Codebook Based Multi-User MIMO for 5G

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Codebook Based Multi-User MIMO for 5G

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Abstract

Better signal strength is required to provide a good signal service to the UE. For this, different methods and techniques are available, one of them is codebook type II precoding. This method has a potential to provide an amount of energy to the user in the required direction more precisely than Codebook type I. Therefore this method will be put to the test, for a given SNR range, by comparing the quality of the beamformed signal to non-beamformed signal.

Additional studies have been made about the different characteristics of the channel with simple changes in the base station with a different antenna configuration exploiting MIMO case. This will lead to have a large array gain and also spectral efficiency is increased in spatial domain. All these characteristics are applied for multi-layers and multi-users. For a better understanding of the topic and for proof of concept, it is being restricted to a single user and a single layer.

Popular Science Summary

Technology has evolved in a small span of time where it has got a revolutionary change in the telecommunication and mobile phone industry. For example, earlier, we have seen that the mobile phones are being used for basic calling and messaging. After that, it has been moving towards different applications which are being added and goes on to support a lot of applications that were not supported before.

With an increase in the facilities in the new phones era, the demand of more application oriented in the mobile phone is craving for the better signal requirements and the good service quality.

To match up the requirements and to satisfy the customers or users demands, a change need to be made to the services and to provide a higher and faster data rates.

The demands and requirements of the user are getting accomplished with a new technology which is 5G NR. It is codebook based. It has been implemented in LTE and LTE-A using codebook type I precoding but, major changes have been made so its directionality is more accurate leading to a better experience to the end user. A new method is being proposed, codebook type II which is in developing stages. So in this method it is being promised with much greater benefits.

Acronym

3GPP 3^{rd} Generation Partnership Project

AP Antenna Port

AWGN Additive White Gaussian Noise

BER Bit Error Rate

CDF Cumulative Distribution Function

CSI Channel State Information

DFT Discrete Fourier Transform

GUI Graphical User Interface

LSB Least Significant Bit

LTE Long-Term Evolution

MIMO Multiple Input Multiple Output

MSB Most Significant Bit

MU-MIMO Multiple Users – Multiple Input Multiple Output

NR New Radio

PA Physical Antenna

PDF Probability Density Function

PMI Precoding Matrix

RI Rank Indicator

RSS Reference Signal Sequences

Rx Receiver

SNR Signal to Noise Ratio

Tx Transmitter

UE User Equipment

W Weight

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Chapter 1: Introduction

This chapter introduces the thesis, the purpose why it is being carried out, goals and the complexities involved. Also, this chapter provides a background of the thesis and what could be done in future work.

1.1 Background

The thesis was carried out and supervised in cooperation with Ericsson AB. The thesis describes a detailed study and analysis of codebook based precoding for 5G. Then the thesis covers a simulation model where codebook type II precoding was implemented. Later, the thesis explores the possibilities of using codebook type II precoding for multi user MIMO and the complexities involved with it. Finally, an analysis of the simulation results for different channel conditions is made and the results and future work are discussed.

1.2 Evolution of Codebook

CSI, better known as Channel State Information, describes how a signal going from the transmitter to the receiver is getting affected by scattering factors, power decay due to distance and fading [1].

Codebook based transmission was introduced when MIMO was implemented in LTE and LTE-Advanced since the actual benefits of MIMO would rely on the accurate channel knowledge at the transmitter. Hence the importance of codebook implementation. 3GPP introduced two types of codebook. In 3gpp LTE, codebook type-I was introduced and in 3GPP NR, codebook type II was introduced. Both codebooks were based on 2D DFT beams and provide CSI feedback for beam selection [1], however, codebook type II was introduced since it was believed that a more accurate CSI feedback was needed and the reason for that was codebook type II would report both wideband and sub-band indices for a more accurate CSI feedback, meaning a better MIMO transmission for NR [2] [3]. Hence the purpose of this project where we study and analyze codebook type II for 5G and how that would benefit multi-user MIMO in the future and the complexities involved in implementing it.

1.3 Project Specification

The main aim of the thesis is to study and implement codebook type II for NR systems. To implement this, the use of CSI is quite important in understanding the state of the channel in the downlink so the UE is required to send back a feedback in the uplink about the channel.

