symbol. The location of continual pilots is defined in Annex G of the DVB-T2 specification document [8]. The location of continual pilots is determined by the FFT size and pilot pattern setting used.

Scattered pilots are inserted if a carrier k in a symbol l satisfies the following equation when using normal carrier mode:

$$k \text{ mod } (D_x \cdot D_y) = D_x(l \text{ mod } D_y) \tag{6.1}$$

The parameters D_x and D_y are determined by the pilot pattern being used; for pilot pattern 1 (PP1) that the Åbo Akademi University simulator uses the values are:

$$\begin{aligned} D_x &= 3 \\ D_y &= 4 \end{aligned}$$

The amplitude of edge pilots and scattered pilots for PP1 is given by

$$\begin{aligned} \text{Re} &= \frac{3}{4}\left(\frac{1}{2} - r_{l,k}\right) \\ \text{Im} &= 0 \end{aligned}$$

The value of $r_{l,k}$ is defined by the PRBS shift register with a polynomial $X^{11} + X^2 + 1$, initialized with all ‘1’s [8].

Table 6.1: Boosting for the continual pilots [8].

FFT Size	1K	2K	4K	8K	16K	32K
A_{CP}	4/3	4/3	$(4\sqrt{2})/3$	8/3	8/3	8/3

The amplitude of the continual pilots depends on FFT size and are defined in Table 6.1.

The pilots for the second transmitter in MISO and MIMO transmissions are located in the same locations as for SISO, but have altered phases.

For the second transmitter, the scattered pilot values are inverted on alternate scattered-pilot bearing carriers:

$$\begin{aligned}\text{Re} &= 2(-1)^{k/D_x} A_{SP}(\tfrac{1}{2} - r_{l,k}) \\ \text{Im} &= 0\end{aligned}$$

Continual pilots for the second transmitter are given by:

$$\begin{aligned}\text{Re} &= \begin{cases} 2(-1)^{k/D_x} A_{CP}(\frac{1}{2} - r_{l,k}) & k \text{ mod } D_x = 0 \\ 2A_{CP}(\frac{1}{2} - r_{l,k}) & \text{otherwise} \end{cases} \\ \text{Im} &= 0\end{aligned}$$

Finally, the edge pilots are inverted compared to the first transmitter on odd OFDM symbols:

$$\begin{aligned}\text{Re} &= 2(-1)^{l} A_{SP}(\tfrac{1}{2} - r_{l,k}) \\ \text{Im} &= 0\end{aligned}$$

The reasoning behind the altered phases is that the different channels can be calculated from the sums and differences of these pilots [9].

6.1.3 Fast Fourier Transform implementation

The Fast Fourier Transform (FFT) block in the simulator does an inverse Fast Fourier Transform on the transmitter side, transforming a frequency domain signal into a time domain signal. The receiver will then perform a forward FFT to restore the frequency domain signal that the remaining blocks can process. The FFT block follows the MIMO processing block in the transmission simulation chain and will thus loop through all antennas in the data block that is given.

The Åbo Akademi University simulator uses the open source FFT library FFTW (Fastest Fast Fourier Transform in the West)[1] to perform the actual FFT transformations. FFTW was deemed suitable for this task as it offers highly optimized transformations that can use several processor cores.

A T2 frame is transformed one symbol at a time. Before transformation, each symbol's zero frequency is centered. In practice, this is implemented by swapping the halves of array that holds the carriers of the symbol, as shown in Figure 6.3.

6.2 MIMO processing

The MIMO platform was implemented in two stages. First, the prerequisite blocks were completed and verified to work correctly. The simulations and results from this will be presented in the following chapters.

Once SISO transmission was working, the actual work on the MIMO platform could begin. The MIMO simulation platform was constructed in a modular manner, so that it will be easy to expand the simulator with additional MIMO transmission schemes in the future. In this thesis, the main focus lies on 2×2 MIMO. It will therefore not discuss higher-order setups.

The MIMO processing is coordinated by the MIMO processing block (see

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[1] http://www.fftw.org/

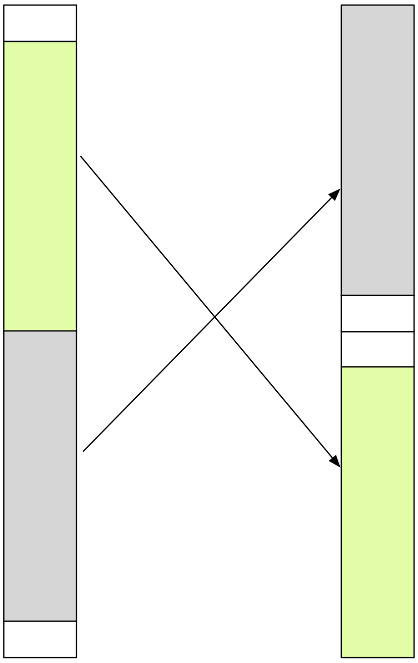

Figure 6.3: Centering of zero frequency of a symbol before Fast Fourier Transformation.

Figure 6.4). The task of the MIMO processing block is to read system parameters to see what kind of transmission is being simulated, and call an appropriate sub-block. When called, the block will choose based on system parameters which MIMO scheme, if any, is to be used and calls the corresponding function. Each MIMO scheme can additionally choose to use different receivers based on system parameters. This design was chosen because it can easily be extended in the future with different MIMO schemes and receivers.

In the current implementation, the MIMO processing block can work in one of three ways:

The first mode is that a simple SISO transmission scheme is used. This mode, signaled by `P2_TYPE = T2_SISO`, will simply pass along the signal without modifying it.

