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Study and Simulation of The MIMO Enabling Technology in The LTE System

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Dedication

This project work is dedicated to our family members especially our parents for their generous support they provided us throughout our entire lives and particularly through the process of pursuing the Master degree. Because of their unconditional love and prayers, we have the chance to complete this project. This work is also dedicated to our brothers and sisters for their unremitting motivation during our study.

Last but not least, deepest thanks go to our friends and all people who took part in making this work real.

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All praises and thanks to Almighty ALLAH, the most beneficent and the most merciful, who gave us the all abilities and helped us to complete this research work.

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Abstract

Multi-antenna (MIMO) techniques are reported to improve the performance of radio communication systems in terms of their capacity and spectral efficiency. Long Term Evolution(LTE), one of the candidates for fourth generation(4G) mobile communication systems has MIMO as one of its underlying technologies and ITU defined channel models for its propagating environment.

This project undertakes a comprehensive verification of the performance of spatial multiplexing MIMO in the downlink sector of LTE. The study and the analysis is done by the use of models built using MATLAB and Simulink to carry out simulations. It is deduced that spatial multiplexing improves spectral efficiency and increases data rate of the transmission. This is more pronounced if more antennas are used in the transmitter and the receiver. Furthermore, precoding operation for open loop and closed loop spatial multiplexing depends on the channel conditions.

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List of Abbreviations

3GPP	3rd Generation Partnership Project
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BCH	Broadcast Channel
CRC	Cyclic Redundancy Check
CSI	Channel State Information
CSR	Cell-Specific Reference
CDMA	Code Division Multiple Access
DSP	Digital Signal Processor
DCI	Downlink Control Information
DLSCH	Downlink Shared Channel
DFT	Discrete Fourier Transform
DB-GSCMs	Double Bounce Geometry-based Stochastic Channel Models
DOD	Distribution of Direction of Departure
DOA	distribution of Direction of Arrival
EDGE	Enhanced Data Rates for GSM Evolution
FDM	Frequency Division Multiplexing
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform.
G	Generation
GSM	Global System for Mobile Communication
GPRS	General Packet Radio Service

GSCMs	Geometry-based Stochastic Channel Models
GUI	graphical user interface
HSDPA	High Speed Downlink Packet Access
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MU-MIMO	Multi-User Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
OFDM	Orthogonal Frequency Division Multiplexing
PDSCH	Physical Downlink Shared Channel
PHL	Physical Layer
PSS	Primary Synchronization Signals
PMI	Precoding Matrix Indicator
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service
RMS	Root Mean Square
SC-FDM	Single-Carrier Frequency Division Multiplexing
SFBC	Space–Frequency Block Coding
SMS	Short Message Service
SSS	Secondary Synchronization Signals
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SVD	Singular Value Decomposition
STBC	Space–Time Block Coding

SFBC	Space-Frequency Block Coding
SU-MIMO	Single-User MIMO
SU-MIMO	Single-User Multiple Input Multiple Output
SB-GSCMs	Single Bounce Geometry-based Stochastic Channel Models
SVD	Singular Value Decomposition
SINR	Signal to Interference plus Noise Ratio
TD	Transmit Diversity
TDD	Time-Division Duple
UE	User Equipment
UMB	Ultra-Mobile Broadband
UMTS	Universal Mobile Telecommunication Systems
ZF	Zero Forcing

Introduction

Over the years, there have been consistent improvements in the design of cellular networks. The advancement is necessary in order to cope with increasing number of users, increasing level of traffic (voice, data, etc.,), and increasing level of sophisticated but useful applications on mobile devices. The quest for higher bandwidth, faster connection times, and seamless handoffs, a scalable solution prompted engineers to seek better solutions.

Various standardization organizations have taken efforts to work on specific agenda, providing an open forum for ideas, contributions, and convergence to agreed technical specifications. The ITU, IEEE, 3GPP, WWRF, etc., held regular meetings to address these issues and they are mostly well attended by key industry players [2]. The

Figure 0.1 shows wireless technologies migration over the years.

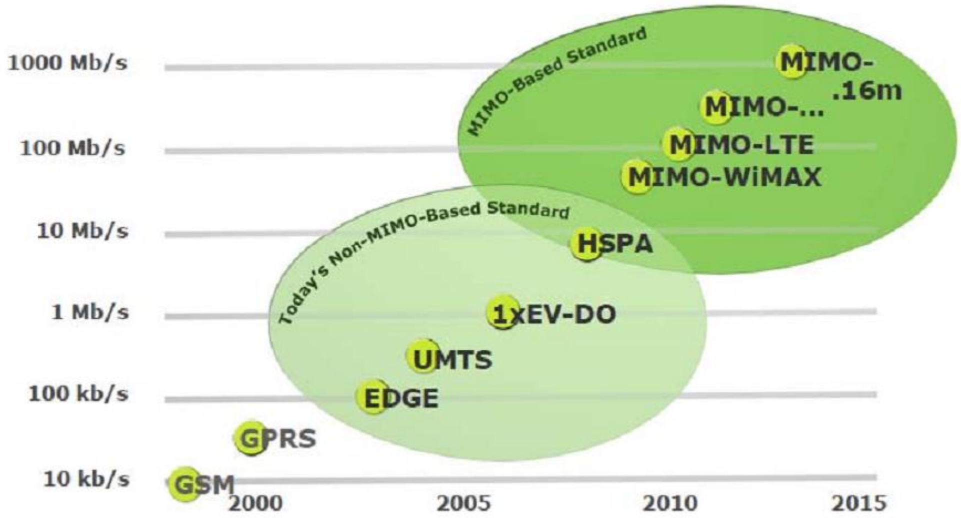

Figure 0.1 Wireless technologies migration

Chapter 1: Overview of LTE System

1.1 Motivation for LTE

LTE (Long Term Evolution) standardization within the 3GPP (3rd Generation Partnership Project) has reached a mature state. Changes in the specification are limited to corrections and bug fixes. Since end 2009, LTE mobile communication systems are deployed as a natural evolution of GSM (Global system for mobile communications) and UMTS (Universal Mobile Telecommunications System). The ITU (International Telecommunication Union) coined the term IMT-Advanced to identify mobile systems whose capabilities go beyond those of IMT 2000 (International Mobile Telecommunications). Specifically, data rate requirements are increased. In order to support advanced services and applications 100Mbps for high and 1Gbps for low mobility scenarios must be realized. Throughout 2009 3GPP worked on a study with the purpose of identifying the LTE improvements required to meet IMT-Advanced requirements. In September 2009 the 3GPP Partners made a formal submission to the ITU proposing that LTE Release 10 & beyond (LTE-Advanced) should be evaluated as a candidate for IMT-Advanced. In October 2010 LTE-Advanced successfully completed the evaluation process in ITU-R complying with or exceeding the IMT-Advanced requirements and thus became an acknowledged 4G technology [1]. Beyond achieving technical requirements, a major reason for aligning LTE with the call for IMT-Advanced is that IMT conformant systems will be candidates for future new spectrum bands that are still to be identified. This ensures that today's deployed LTE mobile networks provide an evolutionary path towards many years of commercial operation [3].

1.2 LTE requirements and specifications

Based on the ITU requirements for IMT-Advanced systems, 3GPP created a technical report summarizing LTE-Advanced requirements in [22]. The IMT-Advanced key features delineated in the circular letter inviting candidate radio interface technologies are given below:

- A high degree of commonality of functionality worldwide while retaining the flexibility to support a wide range of services and applications in a cost efficient manner;
- Compatibility of services within IMT and with fixed networks;
- Capability of interworking with other radio access systems;
- High quality mobile services;
- User equipment suitable for worldwide use;
- User-friendly applications, services and equipment;
- Worldwide roaming capability; and

- Enhanced instantaneous peak data rates to support advanced services and Applications (100 Mbps for high and 1 Gbps for low mobility were established as Targets for research).

1.3 LTE technologies

The enabling technologies of the LTE and its evolution include the OFDM, MIMO, turbo Coding, and link adaption techniques, these technologies trace their origins to well-established areas of research in communications and together help contribute to the ability of the LTE standard to meet its requirements.

1.3.1 OFDM

As elegantly described in Reference [6], the main reasons LTE selects OFDM and its single-carrier counterpart SC-FDM as the basic transmission schemes include the following: robustness to the multipath fading channel, high spectral efficiency, low-complexity implementation, and the ability to provide flexible transmission bandwidths and support advanced features such as frequency-selective scheduling, MIMO transmission, and interference coordination.

OFDM is a multicarrier transmission scheme. The main idea behind it is to subdivide the information transmitted on a wideband channel in the frequency domain and to align data symbols with multiple narrowband orthogonal subchannels known as subcarriers. When the frequency spacing between subcarriers is sufficiently small, an OFDM transmission scheme can represent a frequency-selective fading channel as a collection of narrowband flat fading subchannels. This in turn enables OFDM to provide an intuitive and simple way of estimating the channel frequency response based on transmitting known data or reference signals. With a good estimate of the channel response at the receiver, we can then recover the best estimate of the transmitted signal using a low-complexity frequency-domain equalizer. The equalizer in a sense inverts the channel frequency response at each subcarrier.

1.3.2 SC-FDM

One of the drawbacks of OFDM multicarrier transmission is the large variations in the instantaneous transmit power. This implies a reduced efficiency in power amplifiers and results in higher mobile-terminal power consumption. In uplink transmission, the design of complex power amplifiers is especially challenging. As a result, a variant of the OFDM transmission known as SC-FDM is selected in the LTE standard for uplink transmission. SC-FDM is implemented by combining a regular OFDM system with a precoding based on Discrete Fourier Transform (DFT) [6]. By applying a DFT-based precoding, SC-FDM substantially reduces fluctuations of the transmit power. The resulting uplink transmission scheme can still feature most of the benefits associated with OFDM, such as low-complexity frequency-domain equalization and frequency-domain scheduling, with less stringent requirements on the power amplifier design.

1.3.3 MIMO

MIMO is one of the key technologies deployed in the LTE standards [4]. With deep roots in mobile communications research, MIMO techniques bring to bear the advantages of using multiple antennas in order to meet the ambitious requirements of the LTE standard in terms of peak data rates and throughput.

MIMO methods can improve mobile communication in two different ways: by boosting the overall data rates and by increasing the reliability of the communication link. The MIMO algorithms used in the LTE standard can be divided into four broad categories: receive diversity, transmit diversity, beamforming, and spatial multiplexing. In transmit diversity and beamforming, we transmit redundant information on different antennas. As such, these methods do not contribute to any boost in the achievable data rates but rather make the communications link more robust. In spatial multiplexing, however, the system transmits independent (nonredundant) information on different antennas. This type of MIMO scheme can substantially boost the data rate of a given link. The extent to which data rates can be improved may be linearly proportional to the number of transmit antennas. In order to accommodate this, the LTE standard provides multiple transmit configurations of up to four transmit antennas in its downlink specification. The LTE-Advanced allows the use of up to eight transmit antennas for downlink transmission.

1.3.4 Turbo Channel Coding

Turbo coding is an evolution of the convolutional coding technology used in all previous standards with impressive near-channel capacity performance [7]. Turbo coding was first introduced in 1993 and has been deployed in 3G UMTS and HSPA systems. However, in these standards it was used as an optional way of boosting the performance of the system. In the LTE standard, on the other hand, turbo coding is the only channel coding mechanism used to process the user data.

The near-optimal performance of turbo coders is well documented, as is the computational complexity associated with their implementation. The LTE turbo coders come with many improvements, aimed at making them more efficient in their implementation. For example, by appending a CRC (Cyclic Redundancy Check) checking syndrome to the input of the turbo encoder, LTE turbo decoders can take advantage of an early termination mechanism if the quality of the code is deemed acceptable. Instead of following through with a fixed number of decoding iterations, the decoding can be stopped early when the CRC check indicates that no errors are detected. This very simple solution allows the computational complexity of the LTE turbo decoders to be reduced without severely penalizing their performance.

1.3.5 Link Adaptation

Link adaptation is defined as a collection of techniques for changing and adapting the transmission parameters of a mobile communication system to better respond to the dynamic nature of the communication channel.

Depending on the channel quality, we can use different modulation and coding techniques (adaptive modulation and coding), change the number of transmit or receive antennas (adaptive MIMO), and even change the transmission bandwidth (adaptive bandwidth). Closely related to link adaptation is channel-dependent scheduling in a mobile communication system. Scheduling deals with the question of how to share the radio resources between different users in order to achieve more efficient resource utilizations.

Typically, we need to either minimize the amount of resources allocated to each user or match the resources to the type and priority of the user data. Channel-dependent scheduling aims to accommodate as many users as possible, while satisfying the best quality-of-service requirements that may exist based on the instantaneous channel condition.

1.4 LTE Physical Layer Modeling

Physical layer (PHY) modeling involves all the processing performed on bits of data that are handed down from the higher layers to the PHY. It describes how various transport channels are mapped to physical channels, how signal processing is performed on each of these channels, and how data are ultimately transported to the antenna for transmission.

For example, Figure 1.1 illustrates the PHY model for the LTE downlink transmission [4]. First, the data is multiplexed and encoded in a step known as Downlink Shared Channel processing(DLSCH). The DLSCH processing chain involves attaching a CRC code for error detection, segmenting the data into smaller chunks known as subblocks, undertaking channel-coding operations based on turbo coding for the user data, carrying out a rate-matching operation that selects the number of output bits to reflect a desired coding rate, and finally reconstructing the codeblocks into codewords.