Therefore, to successfully apply codebook type II, the following parts are required:

- Understanding the concepts behind the codebook, how it is defined in the specifications by the 3GPP and attempt to apply it for a single antenna at the UE and a single antenna at the base station and gradually go into 2x2 MIMO then later 4x4 MIMO and establish its benefit.
- Comparing the BER between data transmitted without codebook and data transmitted with codebook for different antenna port layout and oversampling factors and conclude if it is beneficial to use the codebook or not.

- Simulating the system model in different channel conditions and characteristics leading to a better understanding of the ideal conditions where the system could be implemented in the future

1.4 Thesis organization

The rest of the thesis is organized in the following manner:
Chapter 2 is more focused on the theory side. The first section of this chapter mainly discusses about codebook type I in LTE, the different configurations supported, and the required parameters for implementation. The second section of this chapter discusses about codebook type II in NR, the main function on which the codebook is based on and the explanation of the required parameters.

Chapter 3 describes the system model design going through each block and explains the importance of that block in the overall procedure.

Chapter 4 defines the implementation and approach that were used going from general approach, to exploring MIMO case and later considering channel characteristics.

Chapter 5 includes all the results for different scenarios where codebook type II was implemented successfully. Signal constellations and plotting of BER vs SNR are included in this chapter which are analysed later.

Chapter 6 concludes the reports with a quick summary of all the chapters. Final remarks and potential future work are also briefly discussed in this chapter.

Chapter 2: Codebook based precoding

This chapter introduces the two types of codebooks defined for LTE and NR respectively, and defines the parameters required for each codebook.

Codebook based precoding is a promising new technique of beamforming. Precoding means multiple data streams or a single data stream are transmitted from the transmit antennas with independent and appropriate weightings that will lead to maximize the throughput at the receiver side. Codebook precoding was introduced in LTE where predefined matrices were calculated and assigned to the transmitting antennas over the channel. However, precoding has evolved where codebook type II was introduced in NR.

Codebook type II relies on the UE reporting back to the base station with indices that will be used in order to calculate the appropriate weights more precisely for each antenna as will be explained further in this chapter.

2.1 MIMO Channel

The MIMO channel is the medium that the transmitter and the receiver use to establish a connection between them. In what follows, up to 4 antennas at the Tx and 4 antennas at the Rx are considered, i.e. 4x4 MIMO system.

The following figure illustrates a 4x4 MIMO system having H as the channel matrix and adding noise (Gaussian or Rayleigh).

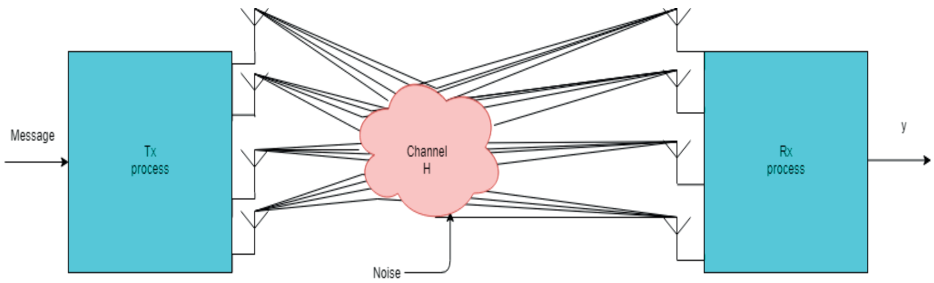

Figure 2.1: MIMO channel representation

A channel is referred as physical transmission medium which is used as a barrier to send a message or an information between one or multiple senders and one or multiple receivers. In communications, the signals are being transmitted from transmitter to receiver. In between the transmitter and receiver, there needs to be a medium to transmit which can be either guided wireless medium or wired medium. In this context, we are using a wireless medium to transmit the signal. [4]

The output y at the receiver follows the following equation:

$$y = HWx + n$$

Where H is the identity matrix, x is the transmitted message, noise n is assumed to be Gaussian in most the project and later on changed to Rayleigh noise in order to simulate different channels behavior, and the precoding matrix W which is described in depth in the following sections of this chapter.