The second mode is MISO transmission which will call the Alamouti coding sub-block. The Alamouti coding sub-block will encode the signal with a

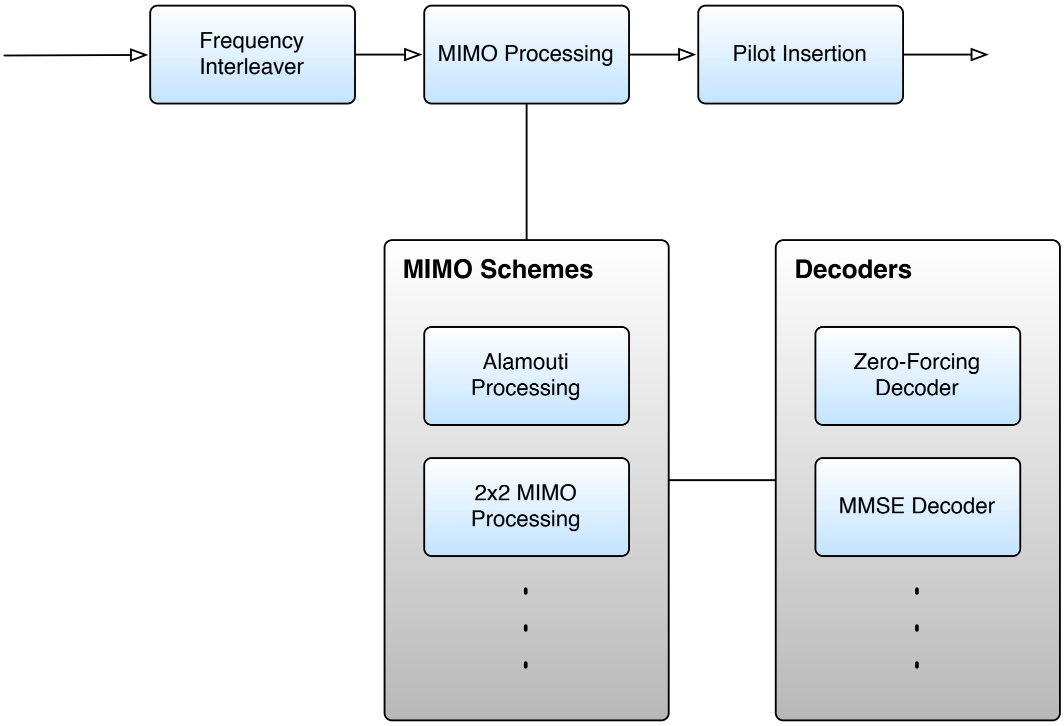

Figure 6.4: Diagram showing the design of the MIMO processing block.

modified Alamouti space-time block code that works on OFDM cells. The block outputs a signal to two antennas, so the output will have a block size double that of the input. The modified Alamouti code used for the first transmitter, $e_{m,l,p}(TX1)$ and the second transmitter, $e_{m,l,p}(TX2)$, is given by:

$$\begin{array}{ll} e_{m,l,p}(TX1) = a_{m,l,p} & e_{m,l,p}(TX1) = a_{m,l,p+1} p \in \{0, 2, 4, 6, \dots, N_{data} - 2\} \\ e_{m,l,p}(TX2) = -a^*_{m,l,p} & e_{m,l,p}(TX2) = a^*_{m,l,p+1} p \in \{0, 2, 4, 6, \dots, N_{data} - 2\} \end{array}$$

The third option is a simple 2×2 MIMO transmission scheme. This scheme does not apply any kind of special coding to the sent data. This mode will split the incoming data to two outputs, sending every other cell to every other transmitter.

Both the MISO and MIMO mode can call on any of the MIMO receivers that are implemented. In this thesis, the zero-forcing receiver and minimum mean-square error receivers shown in section 3.3 were implemented. All receivers accept a channel estimate matrix and a received signal vector as input, allowing the same decoders to be used regardless of the number of transmitters and receivers used. The structure allows for easy addition of more elaborate receiver structures should the need for them arise.

The Armadillo C++ Linear algebra library[2] was chosen to handle matrix and vector operations in the simulator. Armadillo provides classes for matrices and vectors and supports various matrix decompositions through integration with LAPACK[3] and ATLAS[4] libraries.

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[2] http://arma.sourceforge.net/

[3] http://www.netlib.org/lapack/

[4] http://math-atlas.sourceforge.net/

6.3 Channel model

The addition of MIMO capabilities at the transmitter and receiver required a channel model that can simulate a multi-path fading channel. The constructed channel model is a generic Rayleigh (see 2.6.2) channel that works for a given number of transmitters and receivers.

The channel model works by generating a channel transfer matrix, **H**, with N_{TX} columns and N_{RX} rows.

$$\mathbf{H} = \begin{bmatrix} h_{0,0} & h_{0,1} & \cdots & h_{0,N_{RX}-1} \\ h_{1,0} & h_{1,1} & \cdots & h_{1,N_{RX}-1} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_{TX}-1,0} & h_{N_{TX}-1,1} & \cdots & h_{N_{TX}-1,N_{RX}-1} \end{bmatrix}$$

Each element in the H matrix is a circularly symmetric complex Gaussian random variable, where the real and imaginary parts are zero mean i.i.d. (independent and identically distributed) [16].

This matrix is multiplied by the sent signal vector, s:

$$\mathbf{s} = \begin{bmatrix} s_0 \\ s_1 \\ \vdots \\ s_{N_{TX}-1} \end{bmatrix}$$

Finally, an additive white Gaussian noise vector, n, is added to the product. The received vector r with N_{RX} elements is then given by:

$$\mathbf{r} = \mathbf{H} \cdot \mathbf{s} + \mathbf{n} \tag{6.2}$$

This channel model is a very crude model of a multi-path fading channel, but serves as a fair estimation of a richly scattered environment.

CHAPTER
SEVEN

SIMULATION

7.1 Introduction

The simulations performed in this thesis have three goals. First, to identify if the discrepancies between the previous Åbo Akademi University simulation results and those presented in the DVB-T2 Implementation Guidelines [9] were caused by the lack of frequency interleaving and additional time interleaving from the frame builder. Second, the simulations aim to assure that the newly added blocks do not break any of the existing functionality. Finally, simulations with the newly added MIMO blocks were conducted to ensure that they worked correctly.

7.2 Simulation configuration

The simulations were run on several workstation computers running Linux-based operating systems. The workstation computers had Intel Core 2 Duo processors and between two and four GB of RAM. The workload was distributed between the computers as shown in Figure 7.1.

The main computer sends simulation data files for different modulations and code rates to several other computers and starts simulations on them. All computers run their simulation tasks independently and store their results in a central database server. When the simulations are completed, the results can be retrieved from the database and analyzed. The resulting data is plotted using GnuPlot[1] to produce bit-error rate diagrams.