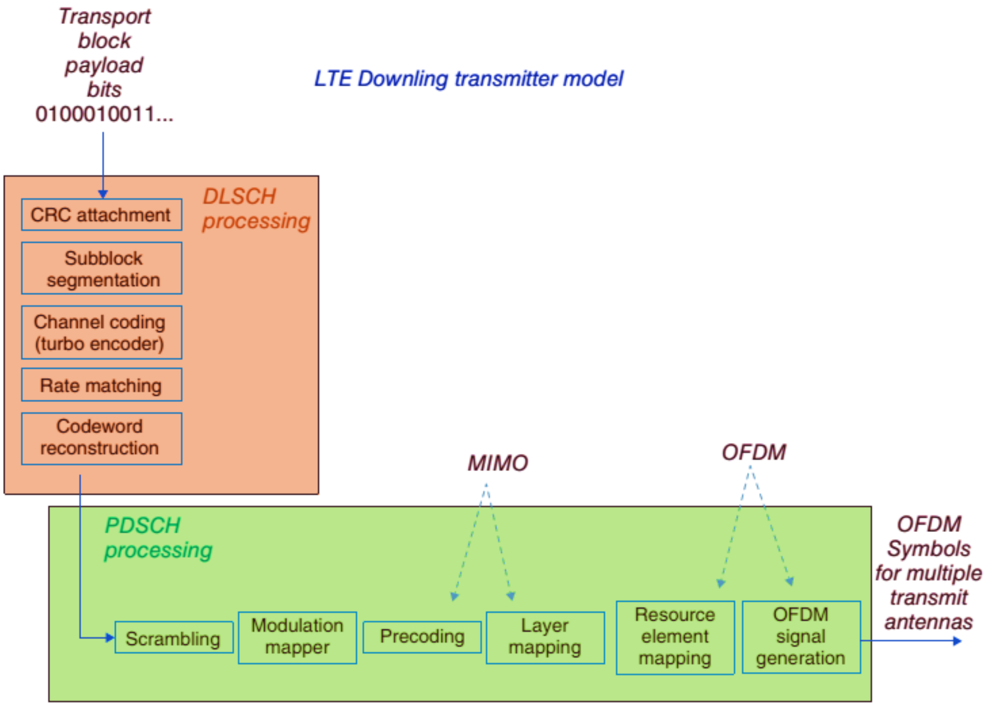

Figure 1.1 Physical layer specifications in LTE

The next phase of processing is known as physical downlink shared channel processing. In this phase, the codewords first become subject to a scrambling operation and then undergo a modulation mapping that results in a modulated symbol stream. The next step comprises the LTE MIMO or multi-antenna processing, in which a single stream of modulated symbols is subdivided into multiple substreams destined for transmission via multiple antennas. The MIMO operations can be regarded as a combination of two steps: precoding and layer mapping. Precoding scales and organizes symbols allocated to each substream and layer mapping selects and routes data into each substream to implement one of the nine different MIMO modes specified for downlink transmission. Among the available MIMO techniques implemented in downlink transmission are transmit diversity, spatial multiplexing, and beamforming. The final step in the processing chain relates to the multicarrier transmission. In downlink, the multicarrier operations are based on the OFDM transmission scheme. The OFDM transmission involves two steps. First, the resource element mapping organizes the modulated symbols of each layer within a time–frequency resource grid. On the frequency axis of the grid, the data are aligned with subcarriers in the frequency domain. In the OFDM signal-generation step, a series of OFDM symbols are generated by applying inverse Fourier transform to compute the transmitted data in time and are transported to each antenna for transmission. IN my opinion, it is remarkable that such a straightforward and intuitive transmission structure can combine all the enabling technologies so effectively that they meet the diverse and stringent IMT-Advanced requirements set out for the LTE standardization. By focusing on PHY modeling, we aim to address challenges in understanding the development of the digital signal processing associated with the LTE standard.

Chapter 2: MIMO Technology

2.1 Introduction

All radio communications systems, regardless of whether mobile radio networks like 3GPP UMTS or wireless radio networks like WLAN, must continually provide higher data rates. In addition to conventional methods, such as introducing higher modulation Types or providing larger bandwidths, this is also being achieved by using multiple Antenna systems (Multiple Input, Multiple Output – MIMO). This application note gives an introduction to basic MIMO concepts and terminology and explains how MIMO is implemented in the different radio communications standards. The MIMO terminology refers to the channel, thus the transmitter is the channel input and the receiver is the channel output. Several different diversity modes are used to make radio communications more robust, even with varying channels. These include time diversity (different timeslots and channel coding), frequency diversity (different channels, spread spectrum, and OFDM), and also spatial diversity. Spatial diversity requires the use of multiple antennas at the transmitter or the receiver end. Multiple antenna systems are typically known as Multiple Input, Multiple Output systems (MIMO). Multiple antenna technology can also be used to increase the data rate (spatial multiplexing) instead of improving robustness. In practice, both methods are used separately or in combination, depending on the channel condition [5].

2.2 MIMO Techniques

2.2.1 Conventional Radio System (SISO)

Conventional systems use one transmit and one receive antenna. In MIMO terminology, this is called Single Input, Single Output SISO (Figure 2.1).

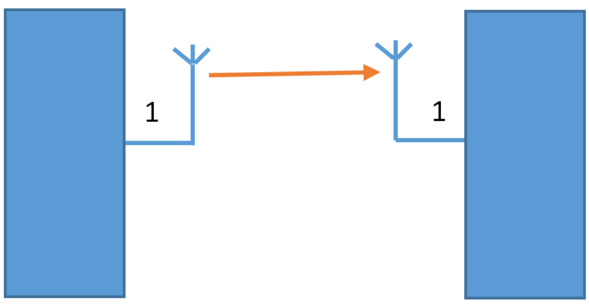

Figure 2.1 SISO antenna configuration

Shannon-Hartley theorem

According to Shannon, the capacity C of a radio channel is dependent on bandwidth B and the signal-to-noise ratio S/N. The following applies to a SISO system:

$$C = B \log_2 (1 + \frac{S}{N}) \tag{2.1}$$

2.2.2 Multiple Antenna Systems

A MIMO system typically consists of m transmit and n receive antennas (Figure 2.2). By using the same channel, every antenna receives not only the direct components intended for it, but also the indirect components intended for the other antennas. A time-independent, narrowband channel is assumed. The direct connection from antenna 1 to 1 is specified with h_{11}, etc., while the indirect connection from antenna 1 to 2 is identified as cross component h_{21}, etc. From this is obtained transmission matrix **H** with the dimension ***n x m***.

$$\mathbf{H} = \begin{bmatrix} \mathbf{h_{11}} & \mathbf{h_{12}} & \mathbf{h_{..}} & \mathbf{h_{1m}} \\ \mathbf{h_{21}} & \mathbf{h_{22}} & \mathbf{h_{..}} & \mathbf{h_{2m}} \\ \mathbf{h_{..}} & \mathbf{h_{..}} & \mathbf{h_{..}} & \mathbf{h_{.m}} \\ \mathbf{h_{n1}} & \mathbf{h_{n2}} & \mathbf{h_{n.}} & \mathbf{h_{nm}} \end{bmatrix} \tag{2.2}$$

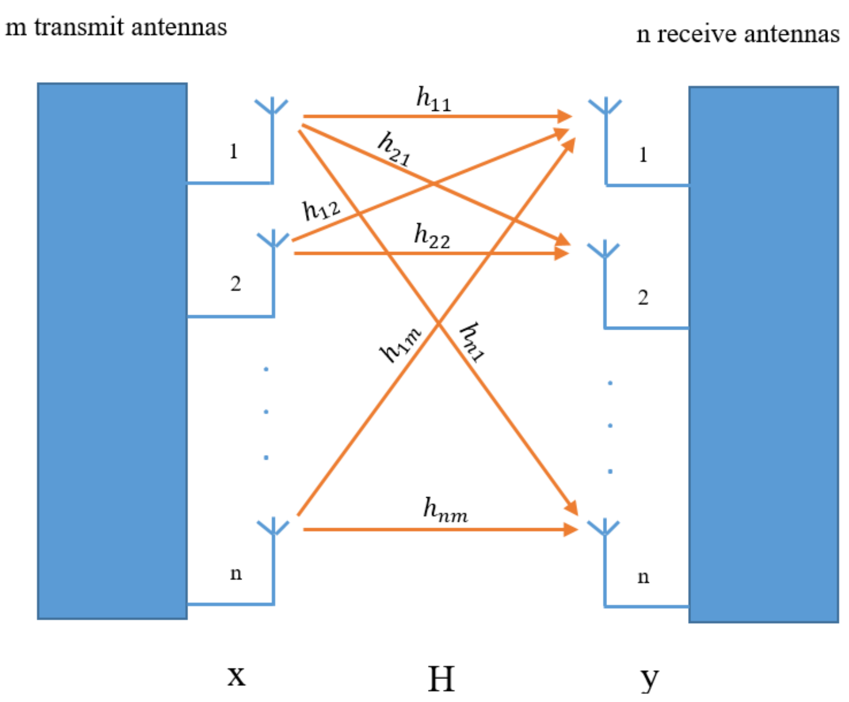

Figure 2.2 General MIMO

The following transmission formula results from receive vector y, transmit vector x, and noise n:

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \tag{2.3}$$

Data to be transmitted is divided into independent data streams. The number of streams M is always less than or equal to the number of antennas; in the case of asymmetrical (m ≠ n) antenna constellations, it is always smaller or equal the minimum number of antennas. For example, a 4x4 system could be used to transmit four or fewer streams, while a 3x2 system could transmit two or fewer streams. Theoretically, the capacity C increases linearly with the number of streams M.

$$C = MB \log_2 (1 + \frac{S}{N}) \tag{2.4}$$

Single User MIMO (SU-MIMO)

When the data rate is to be increased for a single UE (User Equipment), this is called Single User MIMO (SU-MIMO). It is illustrated in Figure 2.3.

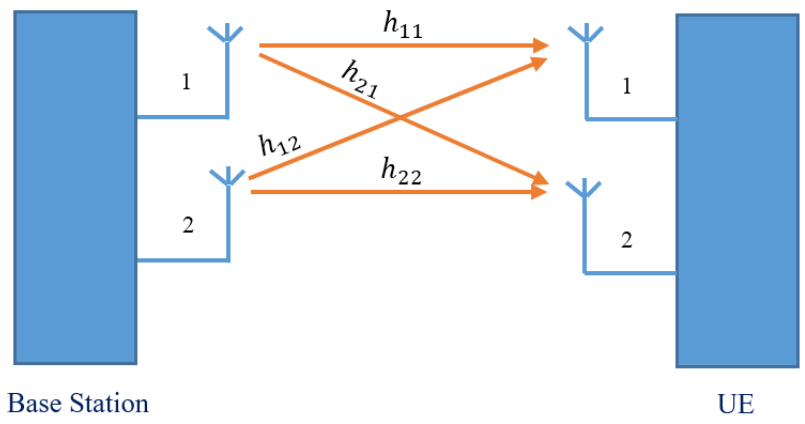

Figure 2.3 SU-MIMO

Multi User MIMO (MU-MIMO)

When the individual streams are assigned to various users, this is called Multi User MIMO (MU-MIMO) illustrated in Figure 2.4. This mode is particularly useful in the uplink because the complexity on the UE side can be kept at a minimum by using only one transmit antenna. This is also called 'collaborative MIMO'.

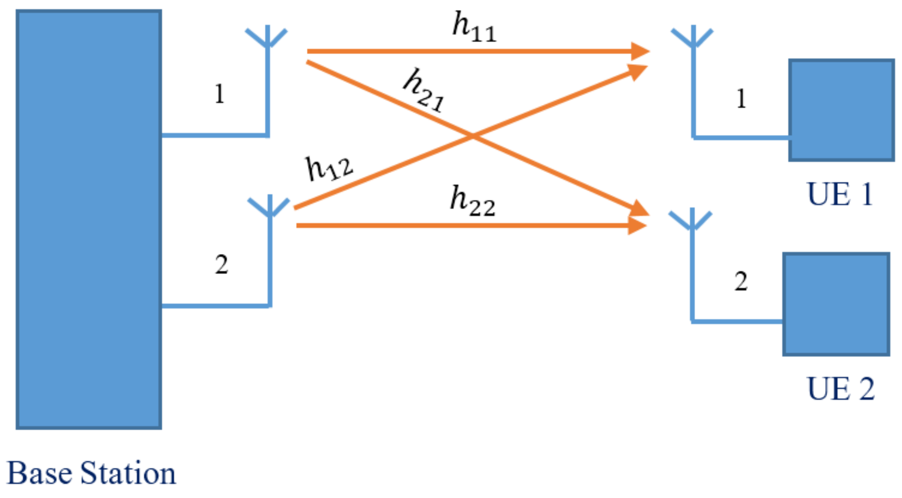

Figure 2.4 MU-MIMO

Cyclic delay diversity (CDD)

CDD introduces virtual echoes into OFDM-based systems. This increases the frequency selectivity at the receiver. In the case of CDD, the signals are transmitted by the individual antennas with a time delay. Because CDD introduces additional diversity components, it is particularly useful as an addition to spatial multiplexing.

2.2.3 Spatial Diversity

The purpose of spatial diversity is to make the transmission more robust. There is no increase in the data rate. This mode uses redundant data on different paths.

RX Diversity

RX diversity uses more antennas on the receiver side than on the transmitter side. The simplest scenario consists of two RX and one TX antenna (SIMO, 1x2) illustrated in Figure 2.5.

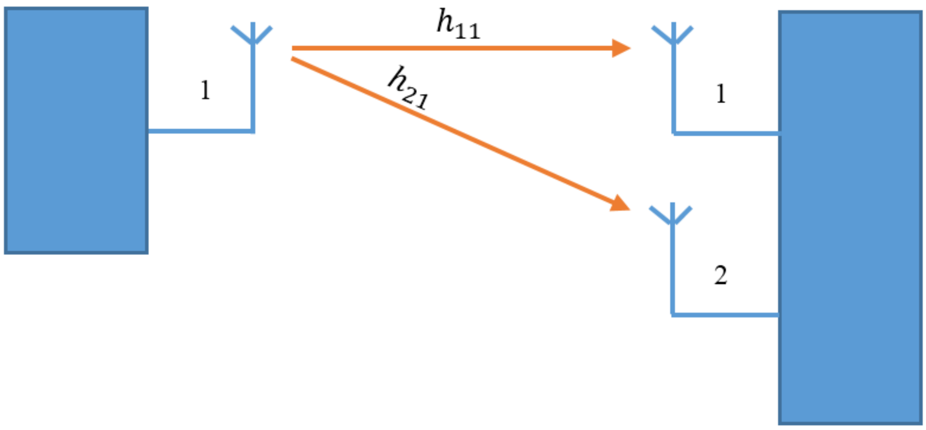

Figure 2.5 SIMO antenna configuration

Because special coding methods are not needed, this scenario is very easy to implement. Only two RF paths are needed for the receiver.

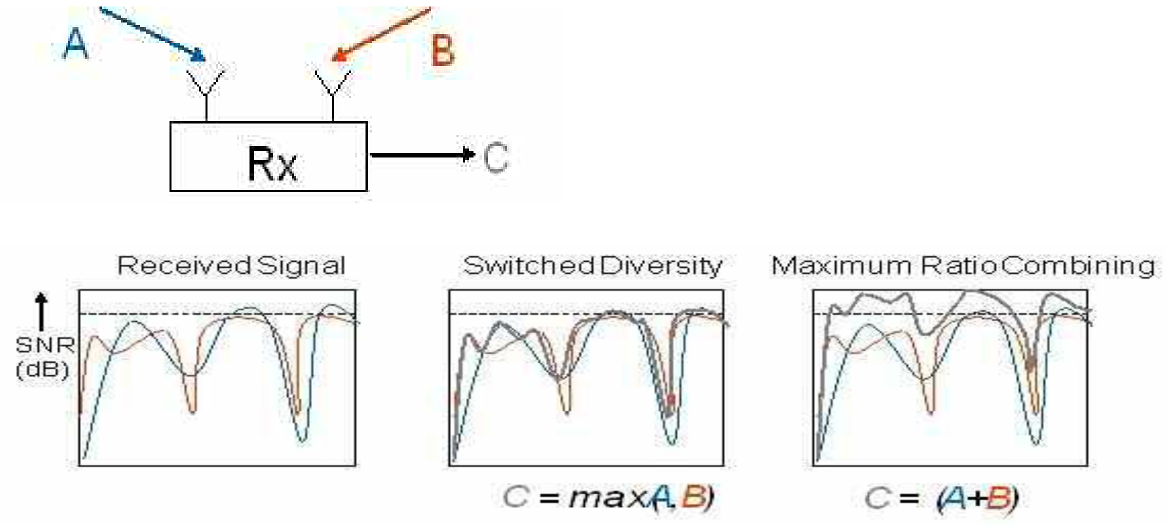

Figure 2.6 RX diversity

Because of the different transmission paths, the receiver sees two differently faded signals. By using the appropriate method in the receiver, the signal-to-noise ratio can now be increased. Switched diversity always uses the stronger signal, while maximum ratio combining uses the sum signal from the two signals (Figure 2.6).