2.2 Codebook Type I in LTE

In order to understand codebook type I, we should know about CSI at the UE side. The CSI always recommends a proper pre-coding matrix for a better signal in the channel. The set of all pre-coding matrices forms the codebook. To assign it in an efficient manner, codebook type I is used in LTE and LTE-A. There are two different configurations supported: 1) Codebook type I single panel:

In type I codebook single panel, the UE is configured with higher layer parameter and the codebook type is set to type I. Each PMI (Precoding Matrix index) corresponds to a codebook index which is shown in table 2.1. So bit map parameter forms a bit sequence from a_5, a_4..a_1,a_0, where a_0 is the LSB and a_5 is the MSB. For layer 1 the bits a_0 to a_3 are associated with codebook indices 0 to 3, for layer 2 bits a_4 and a_5 are associated with codebook indices 0 and 1 as seen in table 2.2.

Table 2.1: Codebook for 1-layer and 2-layer CSI reporting [2]

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

Table 2.2: Bit mapping to layer 1 and layer 2 [2]

Codebook index	Number of Layers	
	1	2
0	a_0	–
1	a_1	a_4
2	a_2	a_5
3	a_3	–

When UE is configured and set to type 1 single panel, the bit map parameter form a sequence $r_7\, r_6\, r_5 \ldots r_0$, where r_7 is the MSB and r_0 is the LSB, the following supported configurations (N_1 N_2) and their corresponding oversampling factors (o_1,o_2) .

Table 2.3: Supported configurations of (N_1,N_2) and (O_1,O_2) [2]

Number of CSI-RS ports	(N_1,N_2)	(O_1,O_2)
4	(2,1)	(4,-)
8	(2,2)	(4,4)
	(4,1)	(4,-)
12	(3,2)	(4,4)
	(6,1)	(4,-)
16	(4,2)	(4,4)
	(8,1)	(4,-)
24	(6,2)(4,3)	(4,4)
	(12,1)	(4,-)
32	(8,2)(4,4)	(4,4)
	(16,1)	(4,-)

Max rank indicator is the same as the number of antennas on each side if the number is the same, i.e. for a 4x4 MIMO, the maximum achievable rank is 4. If the number of antennas at the receiver is different than the number of antennas at the transmitter, the maximum achievable rank indicator is the one with less number of antennas, i.e. for a 2x1 MIMO, the maximum achievable rank is 1.

Type I single panel support up to rank 8 which is associated with the number of layers per Panel. For Rank 1 and 2, the number of supported beams ranges from 1 to 4 while for higher ranks, the number of beams supported is 1.

For Ranks$\geq$ 2, the PMI codebook assumes the precoder structure as

$$W = W_1 \times W_2 \text{ [3]}$$

where $W_1 = \begin{bmatrix} B & 0 \\ 0 & B \end{bmatrix}$ having B the oversampled 2D DFT beams and W_2 represents the beam selection and QPSK co-phasing between two polarizations.

2) Codebook Type I Multi-Panel:

There are a lot of similarities between the two supported codebook type I. However, codebook type I has introduced inter-panel co-phasing denoted by $p = 0,1, \dots, N_g - 1$ where N_g is the number of panels. Inter-panel co-phasing shapes the radiation pattern for panels redirecting its energy in a more specific direction. The supported number of panels is either $N_g = 2$ or $N_g = 4$.

The following table represents the antenna port layout and its corresponding oversampling factors that are supported for multi-panel:

Table 2.4: Supported configurations of (N_g, N_1, N_2) and (O_1, O_2) [2]

Number of CSI-RS ports	(N_g, N_1, N_2)	(O_1, O_2)
8	(2,2,1)	(4, −)
16	(2,2,2)	(4,4)
	(2,4,1), (4,2,1)	(4, −)
32	(2,4,2), (4,2,2)	(4,4)
	(2,8,1), (4,4,1)	(4, −)

Inter-panel co-phasing denoted by p is configurable according to 2 modes:
Mode 1: Wideband inter-panel co-phasing with payload = 2bits/subband having $N_g = 2$ or $N_g = 4$.
Mode 2: Subband inter-panel co-phasing with payload = 4bits/subband having $N_g = 2$.