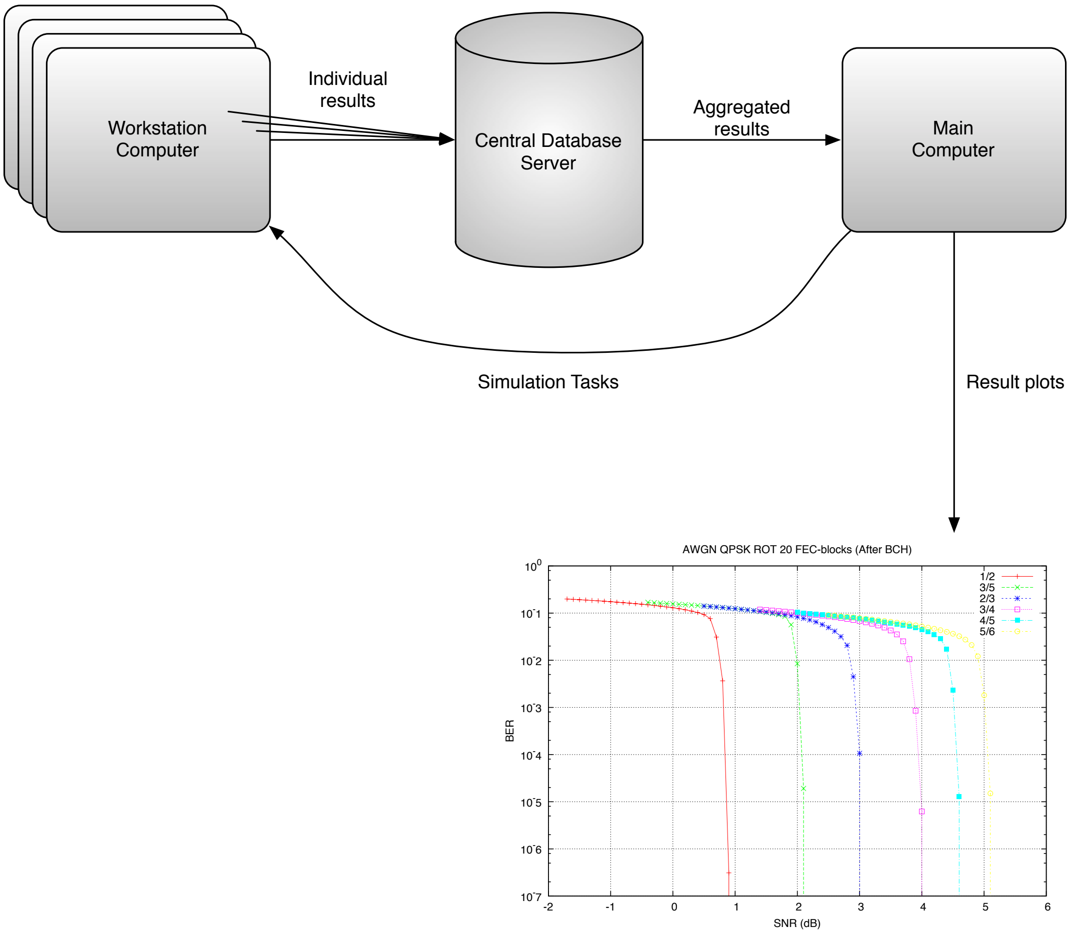

Figure 7.1: Illustration of workflow for performing bit-error rate simulations using the Åbo Akademi University simulator.

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[1] http://www.gnuplot.info/

7.3 Parameter values

The `generatePRBSData` program was used to generate a data file for each combination of code rate and modulation. All simulations were run with a FFT size of 8k. Each file contained the highest number of forward error correction blocks that can fit into one T2-frame. By filling the frame with as many FEC blocks as possible, the overhead of running the blocks operating on T2 frames was kept at a minimum.

7.4 Results

The results from the new SISO simulations were compared to results obtained before the addition of the new blocks constructed in this thesis and with the reference values provided in the DVB-T2 Implementation Guidelines[9].

The signal to noise ratio needed for a 10^{-4} bit error rate in an AWGN channel are listed in tables 7.1 for short FEC code and 7.2 for long FEC code. The results are also presented as bit-error rate diagrams in Appendix B. The IG columns correspond to the reference values from the Implementation Guidelines, the ÅAU Old columns are values from simulations prior to the work in this thesis and the ÅAU New columns are the simulation results from the simulations run as part of this thesis.

The added blocks have contributed to an improvement of 0.1dB compared to the previous simulation results from the ÅAU simulator. With the addition of the new blocks, the simulator now performs comparable with the reference values in many cases, and even better in some cases. It can, however, be noted that the ÅAU simulator performs significantly worse than the Implementation Guideline values with low code rate transmissions.

The new blocks have apparently not broken any existing functionality in the simulator. The new simulations performed can be used as a baseline for

Table 7.1: Required SNR to achieve a bit-error rate of 10^{-4} after BCH decoding using short FEC code in an AWGN channel.

Modulation	Code Rate	IG	ÅAU Old	ÅAU New
QPSK	1/2	0.4	0.5	0.4
	3/5	2.2	2.2	2.1
	2/3	3.1	3.2	3.0
	3/4	4.0	4.1	4.0
	4/5	4.6	4.7	4.6
	5/6	5.1	5.2	5.1
16 QAM	1/2	5.2	5.5	5.4
	3/5	7.5	7.7	7.6
	2/3	8.8	8.8	8.8
	3/4	10.0	10.1	10.0
	4/5	10.8	10.8	10.7
	5/6	11.4	11.4	11.3
64 QAM	1/2	8.7	9.7	9.5
	3/5	12.0	12.4	12.2
	2/3	13.4	13.6	13.5
	3/4	15.2	15.3	15.2
	4/5	16.1	16.1	16.0
	5/6	16.8	16.9	16.7
256 QAM	1/2	12.1	13.5	13.2
	3/5	16.5	17.2	17.0
	2/3	17.7	18.2	18.0
	3/4	19.9	20.1	20.0
	4/5	21.2	21.3	21.2
	5/6	22.0	22.1	22.0

Table 7.2: Required SNR to achieve a bit-error rate of 10^{-4} after BCH decoding using long FEC code in an AWGN channel.