TX Diversity

When there are more TX than RX antennas, this is called TX diversity. The simplest scenario uses two TX and one RX antenna (MISO, 2x1).

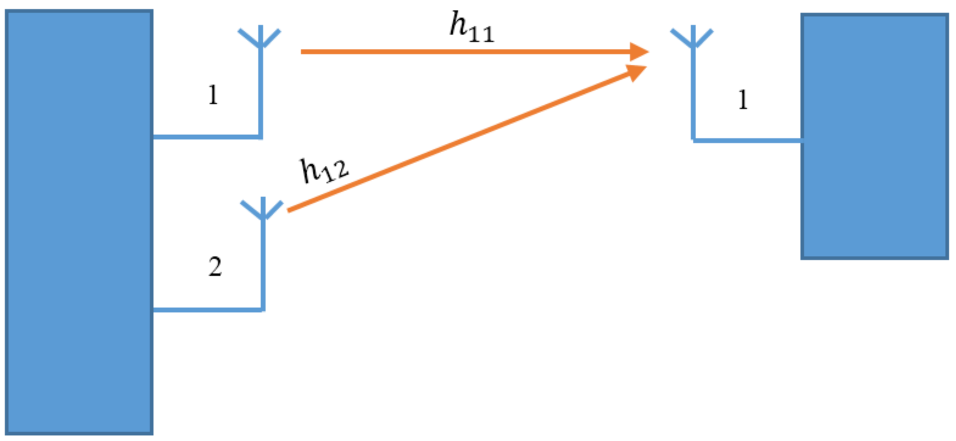

Figure 2.7 MISO antenna configuration

In this case, the same data is transmitted redundantly over two antennas (Figure 2.7). This method has the advantage that the multiple antennas and redundancy coding is moved from the mobile UE to the base station, where these technologies are simpler and cheaper to implement. To generate a redundant signal, space-time codes are used. Alamouti developed the first codes for two antennas. Space-time codes additionally improve the performance and make spatial diversity usable. The signal copy is transmitted not only from a different antenna but also at a different time. This delayed transmission is called delayed diversity. Space-time codes combine spatial and temporal signal copies as illustrated in Figure 2.8. The signals s_1 and s_2 are multiplexed in two data chains. After that, a signal replication is added to create the Alamouti space-time block code.

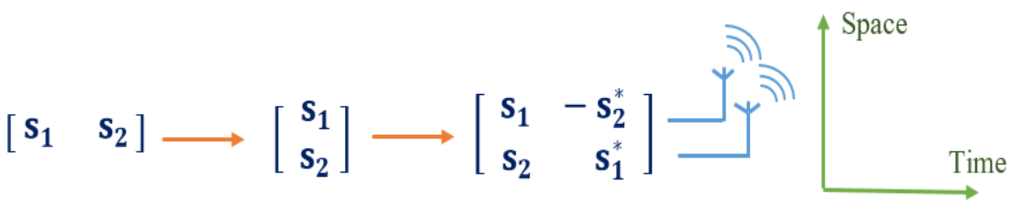

Figure 2.8 Alamouti coding

Additional pseudo-Alamouti codes were developed for multiple antennas [14] [15]. The coding can also be handled in the frequency domain. This is called Space frequency coding.

2.2.4 Spatial Multiplexing

Spatial multiplexing is not intended to make the transmission more robust; rather it increases the data rate. To do this, data is divided into separate streams; the streams are transmitted independently via separate antennas as shown in Figure 2.9. Because MIMO transmits via the same channel, transmissions using cross components not equal to 0 will mutually influence one another.

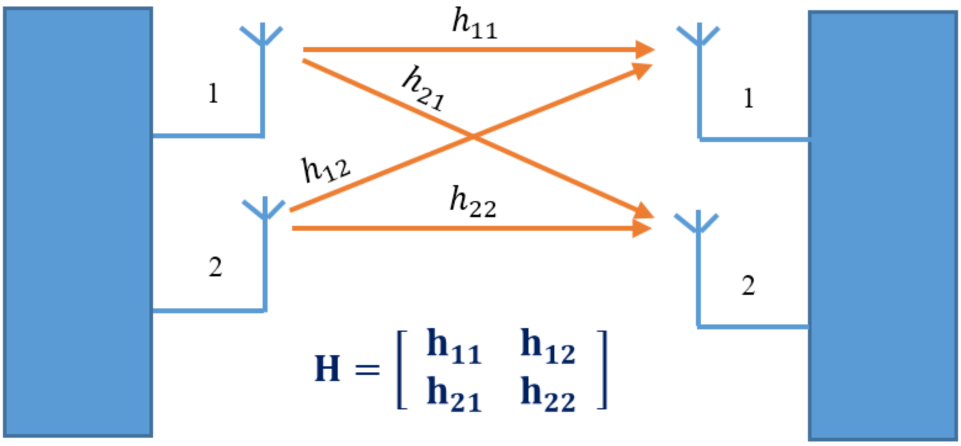

Figure 2.9 MIMO 2x2 antenna configuration

If transmission matrix H is known, the cross components can be calculated on the receiver. In the open-loop method, the transmission includes special sections that are also known to the receiver. The receiver can perform a channel estimation. In the closed-loop method, the receiver reports the channel status to the transmitter via a special feedback channel. This makes it possible to respond to changing circumstances. This technique is discussed in chapter 3 and 4.

2.2.5 Beamforming

Antenna technologies are the key in increasing network capacity. It started with sectorized antennas. These antennas illuminate 60 or 120 degrees and operate as one cell. In GSM, the capacity can be tripled, by 120 degree antennas. Adaptive antenna arrays intensify spatial multiplexing using narrow beams. Smart antennas belong to adaptive antenna arrays but differ in their smart direction of arrival (DoA) estimation. Smart antennas can form a user-specific beam. Optional feedback can reduce complexity of the array system. Beamforming is the method used to create the radiation pattern of an antenna array. It can be applied in all antenna array systems as well as MIMO systems. As shown in Figure 2.10 Smart antennas are divided into two groups:

- Phased array systems (switched beamforming) with a finite number of fixed predefined patterns.
- Adaptive array systems (AAS) (adaptive beamforming) with an infinite number of patterns adjusted to the scenario in real-time.

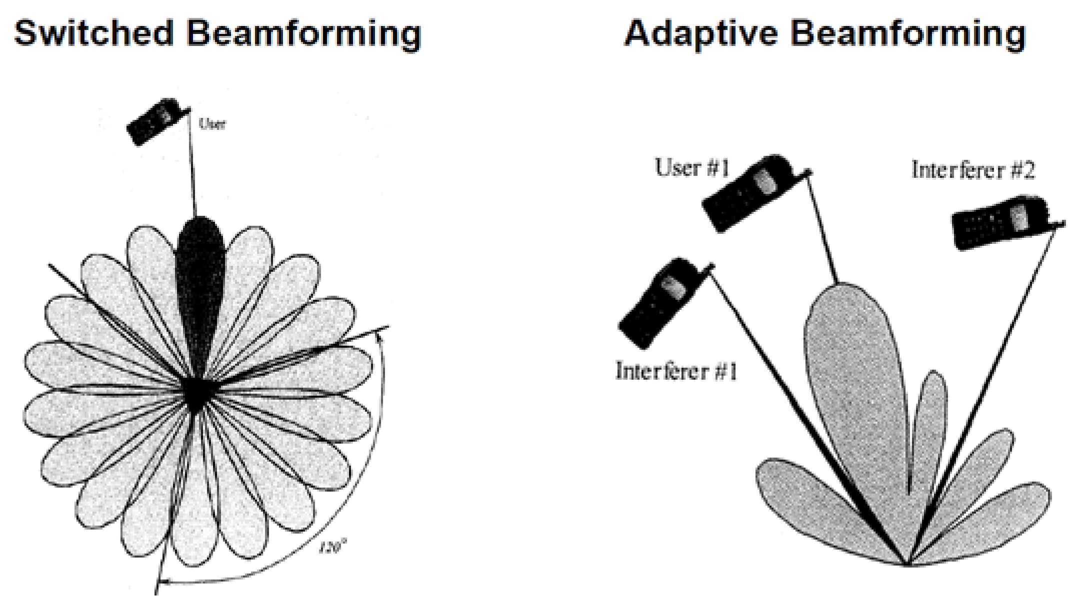

Figure 2.10 Switched beamforming and adaptive beamforming

Switched beamformers electrically calculate the DoA and switch on the fixed beam. The user only has the optimum signal strength along the center of the beam. The adaptive beamformer deals with that problem and adjusts the beam in real-time to the moving UE. The complexity and the cost of such a system is higher than the first type.

2.3 MIMO Modes in LTE

Table 2.1 summarizes the LTE transmission modes and the associated multi-antenna transmission schemes [8]. Mode uses receive diversity and mode 2 is based on transmit diversity. Modes 3 and 4 are single-user implementations of spatial multiplexing based on open-loop and closed-loop precoding, respectively. Mode 3 also uses CDD (discussed earlier).

LTE transmission modes	
Mode 1	Single-antenna transmission
Mode 2	Transmit diversity
Mode 3	Open-loop codebook-based precoding
Mode 4	Closed-loop codebook-based precoding
Mode 5	Multi-user MIMO version of transmission mode 4
Mode 6	Single-layer special case of closed-loop codebook-based precoding
Mode 7	Release 8 non-codebook-based precoding supporting only a single layer, based on beam forming
Mode 8	Release 9 non-codebook-based precoding supporting up to two layers
Mode 9	Release 10 non-codebook-based precoding supporting up to eight layers

Table 2.1 LTE transmission modes and their associated multi-antenna transmission schemes

LTE mode 5 specifies a very simple implementation of multi-user MIMO based on mode 4 with the maximum number of layers set to one. Mode 6 features beam forming and a special case of mode 4 where the number of layers is set to two. LTE modes 7–9 implement versions of spatial multiplexing without the use of codebooks, with a number of layers of 1, up to 2, and 4–8, respectively. The LTE-Advanced (Release 10) introduced major enhancements to downlink MU-MIMO by introducing modes 8 and 9. For example, mode 9 supports eight transmit antennas for transmissions of up to eight layers. These advances result directly from the introduction of new reference signals (CSI-RS and DM-RS), enabling a non-codebook-based precoding and thus adopting a lower-overhead double-codebook structure [4]. In this the project, we have focused on the third and the fourth transmission modes used in the LTE standard.

Chapter 3: Spatial Multiplexing

3.1 Introduction

In this chapter we will discuss details regarding the spatial-multiplexing approach to MIMO transmission in the LTE standard. These include channel model and capacity calculation and the way in which it implements precoding and layer mapping, which eventually lead to generation of OFDM signals for simultaneous transmission over multiple antennas.

3.2 MIMO Channel Model and Capacity

For the case of multiple antennas at both the receiver and the transmitter ends (Figure 3.1), the channel exhibits multiple inputs and multiple outputs [9].

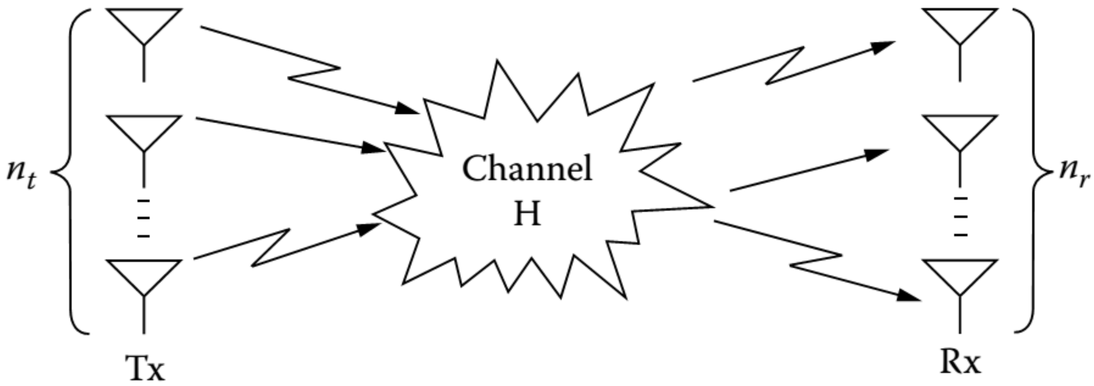

Figure 3.1 The MIMO channel

We consider an antenna array with n_t elements at the transmitter and an antenna array with n_r elements at the receiver. The impulse response of the channel between the *j*th transmitter element and the *i*th receiver element is denoted as $h_{ij}(\tau,t)$. The MIMO channel can then be described by the $n_r \times n_t$ $\mathbf{H}(\tau,t)$ matrix:

$$\mathbf{H}(\tau,\mathbf{t}) = \begin{bmatrix} \mathbf{h}_{11}(\tau,\mathbf{t}) & \mathbf{h}_{12}(\tau,\mathbf{t}) & \mathbf{h}_{..} & \mathbf{h}_{1\mathbf{n}_\mathbf{t}}(\tau,\mathbf{t}) \\ \mathbf{h}_{21}(\tau,\mathbf{t}) & \mathbf{h}_{22}(\tau,\mathbf{t}) & \mathbf{h}_{..} & \mathbf{h}_{2\mathbf{n}_\mathbf{t}}(\tau,\mathbf{t}) \\ \mathbf{h}_{..} & \mathbf{h}_{..} & \mathbf{h}_{..} & \mathbf{h}_{.\mathbf{n}_\mathbf{t}} \\ \mathbf{h}_{\mathbf{n}_\mathbf{r}1}(\tau,\mathbf{t}) & \mathbf{h}_{\mathbf{n}_\mathbf{r}2(\tau,\mathbf{t})} & \mathbf{h}_{\mathbf{n}.} & \mathbf{h}_{\mathbf{n}_\mathbf{r}\mathbf{n}_\mathbf{t}}(\tau,\mathbf{t}) \end{bmatrix} \quad (3.1)$$

The matrix elements are complex numbers that correspond to the attenuation and phase shift that the wireless channel introduces to the signal reaching the receiver with delay τ . The input-output notation of the MIMO system can now be expressed by the following equation:

$$\mathbf{y}(\mathrm{t}) = \mathbf{H}(\tau, \mathrm{t}) \otimes \mathbf{s}(\mathrm{t}) + \mathbf{u}(\mathrm{t}) \qquad (3.2)$$

where $\otimes$ denotes convolution, $\mathbf{s}(t)$ is a $n_t \times 1$ vector corresponding to the n_t transmitted signals, $\mathbf{y}(t)$ is a $n_r \times 1$ vector corresponding to the n_r received signals and $\mathbf{u}(t)$ is the additive white noise.

If we assume that the transmitted signal bandwidth is narrow enough that the channel response can be treated as flat across frequency, then the discrete time description corresponding to Equation 3.2 is

$$\mathbf{r}_\tau = \mathbf{H}\mathbf{s}_\tau + \mathbf{u}_\tau \qquad (3.3)$$

General Capacity Formula

The capacity of a MIMO channel was proved in [1, 4] that can be estimated by the following equation:

$$\mathrm{C} = \max_{\mathrm{tr}(\mathrm{R_{ss}}) \leq \mathrm{p}} \log_2 \left[\det\left(\mathbf{I} + \mathbf{H}\mathbf{R}_{\mathbf{ss}}\mathbf{H}^{\mathbf{H}}\right)\right] \qquad (3.4)$$

where $\mathbf{H}$ is the $n_r \times n_t$ channel matrix , $\mathbf{R}_{\mathbf{ss}}$ is the covariance matrix of the transmitted vector **s,** $\mathbf{H}^{\mathbf{H}}$ is the transpose conjugate of the **H** and p is the maximum normalized transmit power. Equation 3.4 is the result of extended theoretical calculations, and its practical use is not obvious. Nevertheless, we can perform linear transformations at both the transmitter and receiver converting the MIMO channel to $n = \min(n_r, n_t)$ SISO subchannels (given that the channel is linear) and, hence, reach more insightful results. (given that the channel is linear) and, hence, reach more insightful results. These transformations can be found in [1] and are briefly described in the following section.

3.3 Precoding

The spectral-efficiency benefits associated with MIMO processing hinge on the availability of a rich scattering environment. A MIMO channel with a high degree of scattering enables independent multipath links to be made from each transmit antenna to each receive antenna. As a result, the matrix of channel gains connecting each pair of transmit and receive antennas pairs will have a full rank and the resulting MIMO equation will be solvable.

In a typical MIMO transmission, however, the assumption regarding a high level of scattering cannot be guaranteed. As a result, in order to design a practical system, steps must be taken to reduce the probability of channel matrices with reduced ranks occurring. Precoding is one of the most effective approaches taken by the LTE standard to combating the rank-deficiency problem [4].

3.3.1 Precoder-based spatial multiplexing

Linear precoding in the case of spatial multiplexing implies that linear processing by means of a size $N_T \times N_L$ precoding matrix is applied at the transmitter side, as illustrated in Figure 3.2, in the general case N_L is equal or smaller than N_T, implying that N_L signals are spatially multiplexed and transmitted using N_T transmit antennas.

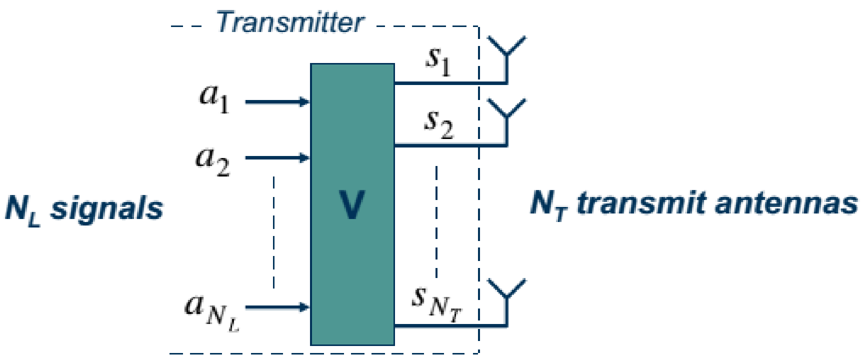

Figure 3.2 Precoder-based spatial multiplexing

It should be noted that precoder-based spatial multiplexing can be seen as a generalization of precoder-based beam-forming with the precoding vector of size $N_T \times 1$ replaced by a precoding matrix of size $N_T \times N_L$.

The precoding of Figure 3.2 can serve two purposes:

- In the case when the number of signals to be spatially multiplexed equals the number of transmit antennas ($N_T = N_L$), the precoding can be used to "orthogonalize" the parallel transmissions, allowing for improved signal isolation at the receiver side.
- In the case when the number of signals to be spatially multiplexed is less than the number of transmit antennas ($N_T < N_L$), the precoding also provides the mapping of the N_L spatially multiplexed signals to the N_T transmit antennas, including the combination of spatially multiplexing and beam-forming.

To confirm that precoding can improve the isolation between the spatially multiplexed signals, express the channel matrix H as its singular-value decomposition [38]:

$$\mathbf{H} = \mathbf{W}.\mathbf{D}.\mathbf{V}^{\mathbf{H}} \tag{3.5}$$

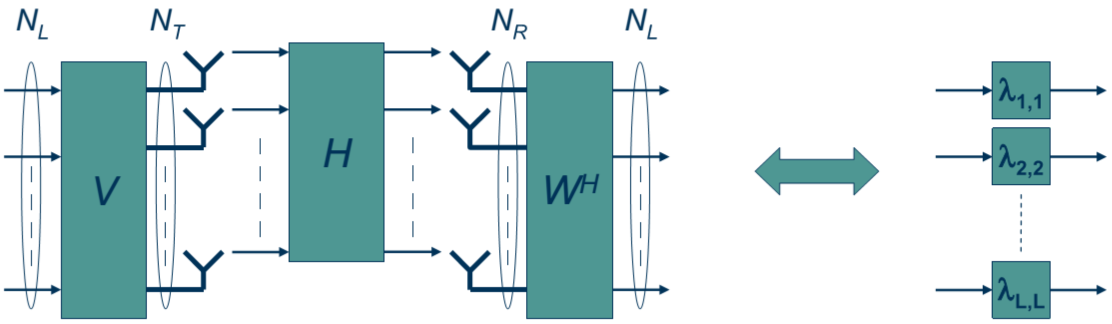

Figure 3.3 Orthogonalization of spatially multiplexed signals by means of precoding. $\lambda_{i,i}$ is the ith singular value of the matrix H

where the columns of **V** and **W** each form an orthonormal set and **D** is an $N_L \times N_L$ diagonal matrix with the N_L strongest singular values of **H** as its diagonal elements. By applying the matrix **V** as precoding matrix at the transmitter side and the matrix $\mathbf{W^H}$ at the receiver side, one arrives at an equivalent channel matrix $\mathbf{H}' = \mathbf{D}$ as shown in Figure 3.3. As $\mathbf{H}'$ is a diagonal matrix, there is no interference between the spatially multiplexed signals at the receiver. At the same time, as both **V** and **W** have orthonormal columns, the transmit power as well as the demodulator noise level (assuming spatially white noise) are unchanged.

Clearly, in the case of precoding each received signal will have a certain "quality," depending on the eigenvalues of the channel matrix (as shown in right part of Figure 3.3). This indicates potential benefits of applying dynamic link adaptation in the spatial domain-that is, the adaptive selection of the coding rates and/or modulation schemes for each signal to be transmitted.

To determine the precoding matrix **V**, knowledge about the channel matrix H is needed. A common approach is to have the receiver estimate the channel and decide on a suitable precoding matrix from a set of available precoding matrices (the precoder codebook). The receiver then feeds back information about the selected precoding matrix to the transmitter.

3.3.2 Precoder-Matrix Codebook

The finite sets of precoder matrices used in the LTE standard are known as the precoder codebook. Table shows the precoder codebooks for two transmit antennas.

The precoding operation essentially spreads the input signal and reduces the probability of error by combating rank-deficiency problems. The efficacy of precoding in reducing the probability of rank deficiencies can be explained by interpreting the precoder matrix columns as beamforming vectors. In the case of single-layer transmission, for example, choosing each codebook index results in a multiplication of the transmitted signal *X* with different beamforming vectors. This multiplication is essentially a transformation that rotates the transmitted signal in various directions. Since precoder vectors are orthonormal, the direction of rotation results in phase differences of $\{0, \pi, \frac{\pi}{2}, -\frac{\pi}{2}\}$. Large phase differences make it more likely that different streams will take different multipath trajectories before arriving at any receive antenna. This in turn reduces the possibility of channel matrices with linearly dependent rows or columns occurring and increases the chance of there being full-rank channel matrices.

Codebook index	**Number of layers**	
	1	2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\j & -j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	-

Table 3.1 Precoding matrices for two transmit antennas in LTE spatial multiplexing

The same interpretation applies to the two-antenna and four-antenna precoder matrices. For example, in the case of two transmit antennas, when we multiply the two modulated substreams by any of the precoder matrices, $\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\j & -j\end{bmatrix}$ for example, each substream is steered like a beamformer by each of the precoder matrix column vectors. Since these vectors are orthonormal, they can represent rotation operations in different N-dimensional directions [6] When viewed as a beamformer, precoding enhances the chance of the transmitted streams following different multipaths, since it can force each substream to take different directions, as specified by the angle of rotation. This explains why spatial-multiplexing systems that use precoding have been shown to provide dramatic performance gains over unprecoded systems.

3.3.3 Open Loop Precoding

In open loop operations, the eNodeB receives minimal information from the UE: a Rank Indicator (RI), the number of layers that can be supported under the current channel conditions and modulation scheme; and a Channel Quality Indicator (CQI), a summary of the channel conditions under the current transmission mode, roughly corresponding to SNR. The eNodeB then uses the CQI to select the correct modulation and coding scheme for the channel conditions. Combined with this modulation and coding scheme, CQI can also be converted into an expected throughput. The eNodeB adjusts its transmission mode and the amount of resources devoted to the UE based on whether the CQI and RI reported by the UE matches the expected values, and whether the signal is being received at an acceptable error rate.

3.3.4 Closed Loop Precoding

In closed loop operations, the UE analyzes the channel conditions of each Tx, including the multipath conditions. The UE provides an RI as well as a Precoding Matrix Indicator (PMI), which determines the optimum precoding matrix for the current channel conditions. Finally, the UE provides a CQI given the RI and PMI, rather than basing CQI on the current operation mode Figure 3.4 illustrates an example of this process. This allows the eNodeB to quickly and effectively adapt the transmission to channel conditions. Closed loop operations are particularly important for spatial multiplexing, where MIMO offers the greatest throughput gains.

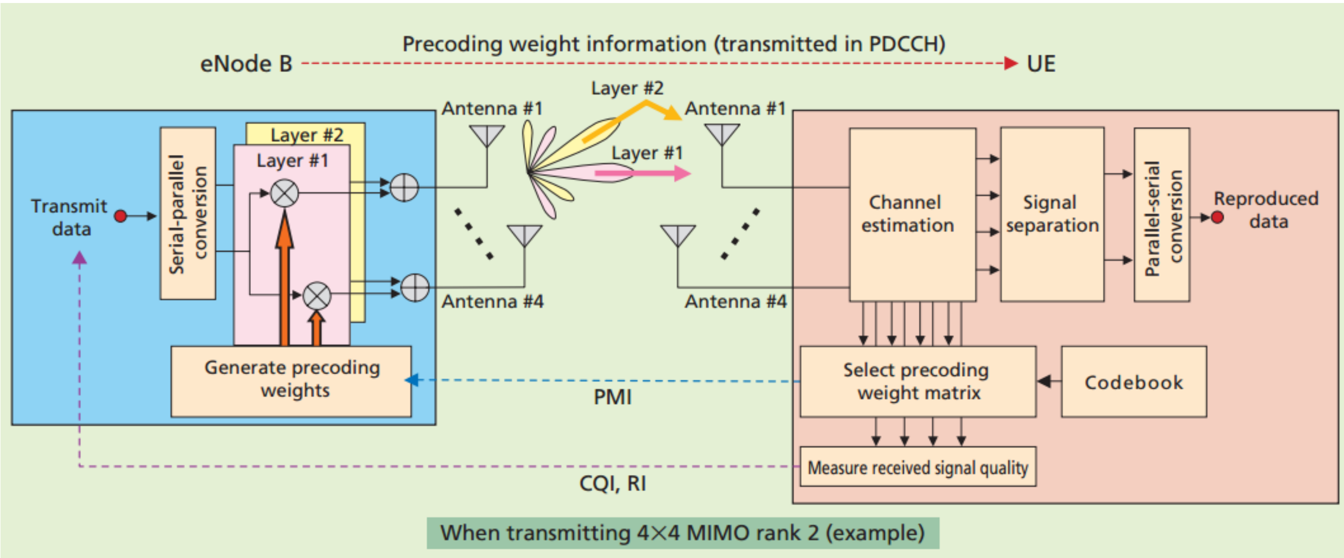

Figure 3.4 Closed loop SU-MIMO transmission using code-book-based precoding

Chapter 4: System Model in MATLAB and Simulink

4.1 Introduction

Instead of developing MATLAB scripts to perform various operations in the loop and call the algorithms and visualization functions iteratively, the Simulink model is developed to perform these tasks.

a block is created to each part of this system model (Transmitter, Channel, Receiver) by the help of some specific MATLAB functions which are explained in this chapter.

4.2 System Model

In this section, we compose a system model for the physical layer PHY of the LTE standard by integrating various enabling technologies. The system model is composed of a transmitter, a channel model, and a receiver.

4.2.1 Transmitter Model

In the transmitter, the signal processing chain is applied to the payload bits provided by the transport channel. The processing depends on the transmission mode. The transmission mode manifests itself as the choice of MIMO technique used at any given subframe. In this model the focus is on the first four modes.

In each subframe, the scheduler selects one of the four transmission modes: Single Input Multiple Output SIMO (mode1), transmit diversity (mode 2) to boost the overall link reliability, open loop spatial multiplexing (mode 3) and closed loop spatial multiplexing (mode 4) to boost data rates.

In each transmission mode, we go through a series of operations that are a combination of Downlink Shared Channel (DLSCH) and Downlink Shared Physical Channel (PDSCH) processing steps. Figure 4.1 illustrates the processing chain in the downlink transmitter [4].