Modulation	Code Rate	IG	ÅAU Old	ÅAU New
QPSK	1/2	0.8	0.9	0.9
	3/5	2.1	2.2	2.1
	2/3	2.9	3.0	3.0
	3/4	3.9	4.0	3.9
	4/5	4.5	4.6	4.6
	5/6	5.0	5.1	5.1
16 QAM	1/2	5.7	6.1	6.0
	3/5	7.4	7.7	7.7
	2/3	8.6	8.8	8.7
	3/4	9.8	9.9	9.8
	4/5	10.6	10.7	10.7
	5/6	11.2	11.3	11.2
64 QAM	1/2	9.6	10.3	10.3
	3/5	11.7	12.4	12.4
	2/3	13.2	13.5	13.4
	3/4	14.9	15.0	15.0
	4/5	15.9	16.0	16.0
	5/6	16.6	16.7	16.6
256 QAM	1/2	12.8	14.3	14.2
	3/5	15.6	16.9	16.8
	2/3	17.5	18.0	17.9
	3/4	19.7	19.9	19.9
	4/5	21.1	21.2	21.1
	5/6	21.8	21.9	21.9

comparing the performance of MIMO schemes built upon the new MIMO simulation platform.

7.5 MIMO simulations

A second run of simulations was done using both MIMO and MISO configurations. This was done to ensure that the blocks work correctly. As the simulator still lacks proper channel estimation, an exhaustive simulation like the one performed with SISO was not possible.

Instead, the MIMO and MISO blocks were tested by transmitting the data through a Rayleigh channel without noise and saving perfect channel estimates for each data cell. This setup made it possible to run the data stream through both transmitter and receiver parts of the new blocks and assure that the data could be fully recovered.

The simulations showed that the simulator could successfully restore the sent data using both the MIMO and MISO configuration.

CHAPTER
EIGHT

CONCLUSIONS AND FURTHER WORK

8.1 Conclusions

The thesis accomplished the tasks set for it at the beginning. A simple, yet flexible, platform for evaluating MIMO transmission schemes in a DVB-T2 simulator was constructed. In addition to the MIMO platform, the existing Åbo Akademi University simulator was extended with blocks that allow simulations to be run in time-domain.

There are still some discrepancies between the results obtained from the Åbo Akademi University simulator when comparing to reference data provided by the DVB-T2 Implementation Guidelines(IG). The variance between the results is largest for low code rates, with the ÅAU simulator requiring 1.5dB higher signal to noise ratio than the IG implementation. At higher code rates, the discrepancy diminishes significantly, and the ÅAU simulator even outperforms the IG implementation on a few combinations of modulation and code rate. The fact that low code rate signals differ so significantly from the reference values suggests that the implementation of lower code rates is incorrect in the ÅAU simulator.

The MIMO simulation platform was tested and found working with noise-free signals. Simulations using channels that included noise could not be conducted as the ÅAU simulator is still lacking proper channel estimation mechanisms.

8.2 Further work

The work conducted in this thesis has prepared the Åbo Akademi University DVB-T2 simulator so that it may be used to run MIMO simulations for example to evaluate possible MIMO schemes for DVB-NGH. There are still some parts of the simulator that need to be finished so that simulations can be run with a complete simulation chain.

First, the simulator needs channel models that can accurately model real world environments. Without proper channel models, the results obtained will be of limited use as a base for decision making and performance comparison. Reliable channel estimates should be calculated from the sent pilot signals so that the simulated transmissions resemble actual conditions. The collection of MIMO receivers should also be expanded with more elaborate receivers that perform better under low SNR conditions.

Along with these MIMO related additions, the ÅAU simulator should be extended with the final blocks that are still missing. Especially, pilot symbols and the Layer 1 signaling should be carried in the signal and read from it instead of from system parameters to obtain results that model real situations more accurately.

SAMMANFATTNING

INTEGRATION AV MIMO-STÖD I EN DVB-T2-SIMULATOR

Introduktion

En allt större efterfrågan på högdefinitionsvideo och pålitligare sändningar har lett till att man undersökt nya metoder för trådlös videosändning. Detta arbete fokuserar på flerantennsystem (MIMO, eng. multiple input multiple output) som utnyttjar flera antenner vid sändning och mottagning av signaler. Genom att använda flera antenner kan MIMO-system erbjuda flera fördelar jämfört med traditionella enkelantennsystem, även kallade SISO (eng. single input single output).

Syftet med detta arbete är att bygga en plattform på vilken man kan simulera och utvärdera prestandan hos olika MIMO-system i DVB-T2-sändningar. DVB-T2 är en andragenerationsstandard för digital videosändning som strävar efter att vara ett mer flexibelt system än sin föregångare DVB-T. DVB-T2 är utvecklad för att kunna sända högdefinitionsvideo och utnyttja frekvensområden som har blivit lediga då länder har slutat sända analog television.

Arbetet börjar med en genomgång av grundläggande koncept i trådlös kommunikation för att kunna förklara hur flerantennsystem fungerar.

Därefter beskrivs fördelarna hos flerantennsystem och olika tekniker som används vid MIMO-sändning. Arbetet ger även en överblick över DVB-T2-standarden och följandegenerationsstandarden DVB-NGH för videosändning till handhållna enheter.

Till följande beskrivs Åbo Akademis DVB-T2-simulator som har utvidgats med den nya MIMO-simuleringsplattformen. Slutligen beskrivs implementationen av MIMO-plattformen och de simuleringar som gjorts för att säkerställa funktionaliteten hos plattformen.

Trådlös kommunikation

Även om signaler hanteras digitalt, sker trådlös kommunikation i sista hand alltid via analoga signaler. För att förvandla en digital signal till en analog signal används en teknik som kallas *modulering*. Modulering innebär att man ändrar en bärvåg utgående från de data som sänds.

Då en signal skickas trådlöst kommer signalen att fortplantas via flera hinder innan den når mottagaren. Detta innebär att signalen kommer att bestå av en kombination av flera fas- och amplitudförskjutna versioner av den sända signalen. Denna förvrängning av den mottagna signalen kallas för förblekning (eng. fading).

Det finns ett flertal tekniker som kan användas för att minska på förblekningen av signaler. Dessa tekniker går ut på att man sprider ut signalen i tid, frekvens eller rum. *Tidsdiversitet* innebär att signalen delas upp och sänds under en tidsperiod som är längre än tiden som en kanal är stabil. *Frekvensdiversitet* innebär att den sända signalen delas upp och sänds över ett bredare frekvensområde. *Rumsdiversitet* och *polariseringsdiversitet* delar upp signalen på flera antenner vilkas signaler överförs via olika kanaler.

Syftet med diverstitetsteknikerna är att sprida informationen på ett sådant sätt, att även om en del av informationen går förlorad, så kan den återskapas med hjälp av *felkorrigering*. I DVB-T2-sändningar används s.k.

framåtriktade felkorrigeringskoder. Att koderna är framåtriktade innebär att de sänder redundanta data som kan användas av mottagaren för att återskapa information. Andelen egentlig information jämfört med redundant information kallas för *kodförhållande*.