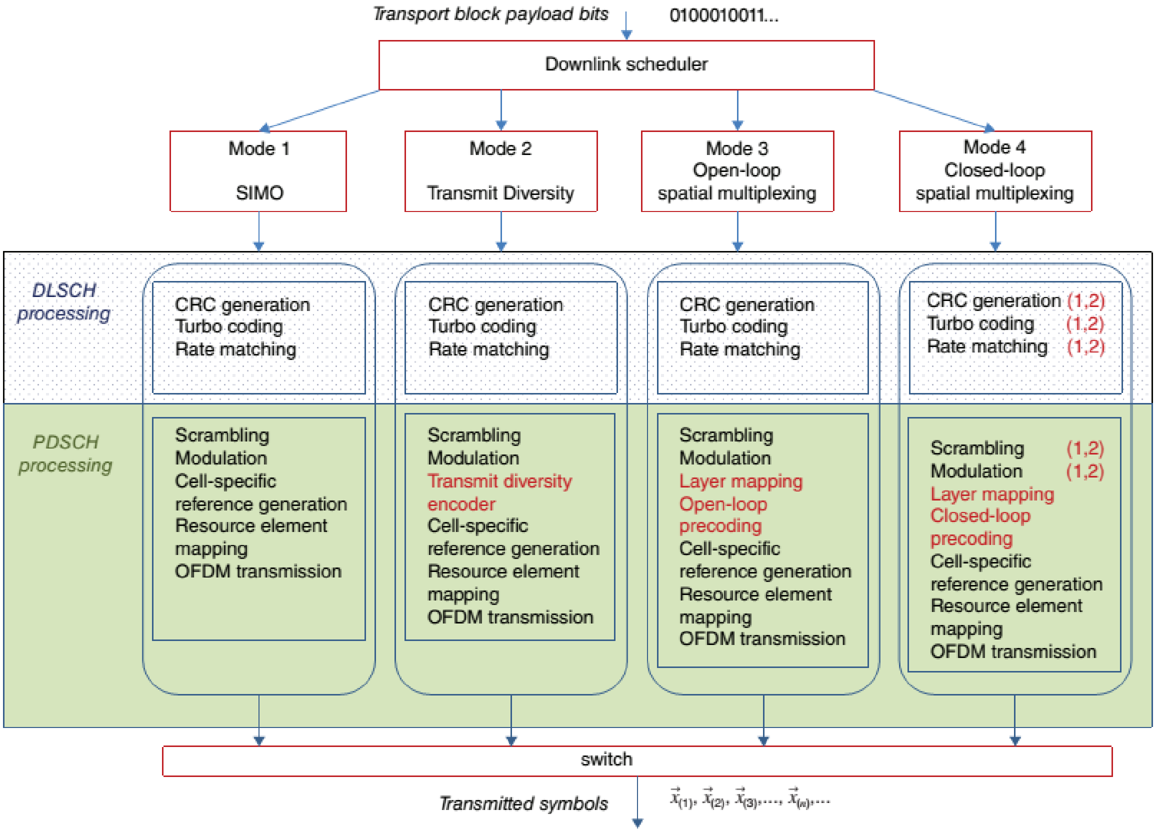

Figure 4.1 LTE downlink system model: transmission modes 1–4, transmitter operations

4.2.2 MATLAB Model for The Transmitter

commlteMIMO_Tx:

This matlab function shows the LTE downlink transmitter operations for the transmission mode used in any given subframe. It can be viewed as a combination of the open-loop, and closed-loop spatial-multiplexing transmitters. The function takes as input the subframe number (*nS*) and the three parameter structures (*prmLTEDLSCH*, *prmLTEPDSCH*, *prmMdl*). As the function is called in each subframe, it first generates the transport-block payload bits and then proceeds with the common DLSCH and PDSCH operations. Using a MATLAB *switch-case* statement, it then performs MIMO operations specific to the selected transmitted mode. The MIMO output symbols and the cell-specific resource symbols (pilots) generated are then mapped into the resource grid. The OFDM transmission operations applied to the resource grid finally generate the output transmitted symbols (*txSig*).

4.2.3 Channel Model

Channel modeling is performed by combining a MIMO fading channel with an AWGN (Additive White Gaussian Noise) channel. MIMO channels specify the relationships between signals transmitted over multiple transmit antennas and signals received at multiple receive antennas. Typical parameters of MIMO channels include the antenna configurations, multipath delay profiles, maximum Doppler shifts, and spatial correlation levels within the antennas in both the transmitter side and the receiver side.

4.2.4 MATLAB Model for The Channel

commlteMIMO_Ch:

This Matlab function shows how channel modeling is performed by combining a multipath MIMO fading channel with an AWGN channel. First, by calling the *MIMOFadingChan* function, we generate the faded version of the transmitted signal (*rxFade*) and the corresponding channel matrix (*chPathG*). The MIMO fading channel computes the faded signal as a linear combination of multiple transmit antennas. As a result, the output signal (*rxFade*) may not have an average power (signal variance) of one. To compute the noise variance needed to execute the *AWGNChannel* function, we need to first compute the signal variance (*sigPow*) and then derive the noise variance as the difference between the signal power and the SNR value in dB.

4.2.5 Receiver Model

In the receiver, the signal processing chain is applied to the received symbols following channel modeling. At the receiver, essentially the inverse operations to those of the transmitter are performed in order to obtain a best estimate of the transmitted payload bits. Figure 4.2 illustrates the processing chain in the downlink receiver [4]. At this point, we perform the MIMO detection operations based on the scheduled transmission mode in order to recover the best estimates of the modulated symbols. In SIMO mode, receiver detection is same as frequency-domain equalization. In transmit-diversity mode, the transmit-diversity combiner operation is performed. In spatial-multiplexing modes, the MIMO receiver operations are performed in order to solve the MIMO equation for each received symbol given the estimated channel matrix and then different substreams are explicitly mapped back to a single modulated stream using the layer-demapping operation.

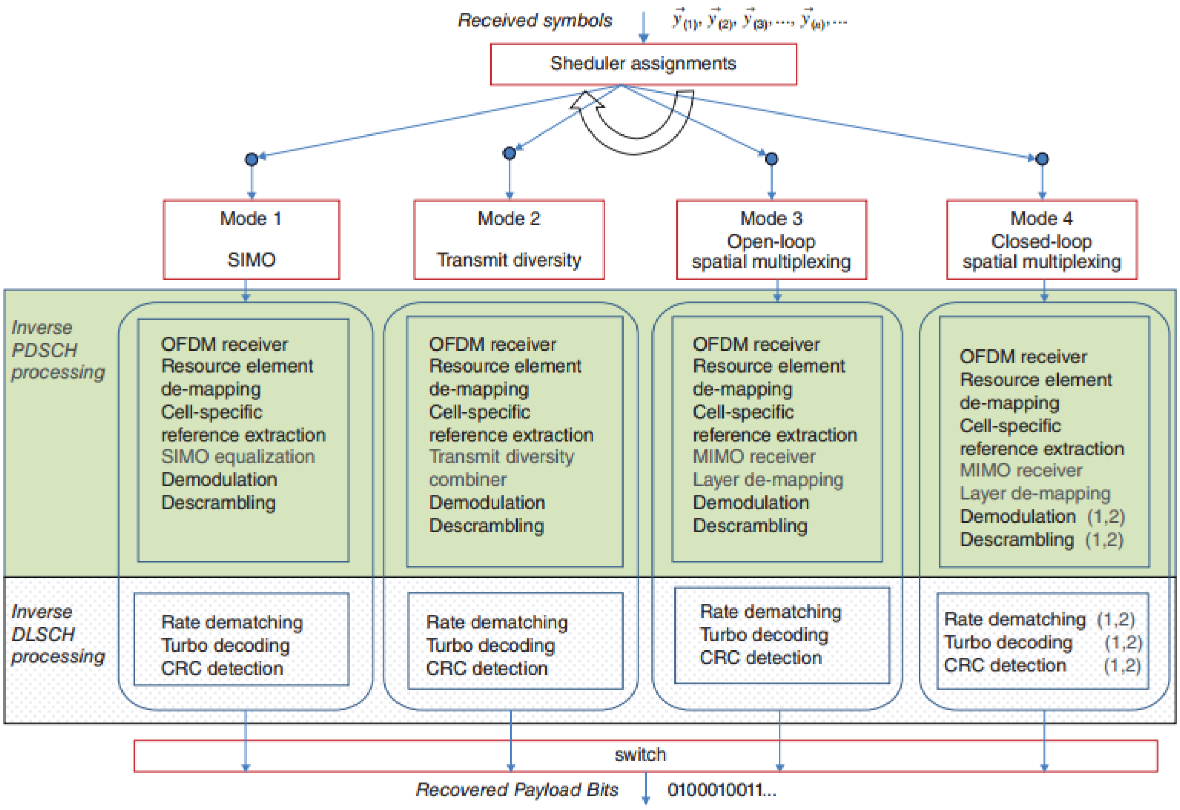

Figure 4.2 LTE downlink system model: transmission modes 1–4, receiver operations

4.2.6 MATLAB Model for The Receiver

commlteMIMO_Rx:

This MATLAB function shows the LTE downlink receiver operations for a given transmission mode used in any subframe. The function takes as input the subframe number (*nS*), the OFDM signal processed by the channel (*rxSig*), an estimate of the noise variance per received channel (*nVar*), the channel-path gain matrices (*chPathG*), the transmitted cell-specific reference signals (*csr_ref*), and the three parameter structures (*prmLTEDLSCH*, *prmLTEPDSCH*, *prmMdl*). It generates as its output a best estimate of the transport-block payload bits (*dataOut*). the function first performs common OFDM receiver and demapping operations in order to recover the resource grid and estimate the channel response and then, using a MATLAB *switch-case* statement, performs MIMO receiver operations specific to the selected transmitted mode (represented by the *prmLTEPDSCH.txMode* variable). Finally, by performing common demodulation, descrambling, channel decoding, and CRC-detection operations, the function computes its output signal.

4.2.7 System Model in MATLAB

commlteSystem:

This testbench represents the system model for the PHY of the LTE standard. First it calls the initialization function (*commlteSystem_initialize*) to set all the relevant parameter structures (*prmLTEDLSCH*, *prmLTEPDSCH*, *prmMdl*). Then it uses a while loop to perform subframe processing by calling the MIMO transceiver function composed of the transmitter (*commlteSystem_Tx*), the channel model (*commlteSystem_Channel*), and the receiver (*commlteSystem_Rx*). Finally, it updates the Bit Error Rate (BER) and calls the visualization function to illustrate the channel response and modulation constellation before and after equalization. By comparing the transmitted and received bits, we can then compute various measures of performance based on the simulation parameters.

The functions that are called to run (commlteSystem) testbench are listed in the Appendix.

4.2.8 System Model in Simulink

The Simulink model is built to express the LTE transceiver system by using blocks from the Simulink library. Figure 4.3 shows Simulink blocks that represent previously developed MATLAB algorithms.

Model Parameters

By running this model, the simulation of LTE model is performed without the need to specify parameters as a MATLAB script. A Parameter Dialog shown in Figure 4.4 is added to the model that lets simulation parameters set interactively. After setting parameters each time the MATLAB function blocks in the model are recompiled and the simulation follows the full compilation of the model. At the end of simulation BER values are saved for SNR values specified.

Subframe Update (Counter)

The output of the Subframe Update MATLAB Function block is the slot number of the current frame. It works on updating the subframe number.

Error Rate Calculation

The Error Rate Calculation block compares the decoded bits with the original source bits per subframe and dynamically updates the BER measure throughout the simulation.

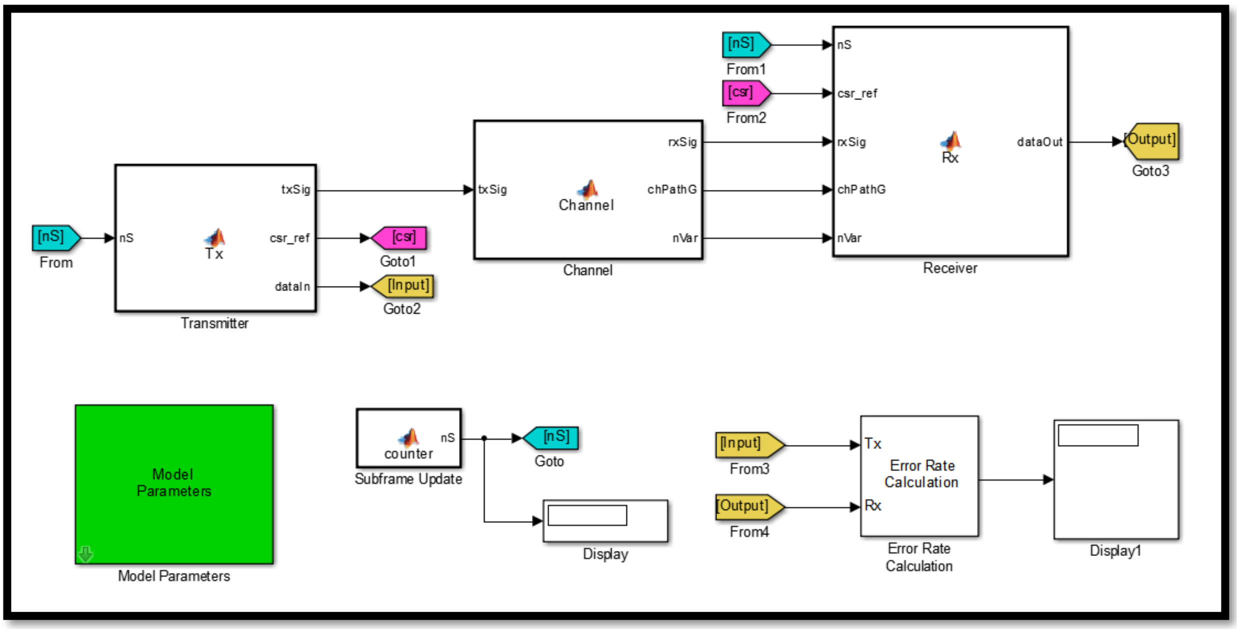

Figure 4.3 Simulink simulation model of an LTE transceiver model

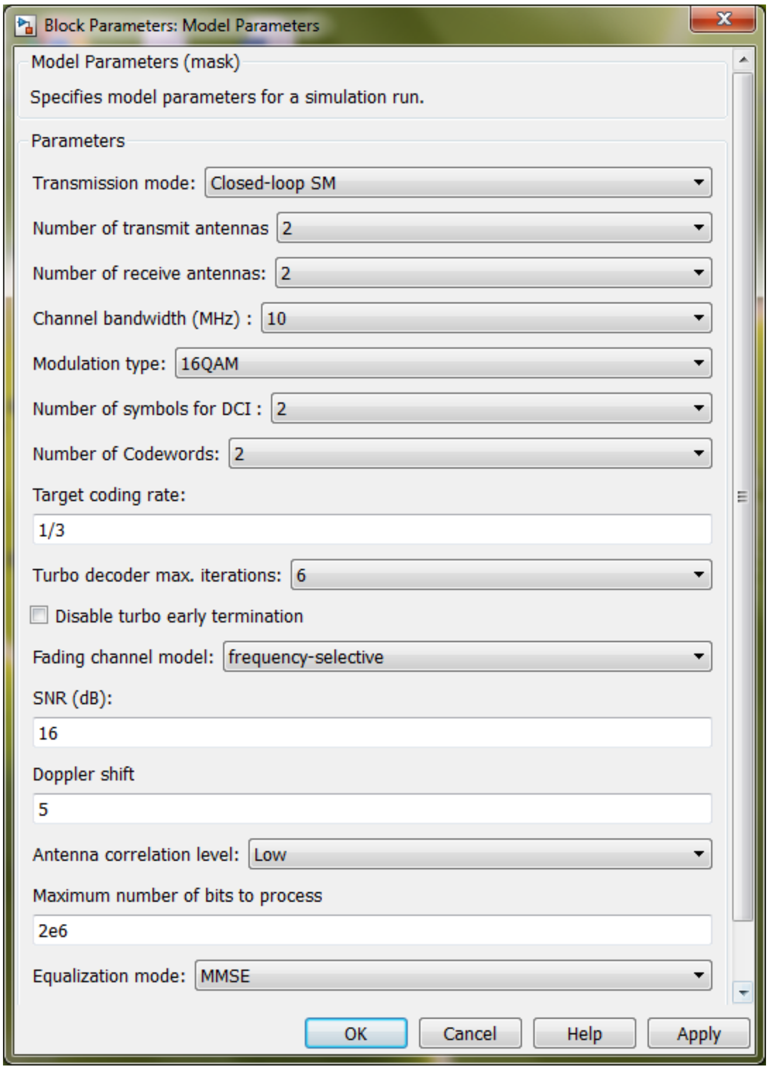

Figure 4.4 parameter dialog for setting LTE system model parameters in the Simulink model

4.2.9 Simulation Parameters Description

- Transmission mode: 1, 2 & 4 for single-antenna transmission, transmit diversity open loop and closed- loop codebook-based precoding respectively.
- Number of transmit antennas: 2 or 4.
- Number of receive antennas: 2 or 4.
- Channel bandwidth (MHz): 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz.
- Modulation type: QPSK, 16QAM, and 64QAM.
- Coding rate.
- Turbo decoder maximum iterations.
- Fading channel model: flat, frequency-selective, EPA 0Hz, 'EPA 5Hz, EVA 5Hz, and EVA 70Hz.
- Doppler shift: a value between 0 to 300 = Maximum Doppler shift.
- Antenna correlation level: low, high and medium.
- Maximum number of bits to process.
- Equalization mode: ZF, MMSE, Sphere Decoder.
- Channel estimation mode: Ideal estimation, Interpolation-based, average over slot and average over frame.