Flerantennsystem

För att kunna särskilja signalbanorna mellan en sändare och en mottagare kan flerantennsystem utnyttja förblekningseffekten som stör enkelantennsystem . Med hjälp av en större mängd signalbanor kan flerantennsystem erbjuda två typer av fördelar gentemot enkelantennsystem: *diversitetsfördel* och *multiplexeringsfördel*.

För att åstadkomma diversitet kombineras signalerna som överförs via de olika signalbanorna på ett konstruktivt sätt. Mottagardiversitet fås då mottagaren utnyttjar flera antenner. I bästa fall kan en mottagare med två antenner få dubbel signalstyrka jämfört med en mottagare med en antenn. Sändardiversitet fås då flera sändare används. Detta kan ske t.ex. med hjälp av kodning av den sända signalen, som i Alamouti-kodning. Diversiteten ökar pålitligheten hos överföringen, men möjliggör inte högre överföringshastighet.

Den andra fördelen hos flerantennsystem är multiplexering. Multiplexering innebär att man använder flera signalbanor för att överföra information i stället för att förbättra signalstyrkan. Multiplexering innebär att en större mängd information kan överföras utan att höja på sändningsstyrkan. För att mottagaren skall kunna skilja åt de sända signalerna är det viktigt att alla signaler har färdats via olika banor.

Det är möjligt att få både högre diversitet och högre överföringskapacitet i flerantennsystem, men högre diversitet innebär lägre överföringskapacitet och tvärtom.

Digital videosändning

Digitaltelevisionstandarden DVB-T2 har utvecklats av Digital Video Broadcasting Project som är ett konsortium bestående av över 270 medlemsorganisationer i mer än 35 länder. DVB utvecklar specifikationer för videosändning som sedan standardiseras av yttre standardiseringsorgan.

DVB-T2-standarden är en vidareutveckling av den nuvarande DVB-T-standarden för marksändning av digitaltelevision. Den nya standarden ger en större flexibilitet i val av sändningsparametrar och erbjuder en möjlighet att sända video på ett mer pålitligt sätt och med högre kvalitet.

DVB-NGH är en följandegenerations standard för videosändning till mobila klienter. Standarden är ännu i utvecklingsstadiet och det utforskas möjligheter att använda flerantennsystem för att uppnå de kommersiella kraven på 50 procent högre prestanda. Standarden kommer med stor sannolikhet basera sig på DVB-T2-standarden för att bilda en enhetlig familj av standarder.

Simuleringsplattform

Detta arbete bygger vidare på den DVB-T2-simulator som har utvecklats av DigiTV-gruppen vid Åbo Akademi. Den existerande simulatorn har använts för att göra bitfelssimuleringar med kanaler som arbetar med data i frekvensdomän.

Utvidgningen av simulatorn skedde i två stadier. Först utökades simulatorn med komponenter som möjliggjorde sändning av tidsdomänssignaler. Då detta var färdigt byggdes en flexibel plattform för MIMO-simulering. Plattformen är byggd på ett sätt som tillåter att olika typer av flerantennsystem och mottagare kombineras fritt. Plattformen har ett väldefinierat gränssnitt så att det enkelt går att lägga till nya MIMO-metoder och mottagararkitekturer.

Simulering

Simuleringarna som kördes i detta arbete hade tre olika syften. Det första syftet var att identifiera orsaken till avvikelser mellan tidigare simuleringsresultat från Åbo Akademis simulator och referensvärden givna av DVB. Det andra syftet var att försäkra att de nya komponenterna fungerade tillsammans med de tidigare implementerade komponenterna. Slutligen undersöktes funktionaliteten hos den nya MIMO-plattformen.

Resultatsanalys

Resultaten av simuleringarna visade att de nya komponenterna fungerade och ledde till förbättrad prestanda. Vid lågt kodförhållande fanns det dock stora skillnader jämfört med referensvärdena vilka tyder på fel i konstruktionen av dessa koder.

MIMO-plattformen kunde endast testas i en kanal utan störningar eftersom simulatorn inte har kanaluppskattnignsmekanismer. Resultaten av körningarna visade dock att MIMO-plattformen kunde återskapa alla data med hjälp av fullständig kännedom om en störningsfri kanal och också att de krav som ställdes på plattformen uppfylldes.

GLOSSARY

Array gain
SNR is improved by combining signals from several antennas.

Co-channel interference
Crosstalk from two transmitters using the same frequency.

Channel capacity
Maximum datarate at which reliable communication is possible.

Coherence bandwidth
Minimum frequency separation between channels

Coherence time
A time during which the transmission channel can be assumed coherent.

Diversity gain
Several replicas of a signal are sent to combat multi-path fading.

Error floor
A phenomenon where the bit-error probability of a code does not approach zero as fast for medium or high SNR as it does for low SNR.

Fading
Fluctuations in signal level due to multi-path or shadowing.

Multiplexing gain
Multiple antennas are used both for transmitting and receiving, re-

sulting in a capacity increase proportional to the number of antennas used.

Shannon limit

Theoretical maximum information transfer rate of a channel at a given level of noise.

Space-time coding

Spreads information both across time and different antennas. Achieves spatial diversity gain without needing prior knowledge of the channel.

Spectral density

Bits of information transferred per second per Hertz.

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APPENDIX
A

SIMULATOR DATA FILE

Example of a simulation data file used. The file is truncated to one data block and line breaks are added to the hexadecimal data for legibility.

```
DVBT2.NUM_SUPERFR_SIM                        =2
DVBT2.P2_TYPE                                ='T2_MISO'
DVBT2.FFT_SIZE                               ='8k'
DVBT2.BWT_EXT                                =1
DVBT2.NUM_T2_FRAMES                          =1
DVBT2.NUM_DATA_SYMBOLS                       =221
DVBT2.GUARD_INTERVAL                         ='1/4'
DVBT2.PILOT_PATTERN                          ='PP1'
DVBT2.NUM_PLP                                =1
DVBT2.SUB_SLICES_PER_FRAME                   =2
DVBT2.L1_MOD                                 ='16-QAM'
DVBT2.L1_COD                                 ='1/2'
DVBT2.L1_FEC_TYPE                            =16200
DVBT2.NUM_TX                                 =2
DVBT2.NUM_RX                                 =1
DVBT2.ENABLE.SAVE_MAT                        =1
DVBT2.ENABLE.SAVE_ASCII                      =0
```

```
DVBT2.ENABLE.TX                                  =1
DVBT2.ENABLE.TX_DATA_SEED                        =0
DVBT2.ENABLE.CH                                  =1
DVBT2.ENABLE.CH_CONV                             =1
DVBT2.ENABLE.CH_GSM_INTF                         =0
DVBT2.ENABLE.RX                                  =1
DVBT2.ENABLE.RX_P1_SYNC                          =1
DVBT2.ENABLE.RX_BER_P1                           =1
DVBT2.ENABLE.RX_BER_P2                           =1
DVBT2.ENABLE.RX_BER_INBAND                       =0
DVBT2.ENABLE.RX_BER_LDPC                         =1
DVBT2.ENABLE.RX_BER_BCH                          =0
DVBT2.CH.CH_TYPE                                 =’AWGN’
DVBT2.CH.CH_SEED                                 =0
DVBT2.CH.NOISE_SNR                               =10
DVBT2.CH.NOISE_SEED                              =0
DVBT2.CH.FREQOFF_HZ                              =0
DVBT2.CH.TIMEOFF_SAMPLES                         =1000
DVBT2.RX.ROTCON_GA                               =1
DVBT2.RX.P1_RAF                                  =’CYCL’
DVBT2.RX.P1_CDSCORRTH                            =0.000000
DVBT2.RX.LDPC_MAXNIT                             =50
DVBT2.TX.DATA_SEED                               =0
DVBT2.L1_SIGNALING.TYPE                          =1
DVBT2.L1_SIGNALING.BWT_EXT                       =0
DVBT2.L1_SIGNALING.S1                            =0
DVBT2.L1_SIGNALING.S2                            =0
DVBT2.L1_SIGNALING.L1_REPETITION_FLAG            =0
DVBT2.L1_SIGNALING.PAPR                          =’NoPAPR’
DVBT2.L1_SIGNALING.TX_ID_AVAILABILITY            =0
DVBT2.L1_SIGNALING.CELL_ID                       =0
DVBT2.L1_SIGNALING.NETWORK_ID                    =0
DVBT2.L1_SIGNALING.T2_SYSTEM_ID                  =0
DVBT2.L1_SIGNALING.REGEN_FLAG                    =0
DVBT2.L1_SIGNALING.L1_POST_EXTENSION             =0
DVBT2.L1_SIGNALING.NUM_RF                        =1
DVBT2.L1_SIGNALING.CURRENT_RF_IDX                =1
```

```
DVBT2.L1_SIGNALING.RESERVED                                  =0
DVBT2.L1_SIGNALING.NUM_AUX                                   =0
DVBT2.L1_SIGNALING.AUX_CONFIG_RFU                            =0
DVBT2.L1_SIGNALING.RF_IDX                                    =1
DVBT2.L1_SIGNALING.FREQUENCY                                 =0
DVBT2.L1_SIGNALING.FEF_TYPE                                  =0
DVBT2.L1_SIGNALING.FEF_LENGTH                                =0
DVBT2.L1_SIGNALING.FEF_INTERVAL                              =0
DVBT2.L1_SIGNALING.RESERVED_2                                =0
DVBT2.L1_SIGNALING.AUX_RFU                                   =0
DVBT2.PLP_ID                                                 =0

DVBT2.PLP.PLP_ID                                             =0
DVBT2.PLP.PLP_TYPE                                           =0
DVBT2.PLP.FIRST_FRAME_IDX                                    =0
DVBT2.PLP.PLP_COD                                            ='1/2'
DVBT2.PLP.PLP_MOD                                            ='QPSK'
DVBT2.PLP.PLP_ROTATION                                       =1
DVBT2.PLP.PLP_FEC_TYPE                                       =16200
DVBT2.PLP.FRAME_INTERVAL                                     =0
DVBT2.PLP.TIME_IL_TYPE                                       =0
DVBT2.PLP.TIME_IL_LENGTH                                     =1
DVBT2.PLP.PLP_NUM_BLOCKS                                     =173
<BLOCK>
DVBT2.PLP_ID                                                 =0
DVBT2.DATA_LENGTH              =879
DVBT2.DATA_TYPE                ='BYTE'
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2e63339fc99a66320db73158a35a255d051758e95ed4abb2cdc6
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fb29d1e6053c7c9475d8be6189f95cbba8990f95b1ebf1b305ef
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155cbb6f2219ba9b7df50be11a1c7f23f829f8a41b13b5ca4ee8
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```

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93ac071fb86d11342d8def4f89d4b66335c1c7e4248367d8ed96
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32234ece765b7571b64d216b28712e25cf3780f9dc
</DATA>
</BLOCK>
```

APPENDIX

B

Simulated bit-error rate diagrams

Below are bit-error rate diagrams for the various modulations, using both short and long FEC codes.

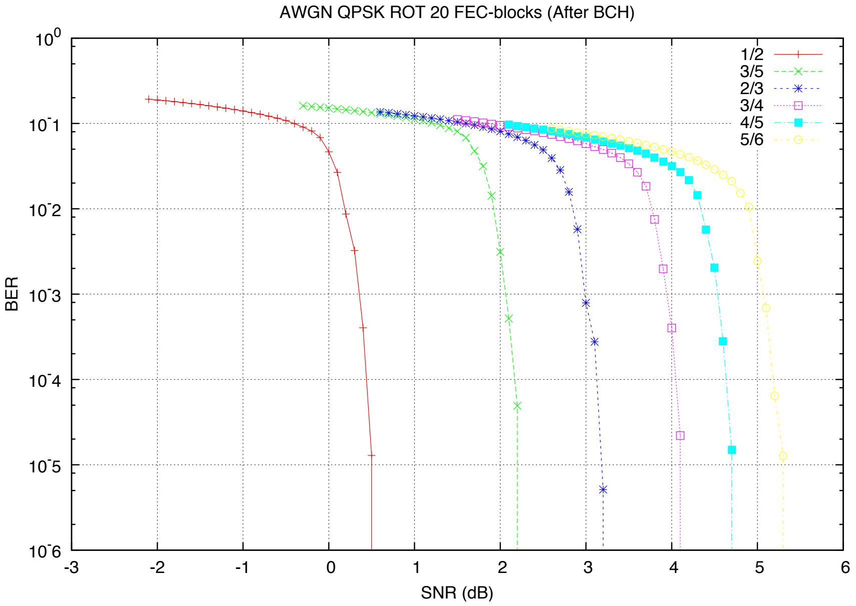

Figure B.1: Bit-error rate for QPSK modulation and short FEC code in a SISO transmission.