Chapter 5: Results and Discussion

5.1 Introduction

So far MATLAB and Simulink model are built for physical layer of LTE system. To see the output and visualize the closed loop and the open loop spatial multiplexing behavior in the channel, the simulation parameters are set for each one and the simulation of its constellation diagram, bit error rate measurement and signal spectra are displayed. Next the performance of both in different antenna configuration are observed. After that same process is done for transmit diversity and spatial multiplexing to figure out more the difference between them. Finally, an overall observation and discussion has been made.

5.2 Open Loop Precoding (Mode 3)

5.2.1 Parameter Setting

For the open loop precoding we set the parameter in MATLAB as follows:

- Transmission mode = 3.
- Number of the transmitting antennas = 2.
- Number of the receiving antennas = 2.
- Channel Bandwith = 10 MHz.
- Modulation Type = 16QAM.
- Number of codewords = 1.
- Turbo decoder maximum iterations = 6.
- Coding Rate = 1/3.
- Channel Model frequency selective with high mobility.
- Maximum number of bits to process = 10^6 bits.
- Maximum number of errors = 10^6 bits.

5.2.2 Results

Constellation Diagram

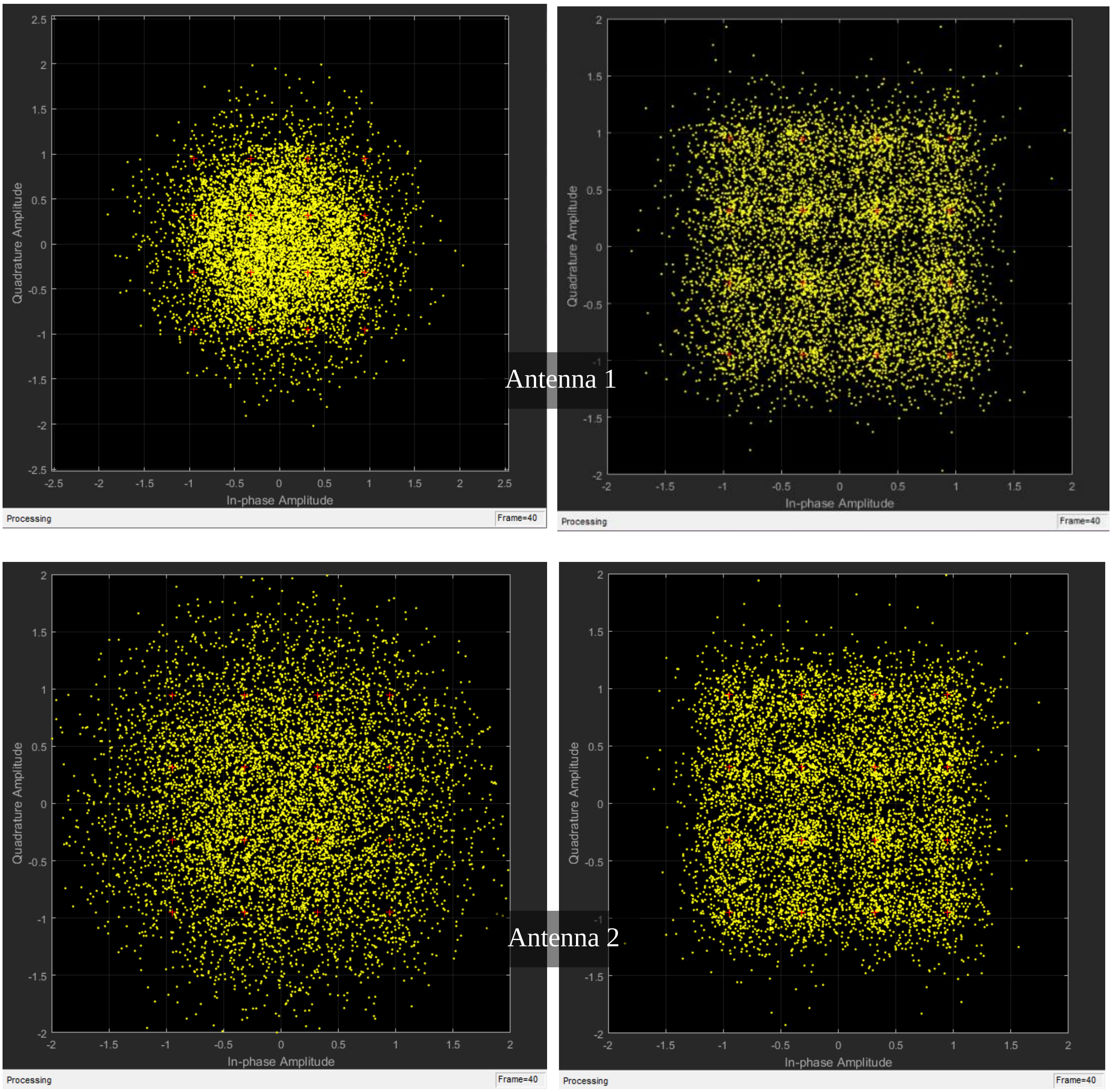

Figure 5.1 MIMO open loop spatial-multiplexing constellation diagram of user data modulated by 16QAM obtained from each of the two receive antennas before and after equalization

Signals Spectra

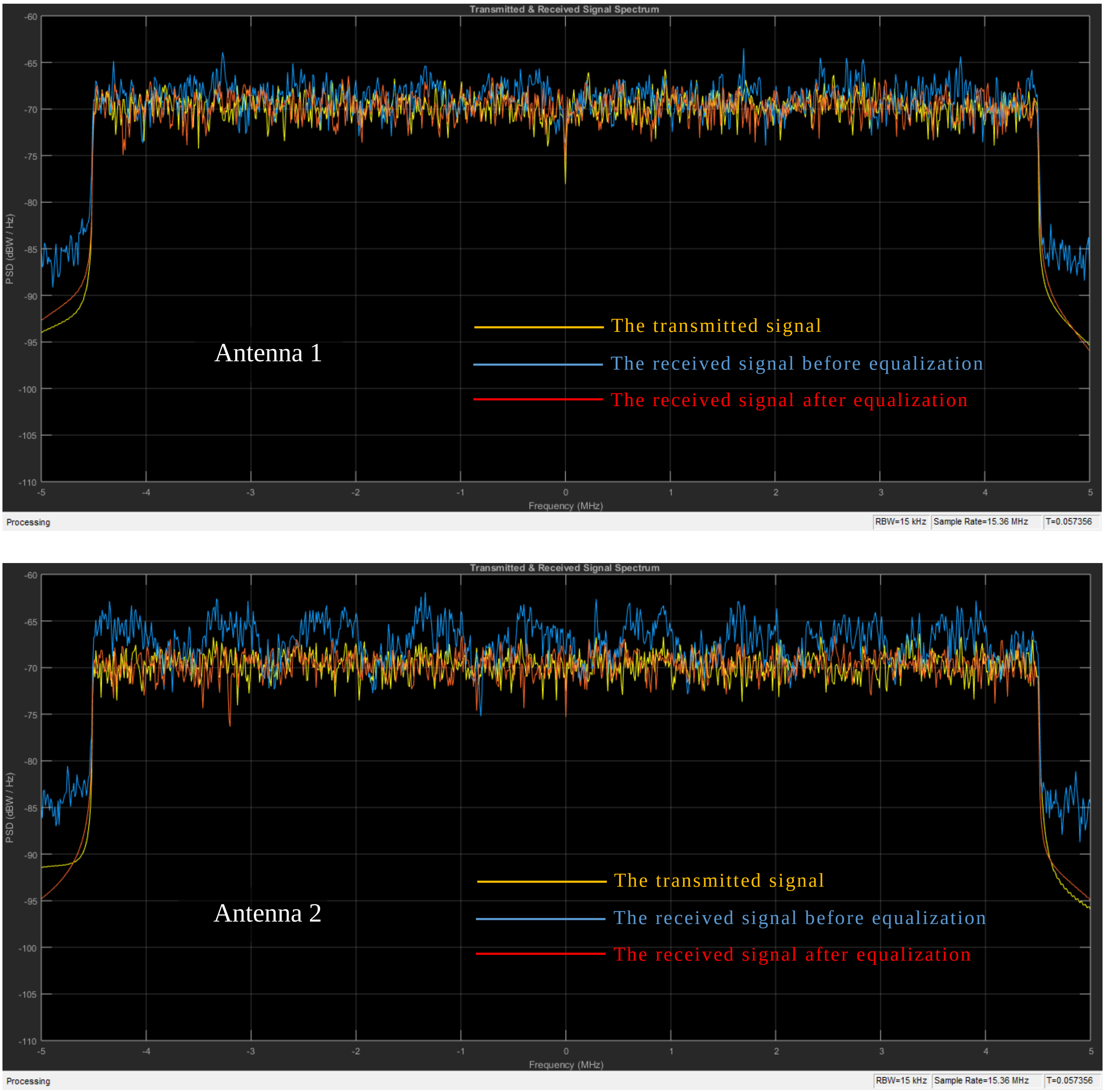

Figure 5.2 LTE MIMO open loop spatial-multiplexing spectra of transmitted and of the received signal obtained from each of the two receive antennas before and after equalization

Bit Error Rate Measurement

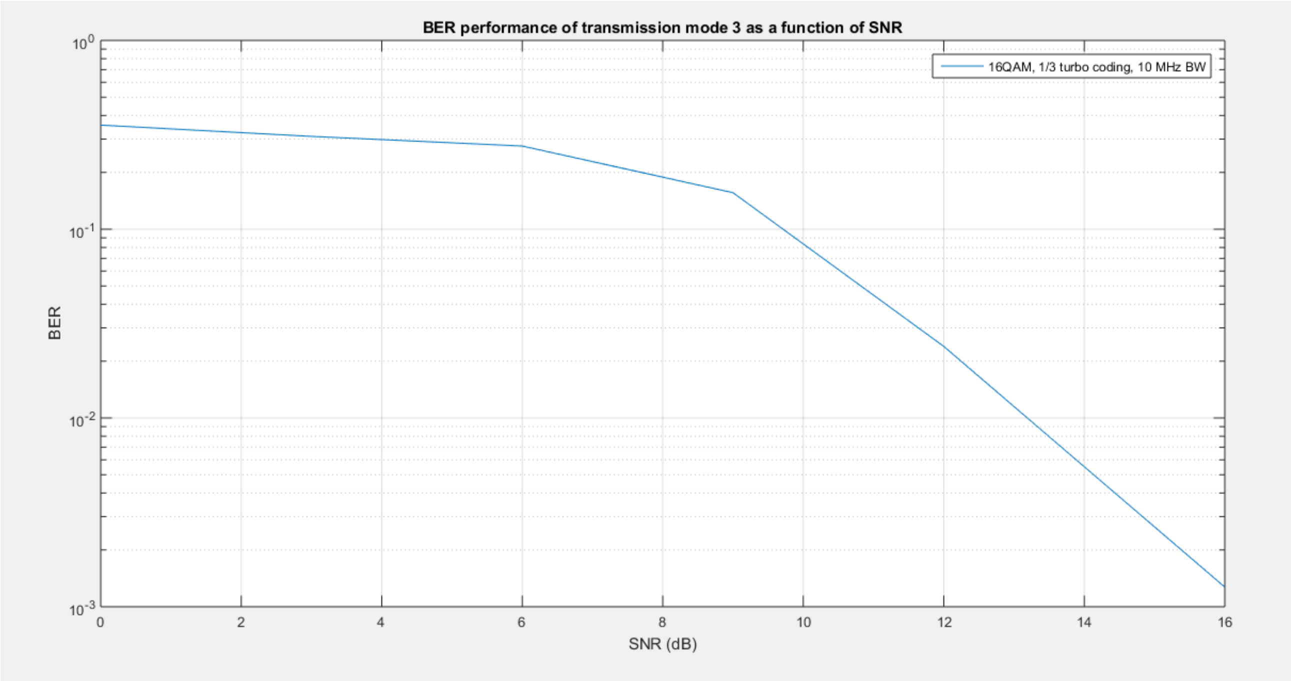

Figure 5.3 BER results: LTE mode 3, spatial-multiplexing, 2 × 2 MIMO channel 16 QAM Modulator

5.3 Closed Loop Precoding (Mode 4)

5.3.1 Parameters Setting

For the closed loop precoding we set the parameter in MATLAB as follows:

- Transmission mode = 4.
- Number of the transmitting antennas = 2.
- Number of the receiving antennas = 2.
- Channel Bandwith = 10 MHz.
- Modulation Type = 16QAM.
- Number of codewords = 1.
- Coding Rate = 1/3.
- Turbo decoder maximum iterations = 6.
- Coding Rate = 1/3.
- Channel Model frequency selective with high mobility.
- Maximum number of bits to process = 10^6 bits.
- Maximum number of errors = 10^6 bits.