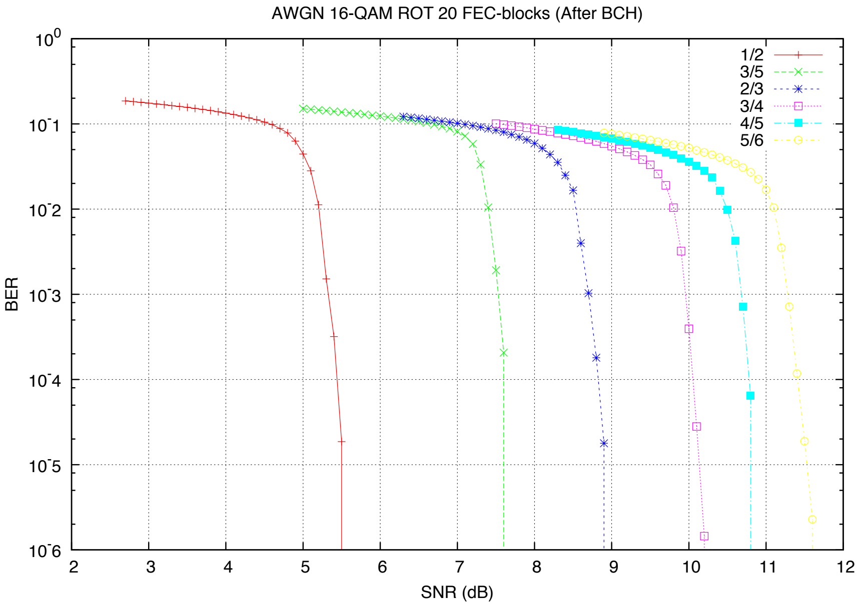

Figure B.2: Bit-error rate for 16-QAM modulation and short FEC code in a SISO transmission.

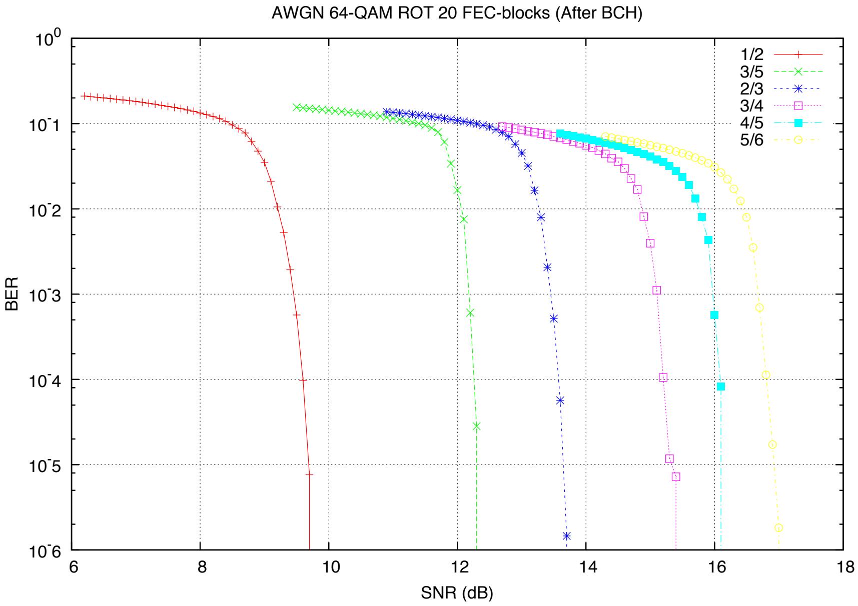

Figure B.3: Bit-error rate for 64-QAM modulation and short FEC code in a SISO transmission.

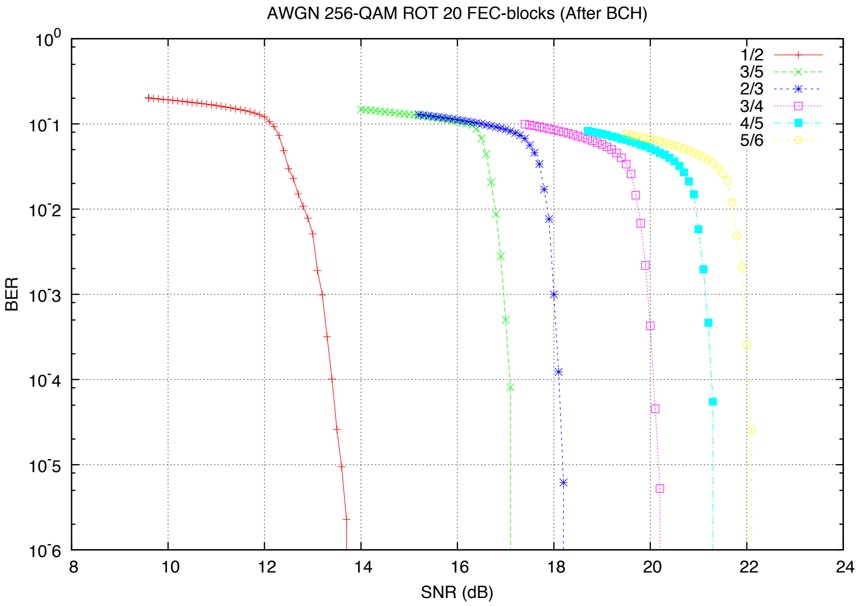

Figure B.4: Bit-error rate for 256-QAM modulation and short FEC code in a SISO transmission.