5.3.2 Results

Constellation Diagram

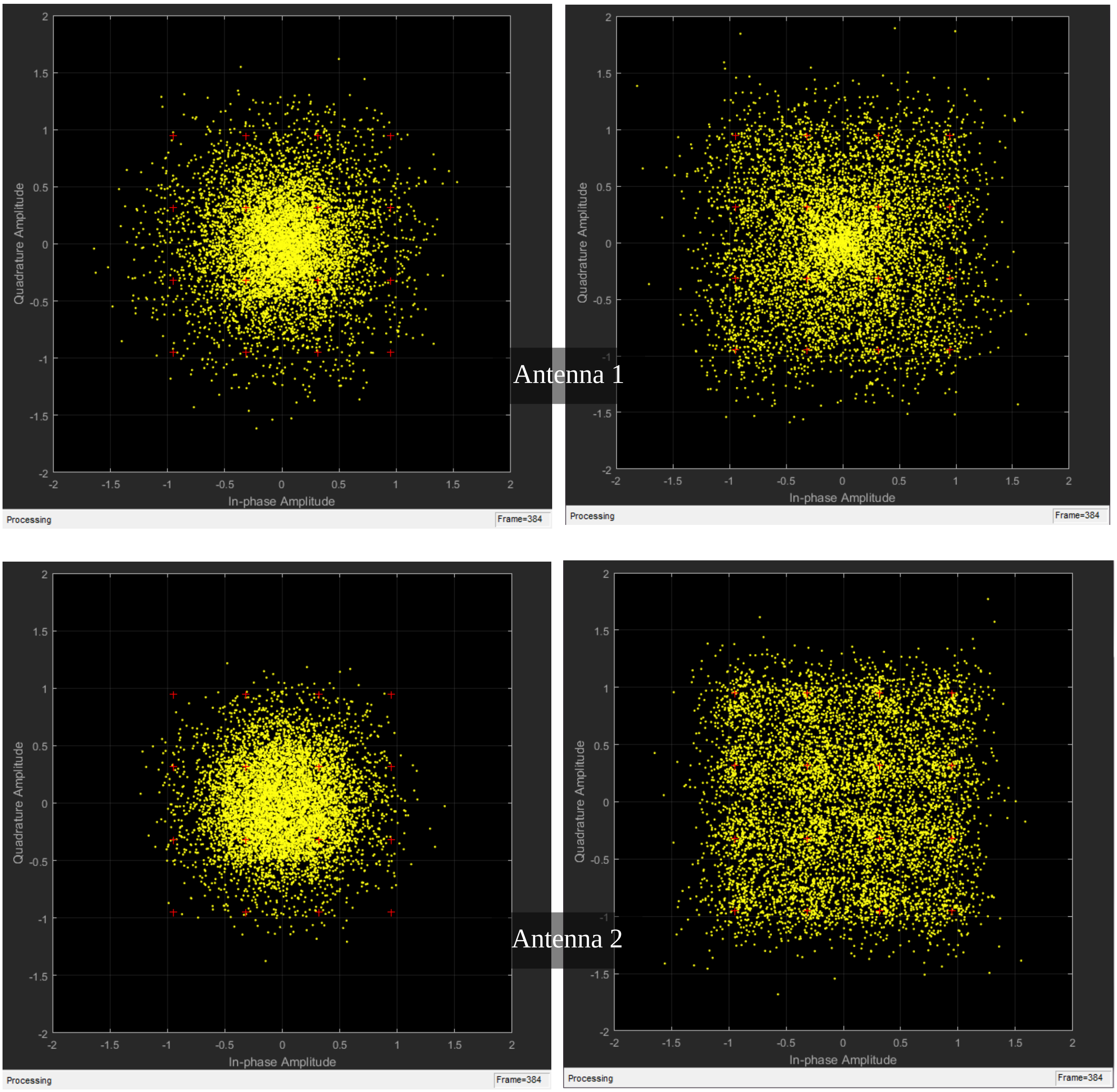

Figure 5.4 MIMO closed loop spatial-multiplexing constellation diagram of user data modulated by 16QAM obtained from each of the two receive antennas before and after equalization

Signals Spectra

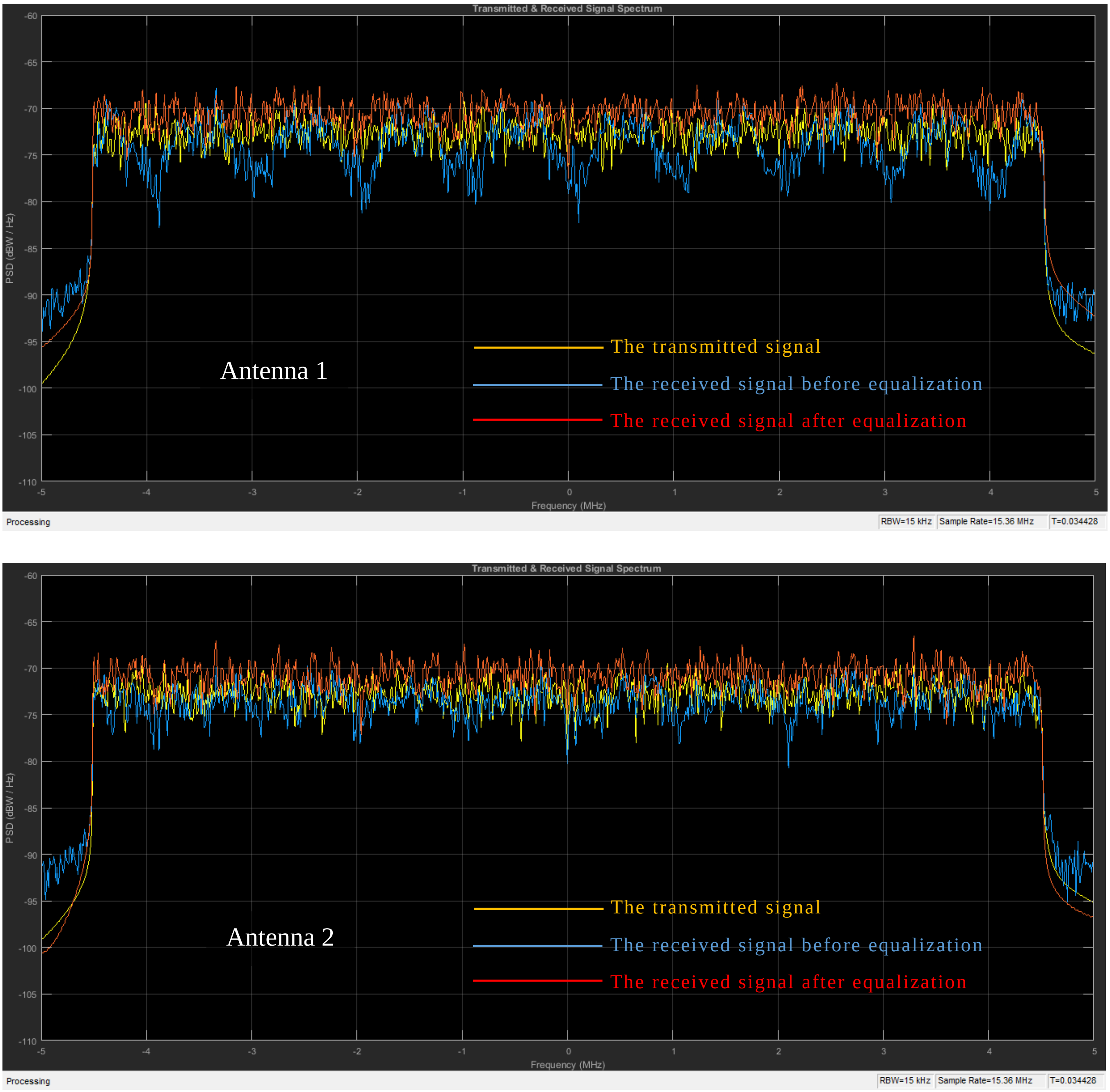

Figure 5.5 LTE MIMO closed loop spatial-multiplexing spectra of transmitted and of the received signal obtained from each of the two receive antennas before and after equalization

Bit Error Rate Measurement

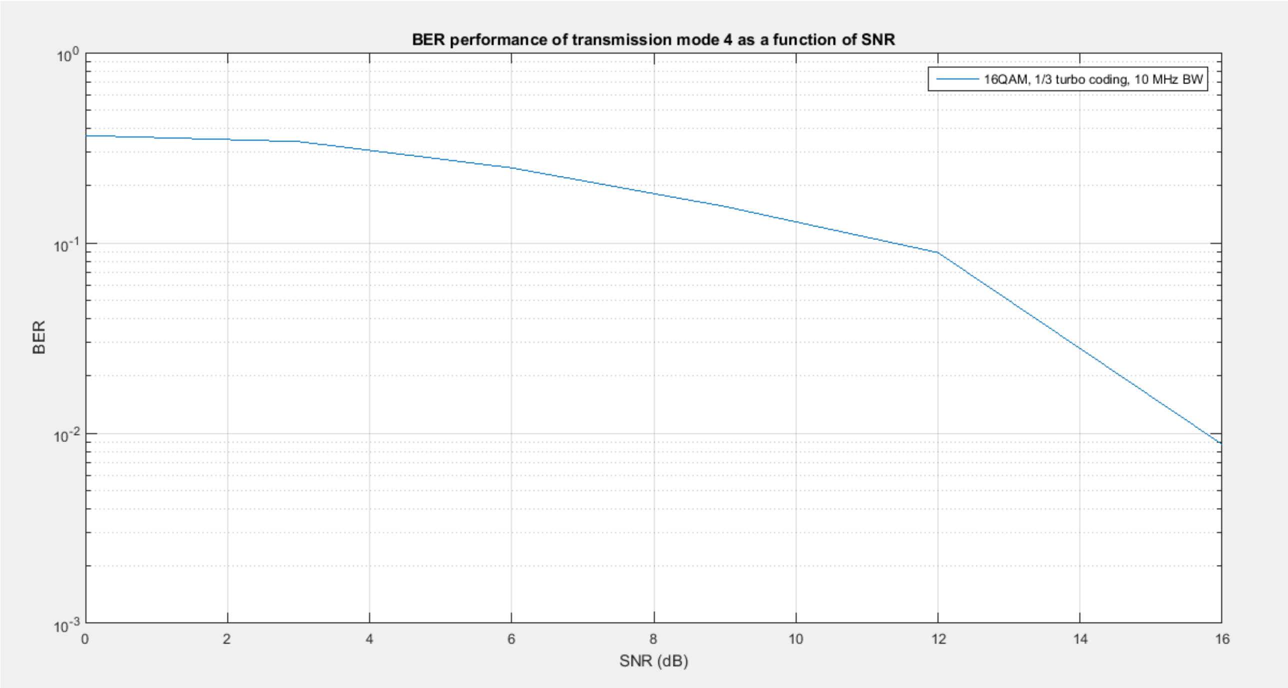

Figure 5.6 BER results: LTE mode 4, spatial-multiplexing, 2 × 2 MIMO channel 16 QAM Modulator

5.4 Performance Analysis and Comparison

In this section we look at performance from different perspectives. By executing the system model in MATLAB with different simulation parameters we can assess the performance of the LTE standard. First we look at the bit error rate performance and data rate of mode 3 and mode 4 with 2 × 2 MIMO and 4 × 4 MIMO antenna configuration. The experiment is performed twice, once for a frequency-selective with low mobility channel model and once for frequency-selective with high mobility channel. The bit error rate BER measurement versus SNR graph is displayed for each one. Then, we compare the effect of the channel model of mode 2 as representative of transmit diversity and mode 4 as representative of spatial multiplexing on bit error rate and data rate.

5.4.1 Spatial Multiplexing with 2 × 2 and 4 × 4 MIMO Configuration

The parameters were set in MATLAB as follows:

- Channel Bandwith = 10 MHz.
- Modulation Type = 16QAM.
- Number of codewords = 1.
- Turbo decoder maximum iterations = 6.
- Coding Rate = 1/2.
- Maximum number of bits to process = 10^6 bits.
- Maximum number of errors = 10^6 bits.

Frequency-Selective with Low Mobility Channel

The channel condition is characterized by a frequency-selective with low mobility channel model and with antennas of medium spatial correlation, and an SNR value of 16 dB. The graph of bit error rate measurement is shown in Figure 5.7.

Bit Error Rate Measurement

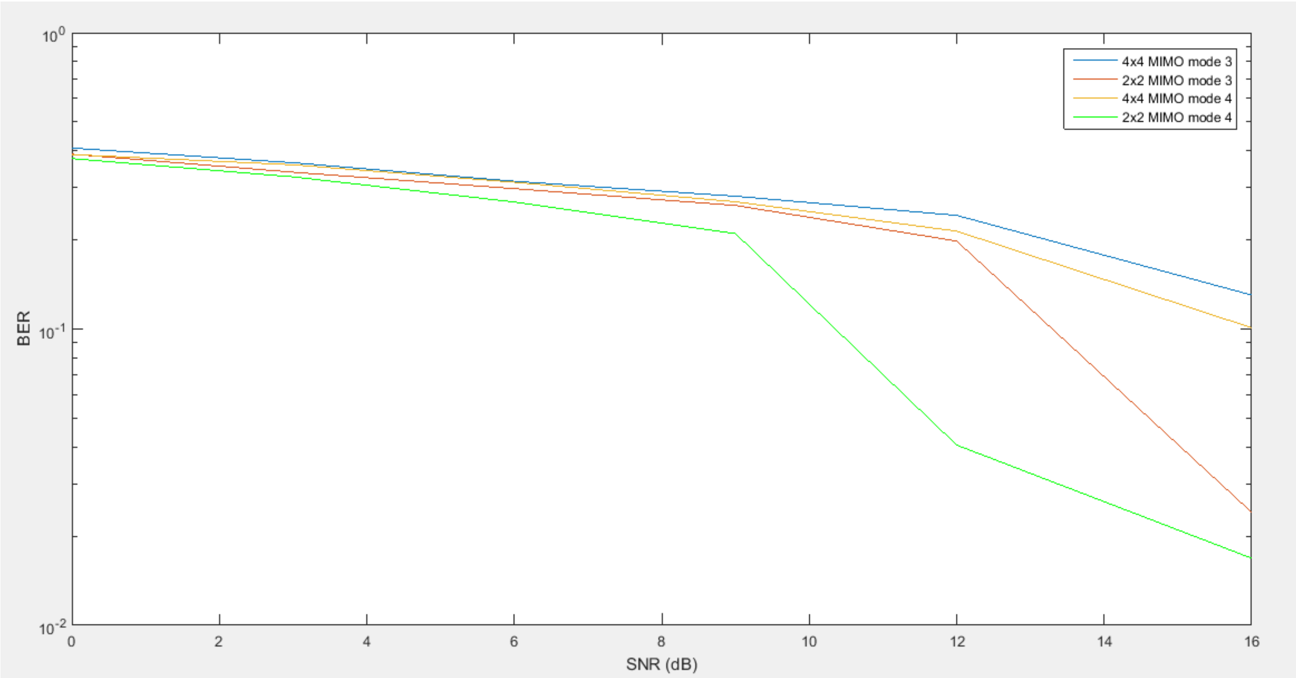

Figure 5.7 BER results: LTE mode 4 and mode 3 spatial-multiplexing with 2x2 and 4x4 MIMO frequency-selective with low mobility channel 16 QAM Modulator

Table 5.1 shows the performance of each mode in terms of data rate, bit error rate and an SNR value of 16 dB.

Performance results	Antenna configuration	Data rate (Mbps)	BER
Mode 3	2 × 2	28.34 Mbps	0.02406
	4 × 4	56.07 Mbps	0.13022
Mode 4	2 × 2	28.34 Mbps	0.01683
	4 × 4	56.07 Mbps	0.10098

Table 5.1 BER performance and data rate as a function of transmission mode: frequency-selective with low mobility channel

Frequency-Selective with High Mobility Channel

The channel condition is characterized by a frequency-selective with high mobility channel model and with antennas of low spatial correlation, and an SNR value of 16 dB. The graph of bit error rate measurement is shown in Figure 5.8.

Bit Error Rate Measurement

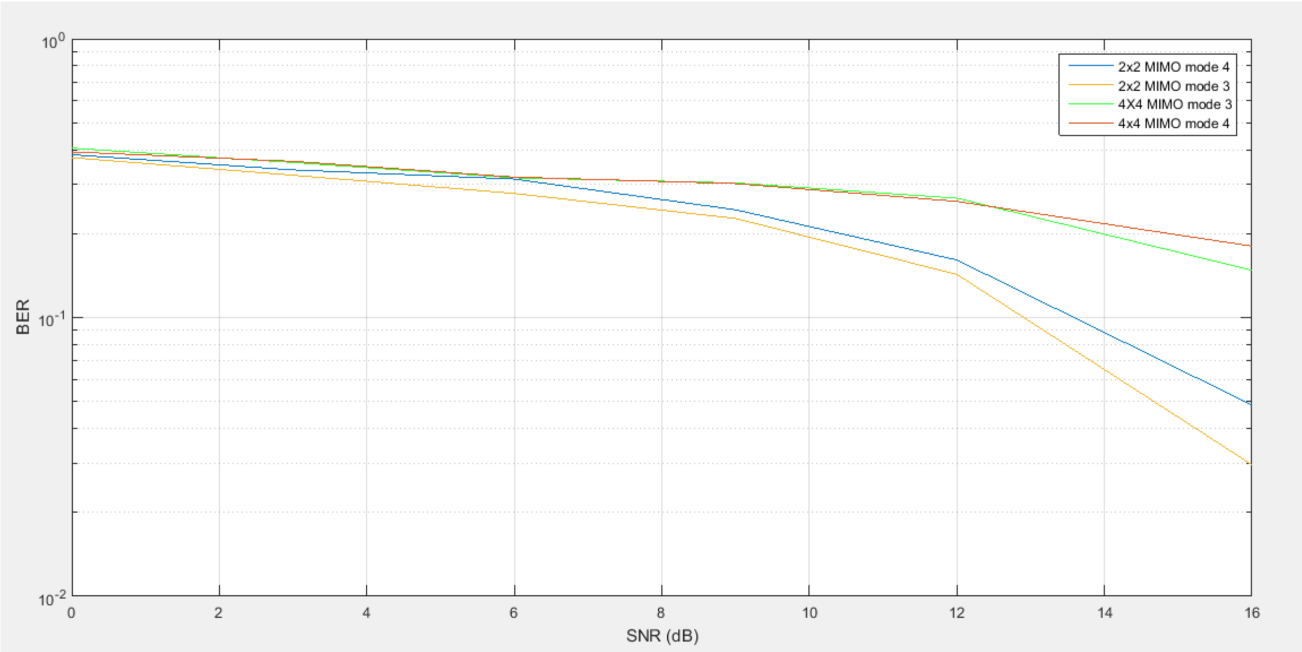

Figure 5.8 BER results: LTE mode 4 and mode 3 spatial-multiplexing with 2x2 and 4x4 MIMO, frequency-selective with high mobility channel 16 QAM Modulator

Table 5.2 shows the performance of each mode in terms of data rate, bit error rate and an SNR value of 16 dB.

Performance results	Antenna configuration	Data rate (Mbps)	BER
Mode 3	2 × 2	28.34 Mbps	0.02965
	4 × 4	56.07 Mbps	0.14779
Mode 4	2 × 2	28.34 Mbps	0.04855
	4 × 4	56.07 Mbps	0.18039

Table 5.2 BER performance and data rate as a function of transmission mode: frequency-selective with high mobility channel

5.4.2 Transmit Diversity and Spatial Multiplexing

To compare and see the performance of transmit diversity and spatial multiplexing with same previous parameters setup, in this section the bit error rate of 4x4 MIMO antenna configuration of mode 2 and mode 4 are measured as function of SNR. The channel condition is characterized by a frequency-selective with low mobility, antennas of low spatial correlation and an SNR value of 16 dB. The graph of bit error rate measurement BER versus SNR is shown in Figure 5.9.

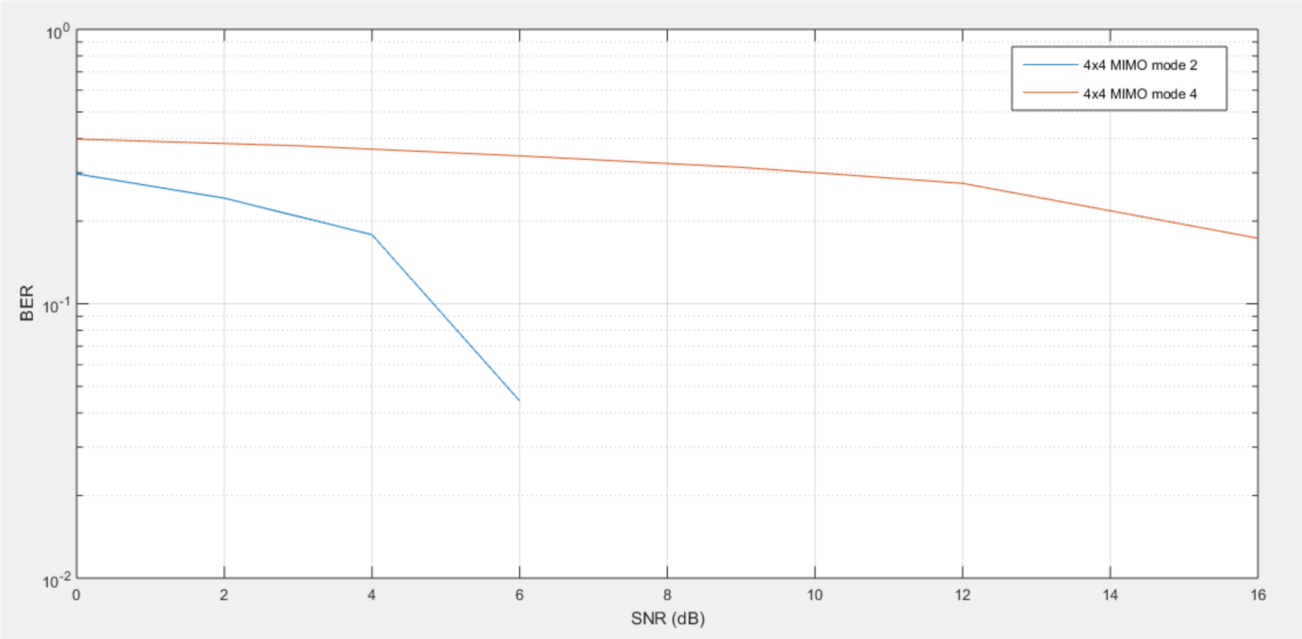

Figure 5.9 BER results: LTE Transmit diversity mode 2 and spatial-multiplexing mode 4 with 4x4 MIMO channel 16 QAM Modulator

The results are profiled in Table 5.3.

Performance results	Antenna configuration	Data rate (Mbps)	BER
Mode 2	4 × 4	12.81 Mbps	0.0
Mode 4	4 × 4	56.07 Mbps	0.17333

Table 5.3 BER performance and data rate as a function of Transmit diversity mode 2 and spatial multiplexing mode 4

5.5 Observation and Discussion

Based on the previous results, we can make the following observations:

- The equalizer in the receiver can compensate for the effect of a fading channel, to result in a constellation and spectrum more closely to the one of the transmitter.
- It is noticed that the BER is inversely proportional to the SNR values.
- The performance in each mode is consistently better in a clean channel than in a noisy channel.
- In spatial multiplexing mode 3 and 4, performance seems rather low under both channel conditions.
- In channel with low mobility, closed loop precoding shows better performance than open loop precoding whereas in channel with high mobility, closed loop precoding appears to be less effective in terms of bit error rate BER.
- 4x4 MIMO antenna configuration of spatial multiplexing works on boosting data rate more than 2x2 antenna configuration does, but with less reliability since the bit error rate is higher.
- It is also observed that the spatial multiplexing technique outperforms the transmit diversity technique in term of data rate. However, transmit diversity technique shows more reliability and robustness than spatial multiplexing does.

Conclusion

LTE system includes many technologies to make the best use of wireless channel characteristics. This includes turbo coding, OFDM and MIMO techniques. MIMO system brings a significant improvement in performance compared to the single antenna case. The purpose of this work is to evaluate the transmission modes of LTE system. Particularly spatial multiplexing techniques that are used in mode 3 and mode 4. The result of both open loop and closed loop precoding operations have been presented. Generally, it can be concluded that MIMO improves bit error rate BER performance and increases data rate of LTE via diversity gain. The performance of MIMO also depends on the user equipment speed which is relates to the Doppler frequency, the target modulation scheme and less on the bandwidth chosen. Spatial multiplexing techniques improves spectral efficiency and increases the data rate of transmission. Its use is suitable for less channel distortion since it has less reliability. Transmit diversity technique in the other hand is preferred for high channel distortion to ensure more reliability and robustness of the transmitted signal. Closed loop spatial multiplexing operation is better than low mobility of user equipment for more exploration of the bandwidth. Making the system adaptive to state of the channel requires the utilization of Link adaptation technique which is used in LTE. Link adaptation ensures the best performance of MIMO system for different channel conditions and its study is an important addition to this work.

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Appendix

MATLAB Functions

commlteMIMO_ params

is a MATLAB script the includes all the parameters used in the simulation:

txMode chanBW, contReg, modType, Eqmode, numTx, numRx, cRate, maxIter, fullDecode chanMdl, corrLvl, chEstOn, numCodeWords, enPMIfback, cbIdx, snrdB, maxNumErrs, maxNumBits

commlteMIMO_initialize

The function sets simulation parameters. This function is used for all MIMO modes, including transmit diversity and spatial multiplexing. The first input argument (txMode) determines which MIMO mode is used: a value of 2 signals a transmit-diversity mode, a value of 3 an open-loop spatial-multiplexing mode, and a value of 4 a closed-loop spatial-multiplexing mode. In order to set prmLTEPDSCH, prmLTEDLSCH, and prmMdl parameter structures, this function calls three functions: prmsPDSCH, prmsDLSCH, and prmsMdl, respectively.

zReport_data_rate

The function zReport_data_rate_average reports the average and instantaneous values of data rates, the coding rate, and the modulation rate. The average values are computed as running means by the dsp.Mean System object of the DSP System Toolbox. The instantaneous data rate is computed as the sum of input bits in all 10 subframes of a frame multiplied by a constant factor of 100 frames per second.

commlteMIMO_TD_step

This function performs a transceiver model for transmit diversity mode 2 of the LTE standard. It includes both the two- and the four-transmit-antenna configurations. In essence, both the 2×2 and the 4×4 schemes specified by LTE are full-rate codes and both offer increased performance benefits, due to their diversity when compared to single-antenna transmissions. The key components highlighted in this example include:

- Generation of payload data for a single subframe (a transport block).

• DLSCH processing: Transport-block CRC (Cyclic Redundancy Check) attachment, codeblock segmentation and CRC attachment, turbo coding based on a 1/3-rate code, rate matching, and codeblock concatenation to generate a code word input to PDSCH.

• PDSCH transmitter processing: Bit-level scrambling, data modulation, layer mapping, and precoding for two and four antennas with transmit diversity encoding, plus resource element mapping and OFDM signal generation.

• Channel modeling: A MIMO fading channel followed by an AWGN channel.

• PDSCH receiver processing: An OFDM signal receiver generating the resource grid, resource element demapping to separate the CSR signal from the user data, channel estimation, SFBC-based combining using channel estimates and soft-decision demodulation and descrambling, and DLSCH decoding.

The channel modeling includes a combination of fading channel and AWGN channel. The receiver operation, which inverts the PDSCH operations, includes the following: the OFDM signal receiver generating the resource grid, resource-element demapping to separate the CSR signal from the user data, channel estimation, and frequency-domain equalization based on the CSR signal and soft-decision demodulation and descrambling.

Finally, the inverse operations of the DLSCH are performed, including: codeblock segmentation, rate dematching, and turbo decoding with an early stopping option based on CRC detection. The receiver output variable data_out and the transmitter input transport block variable dataIn are provided as the first two output arguments of the function. Alongside these variables, a few others are included as outputs to enhance the task of examining the system performance.

commlteMIMO_SM_step

The function shows a transmitter, receiver, and channel model for the fourth mode of the LTE standard, featuring single-codeword spatial multiplexing. Using multiple antennas at both the transmitter and the receiver, we showcase both 2 × 2 and 4 × 4 MIMO antenna configurations. The key components include the following:

• Generation of payload data for a single subframe (a transport block).

• DLSCH processing, as described earlier.

• PDSCH transmitter processing, including bit-level scrambling, data modulation, layer mapping, and precoding for two or four antennas, as well as precoding for spatial multiplexing, resource-element mapping, and OFDM signal generation.

• Channel modeling, including a MIMO fading channel followed by an AWGN channel.

• PDSCH receiver processing, including an OFDM signal receiver to generate the resource grid, resource-element demapping to separate the CSR signal from the user data, channel estimation, MIMO receiver and layer demapping, soft-decision demodulation, descrambling, and DLSCH decoding.

zVisualize

The function performs two tasks. First, it shows the constellation diagram of the user data at the receiver before and after equalization by calling the function zVisConstell, which shows constellation diagrams for data transmitted over multiple transmit antennas. Depending on the number of transmit antennas used, it creates and configures multiple Constellation Diagram System objects from the Communications System Toolbox.

Second, the zVisualize function illustrates the spectra of the transmitted signal and of the received signal both before and after equalization, by calling the function zVisSpectrum, which shows the magnitude spectrum of data transmitted over multiple transmit antennas. Depending on the number of transmit antennas used, it creates and configures multiple Spectrum Analyzer System objects from the DSP System Toolbox.