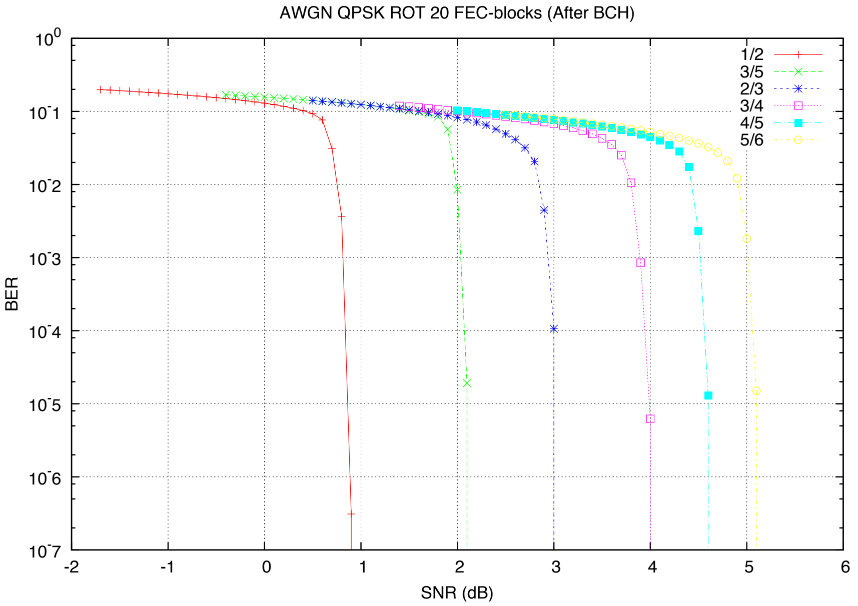

Figure B.5: Bit-error rate for QPSK modulation and long FEC code in a SISO transmission.

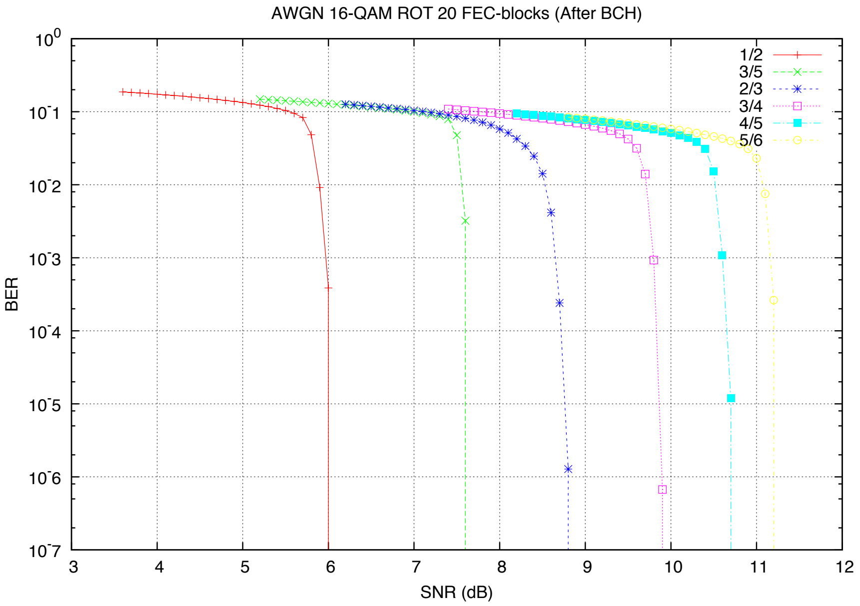

Figure B.6: Bit-error rate for 16-QAM modulation and long FEC code in a SISO transmission.

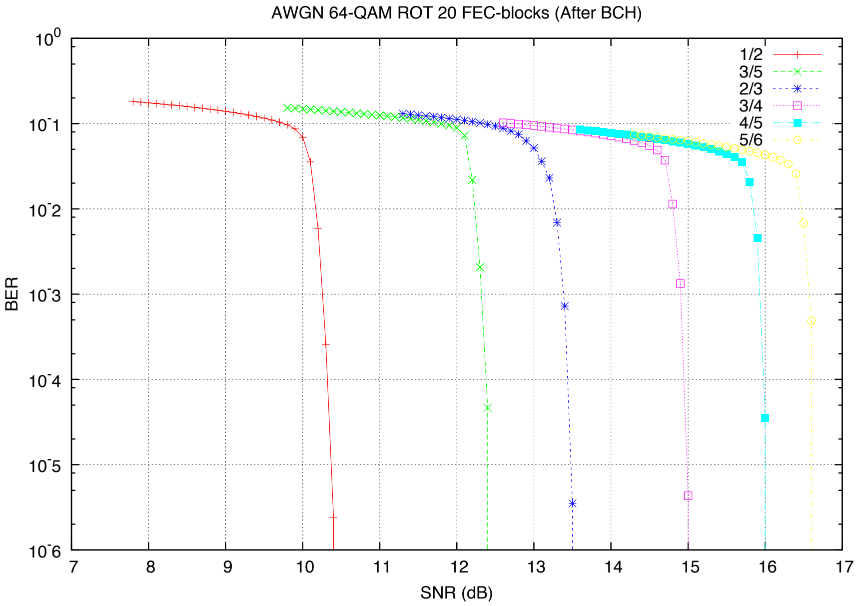

Figure B.7: Bit-error rate for 64-QAM modulation and long FEC code in a SISO transmission.

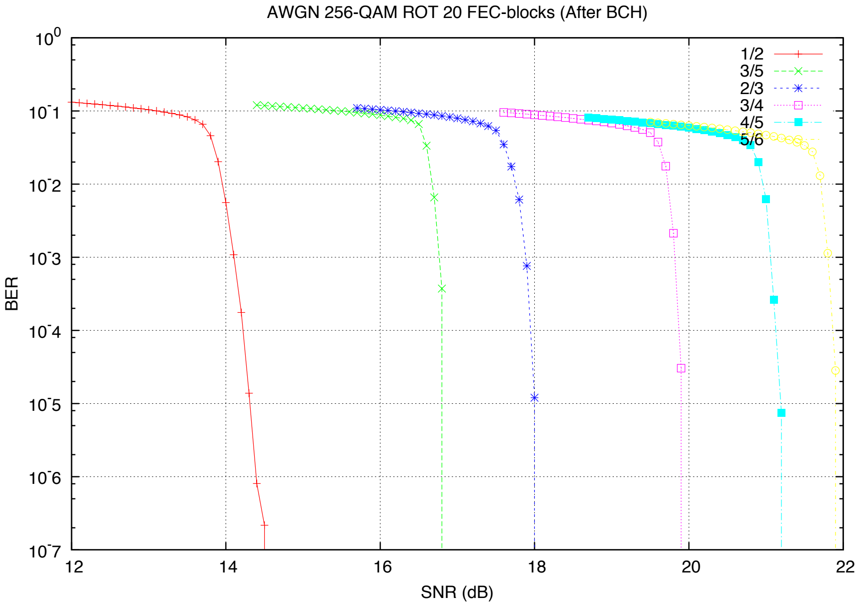

Figure B.8: Bit-error rate for 256-QAM modulation and long FEC code in a SISO transmission.