2.3 Codebook type II in NR

As previously mentioned, Codebook type II was designed to have a better CSI feedback than Codebook type I since a more accurate CSI feedback was needed. Codebook type I had predefined matrices based on the number of layers and CSI-RS ports. The concept of weight beamforming still stands in codebook type II. However, the weight W is no longer predefined. It is based on the UE feedback providing important indices that forms W in codebook type II as seen in the table below. The base station uses these indices creating the new codebook as seen in the table below:

Table 2.5: Codebook Type II for 1-layer and 2-layer CSI reporting [2]

Layers	
$\varepsilon = 1$	$W^{(1)}_{q_1,q_2,n_1,n_2,p_1^{(1)},p_1^{(2)},i_{2,1,1}}$
$\varepsilon = 2$	$W^{(2)}_{q_1,q_2,n_1,n_2,p_1^{(1)},p_1^{(2)},i_{2,1,1},p_2^{(1)},p_2^{(2)},i_{2,1,2}} = \frac{1}{\sqrt{2}}\left[W^{(1)}_{q_1,q_2,n_1,n_2,p_1^{(1)},p_1^{(2)},i_{2,1,1}} \quad W^{(2)}_{q_1,q_2,n_1,n_2,p_2^{(1)},p_2^{(2)},i_{2,1,2}}\right]$
Where $W^{(1)}_{q_1,q_2,n_1,n_2,p_1^{(1)},p_1^{(2)},c_l} = \frac{1}{\sqrt{N_1 N_2 \sum_{i=0}^{2L-1}(p_{l,i}^{(1)} p_{l,i}^{(2)})^2}} \begin{bmatrix} \sum_{i=0}^{L-1} \mu_{m_1^{(i)},m_2^{(i)}} p_{l,i}^{(1)} p_{l,i}^{(2)} \varphi_{l,i} \\ \sum_{i=0}^{L-1} \mu_{m_1^{(i)},m_2^{(i)}} p_{l,i+L}^{(1)} p_{l,i+L}^{(2)} \varphi_{l,i+L} \end{bmatrix}, l = 1,2$	

Main parameters that constitute codebook type II:

- ε: Number of layers. The number of layers currently supported is up to 2 layers However additional studies are in progress to support up to 4 layers.
- q_1,q_2: Rotation factors where
  - $q_1 \in \{0,1,\dots,O_1 - 1\}$ and $q_2 \in \{0,1,\dots,O_2 - 1\}$
- L: Number of beams per layer. $L = 2$ for CSI-RS ports = 4 and $L \in \{2,3,4\}$ for CSI- RS ports > 4

- O_1, O_2 : Oversampling Factors

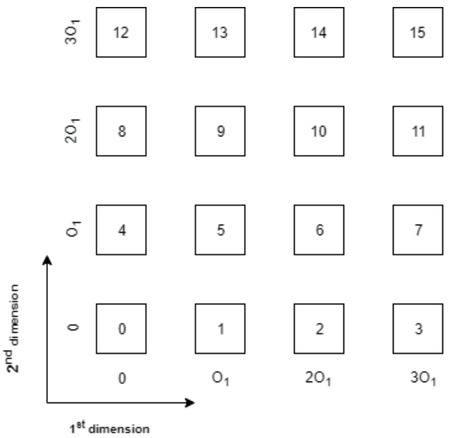

Figure 2.2: Antenna port layout and oversampling factor

Oversampling is the process of sampling a signal at rate much higher than the Nyquist rate. As seen in table 2.3, the two supported configurations of (O_1, O_2) are either (4, -) or (4, 4). Having a 1-D antenna port layout with a (4, -) oversampling factor means that you the signal is oversampled 4 times horizontally. And having a 2-D antenna port layout with a (4, 4) oversampling factor means that the signal is oversampled both horizontally and vertically 4 times as seen in figure 2.2.
Other significant parameters are:

- $p_{l,i}^{(2)}$: Sub-band amplitude value set mapping (1 bit) as seen in table 2.6
- $p_{l,i}^{(1)}$: Wideband amplitude value set mapping (3 bits) as seen in table 2.7
- n_1, n_2 : Parameters indicating the i-th beam in the selected orthogonal basis set where
  - $n_1 = \left[n_1^{(0)}, \dots, n_1^{(L-1)}\right]$ and $n_1^{(i)} \epsilon \{0,1, \dots, N_1 - 1\}$
  - $n_2 = \left[n_2^{(0)}, \dots, n_2^{(L-1)}\right]$ and $n_2^{(i)} \epsilon \{0,1, \dots, N_2 - 1\}$

Table 2.6: Sub-band indices mapping [2]

$k_{l,i}^{(2)}$	$p_{l,i}^{(2)}$
0	$\sqrt{1/2}$
1	1

Table 2.7: Wideband indices mapping [2]

$k_{l,i}^{(1)}$	$p_{l,i}^{(1)}$
0	0
1	$\sqrt{1/64}$
2	$\sqrt{1/32}$
3	$\sqrt{1/16}$
4	$\sqrt{1/8}$
5	$\sqrt{1/4}$
6	$\sqrt{1/2}$
7	1

- $\varphi_{l,i} = e^{j2\pi c_{l,i}/N_{PSK}}$ indicating that sub-band amplitude = 'false', dependent on the combinatorial coefficient and the number of constellation points
- $\mu_{l,m} = \left[u_m \quad e^{j\frac{2\pi l}{O_1 N_1}} u_m \quad \cdots \quad e^{j\frac{2\pi l(N_1-1)}{O_1 N_1}} u_m\right]^T$; $u_m = 1$ for 1-D antenna port layout
- $C(x, y)$: Combinatorial coefficient where $x = N_1 N_2 - 1 - n^{(i)}$ and $y = L - i$ for $i = 0, \ldots, L-1$.
  These combinatorial coefficient are pre-calculated for any (x, y) combination as seen in table 2.8 below.

Table 2.8: Combinatorial coefficient [2]

x \ y	1	2	3	4
0	0	0	0	0
1	1	0	0	0
2	2	1	0	0
3	3	3	1	0
4	4	6	4	1
5	5	10	10	5
6	6	15	20	15
7	7	21	35	35

Chapter 3: Proposed architecture

In the previous chapter, we have explained what the contents of codebook type I and codebook type II are. We would like now to carry out an implementation of codebook type II in multiple scenarios and understand what improvements we can get compared to non-codebook transmissions.

The following block diagram represents the model design that was used:

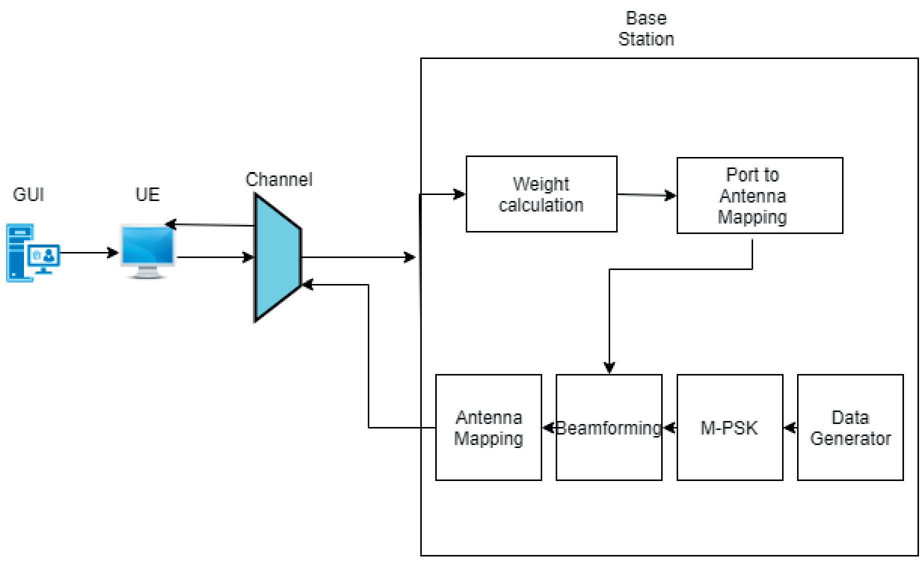

Figure 3.1: Model system design

This block diagram in itself is not state-of-the-art. It is very similar to what was implemented in codebook type I. However, what we did is to adjust it appropriately to support codebook type II. The major modifications are the UE feedback, the weights calculation and beamforming. As previously explained, codebook type I had predefined matrices. According to the codebook index, Weight W was selected then multiplied by the data needed to be transmitted and sent over the channel to be decoded by the receiver. This method indicated that the UE was in a certain sector without identifying the exact position of the UE. What we tried to do is to benefit from the UE feedback to determine important indices as mentioned in the previous chapter, calculating W accordingly and then simulating for different MIMO cases and channel conditions.

3.1 Graphical User interface

The graphical user interface was created to simulate the UE reporting the previously mentioned parameters using Matlab. The options that the user can select from are limited to what is currently supported by the codebook:

- Antenna port layout according to table 2.3
- Oversampling factors according to table 2.3
- Sub-band indices according to table 2.6
- Wideband indices according to table 2.7
- M-PSK: Either 4-PSK or 8-PSK

The number of wideband and sub-band indices are dependent on the antenna port layout chosen. Therefore, the number of slots available in the GUI will adjust accordingly. Also, any wrong entry of the data will prompt an error and will lead the GUI to fail in sending the parameters.

The figure representing the graphical user interface is shown below:

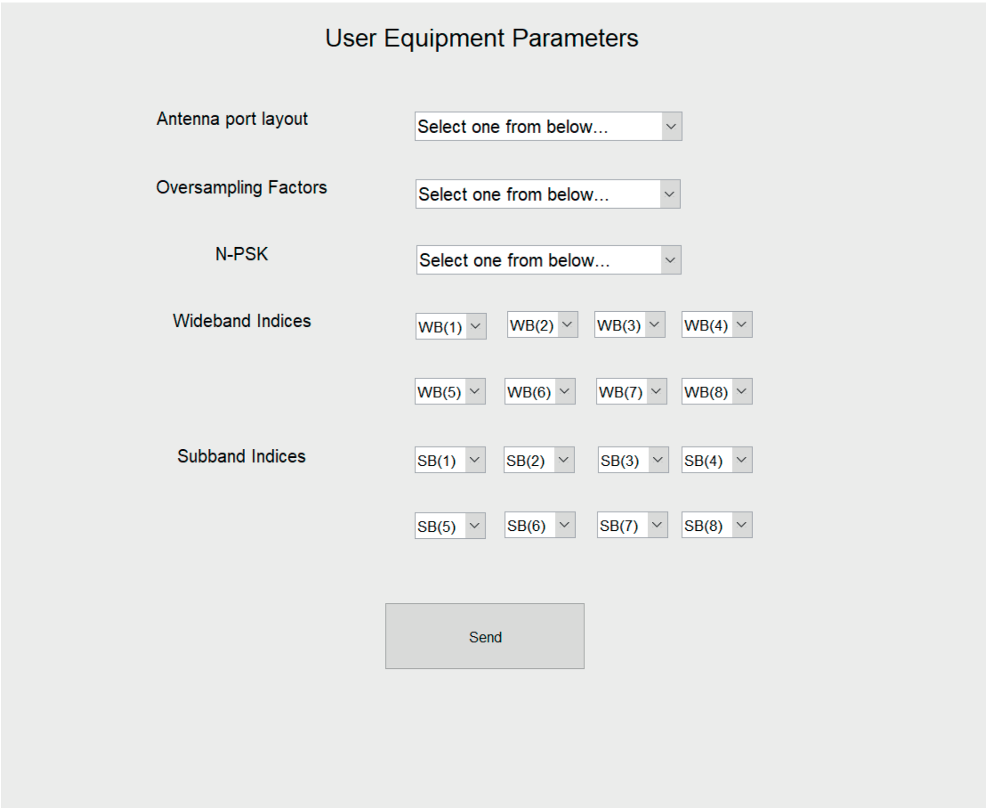

Figure 3.2: User equipment parameters using graphical user interface

3.2 Base Station

The base station is considered to be the major part of the model design. It consists of multiple blocks as mentioned below:

- Data Generator: Generating 10^6 random bits forming the data desired to be transmitted to the UE.
- M-PSK: Based on the user decision (Either Q-PSK or 8-PSK) using the GUI, the data transmitted will be modulated accordingly. No other modulation scheme is supported.
- Weight Calculation: Weight calculation is the basis of codebook type II. It is based on the function defined in table 2.5. It depends on the number of layers, wideband indices, sub-band indices, combinatorial coefficient, number of antenna ports, antenna port layout and oversampling factors. Having multiple antennas means multiple weights. For simplicity purposes, the weight for two antenna or four antennas were assumed to be orthogonal.
- Beamforming: Beamforming is a technique used in constructing antenna radiation pattern. The reason for using beamforming is that the beam is directed to the UE leading to less energy being wasted.

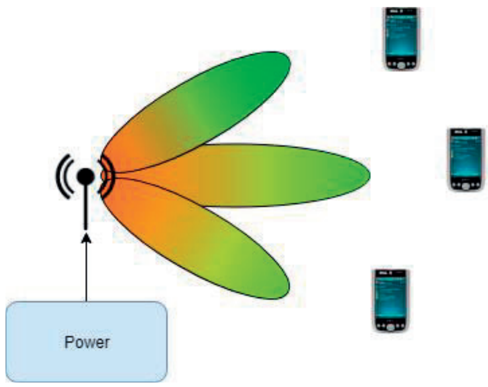

Figure 3.3: Beamforming for multiple UEs

There are different techniques to implement beamforming. One of the most familiar ones is beamforming by precoding where the radiation form is changed by applying a precoding matrix [6]. However, in NR specification, precoding stage is only supported for uplink and not for downlink.

- Antenna port mapping: Antenna ports are considered to be logical entities rather than physical. These ports are distinguished by their RSS [7]. The number of ports defined in codebook Type II, P_{CSI-RS}, is dependent on the antenna port layout chosen, meaning that for a supported configuration of (N_1, N_2), $P_{CSI-RS} = 2N_1N_2$, i.e. Having $(N_1, N_2) = (2,1)$ supported in table 1, $P_{CSI-RS} = 4$. It is up to the base station how these ports are assigned to the physical antennas. The UE is not aware how the mapping has been carried out by the base station rather the UE should handle this during demodulation.

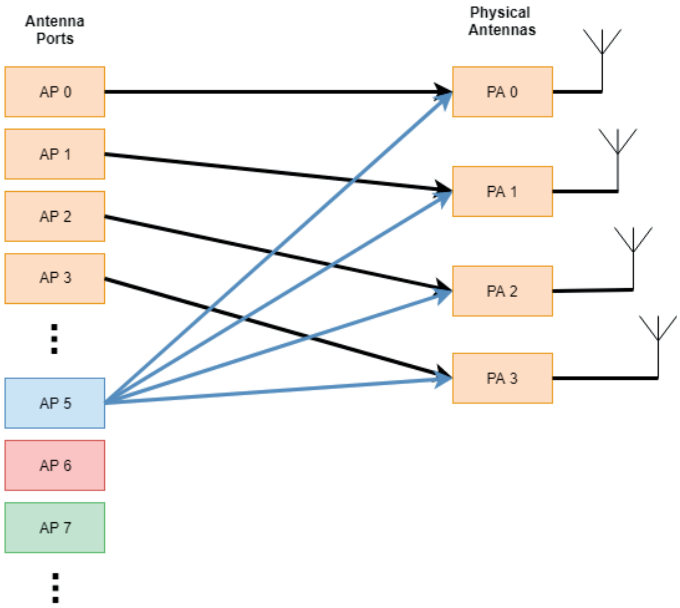

Figure 3.4: Antenna port mapping

- Antenna mapping: Antenna mapping is the process that enables one or multiple users to transmit their data on different antenna ports. It is dependent on the Rank Indicator (RI) and the Weight (W) recommended by the UE based on previous calculations as seen in the block diagram below:

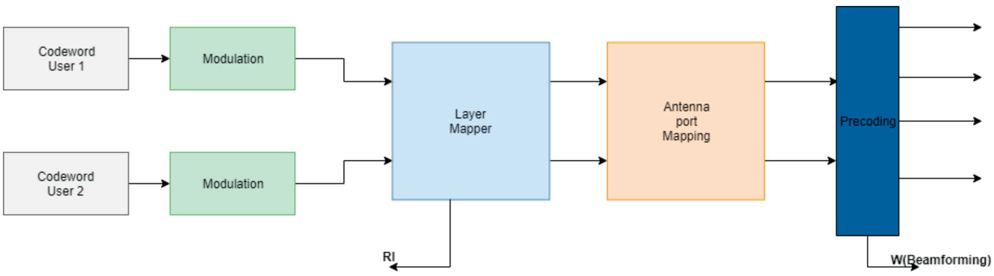

Figure 3.5: Antenna mapping

Chapter 4: Approach and implementation

4.1 General approach and methodology:

This chapter discusses the approach and implementation of the block design that was discussed in chapter 3 with a fully-fledged functionality.

General steps followed in implementing the codebook type II:

- The first step is the setup of the GUI which is shown in the previous section. Through the GUI, different parameters such as antenna port layout, oversampling factors, wideband and sub-band indices are chosen. The assumption made here that these manually chosen parameters represents the UE report to the base station. Therefore, for simplicity purposes, an approximation was made on UE Report stating that UE has chosen these parameters and forward theses parameters to the codebook.
- After GUI selection, the main function for a single layer codebook type II was defined where the required parameters were explained in the second chapter.
- Once the weight is calculated, the modulated signal is multiplied with the weights and transmitted to UE.
- In order to check the effect of codebook on the transmitted signal, a comparison between the beamformed signal and non-beamformed signal will take place for a single antenna given a certain noise power.
- While transmitting it in the channel, a second assumption made is that the channel is static.
- A BER calculation is made for a single antenna with given noise power.
- Once satisfied with the results, multiple antennas transmission between the UE and the base station were implemented for a given SNR range.

4.2 Functional set up of upper algorithm:

The setup starts by generating a QPSK signal with different wideband, sub-band indices that will lead to a better understanding of how these reported indices can affect the beamformed signal. So as to test this case we plot the beamformed QPSK signal with generated QPSK signal for every possible wideband and sub-band indices to understand which CSI gives us better signal. In this test AWGN channel is used.

After, the QPSK implementation of noise is added with varying SNR. This would lead to better understanding of how noise is affecting the signal at every possible stage and counting BER at every SNR.

To transmit the signal over a channel, an accurate number of users and number of antennas is required both at the transmitter side and receiver side.

Implementing using one antenna at transmitter and one antenna at user:

In this section, the case of one antenna at the base station and a single user with single antenna is implemented. After getting the Q-PSK encoded signal, it is sent over a channel that was described in the previous chapter. Then the BER is calculated by comparing the beam formed signal with the originally sent data.

4.3 Exploring the MIMO case:

In order to improve the quality of service, and spectral efficiency, MIMO is needed to achieve better gain, an increase of data rate and reduction of BER.

There are some disadvantages as we increase the number of antennas in both transmitter and receiver mainly complexity in the structure, the number of RF units will increase, more power is required. Yet the advantages are more important and significant when compared with the disadvantages.

After showing the importance of precoding for a single user with a single antenna, 2x2 MIMO was implemented where each antenna had its own weight based on the UE feedback. The data that was sent by the user was multiplied by its appropriate weight and later decoded at the receiver side. Then an analysis of the BER vs SNR was done in order to assess its performance.

The same work was done for 4x4 MIMO transmission. Each antenna had its own weight. These weights were orthogonal to each other yet they had different wideband and sub-band indices sent by the UE. A comparison was done after decoding the transmitted message at the receiver in order to assess the benefits of beamforming for a 4x4 MIMO compared to all previously mentioned scenarios.

4.4 Different channels implementation:

As in the above task the implementation is done by increasing the number of antennas and keeping a single channel. In this section, 2 different channels are used to determine the transmitted signal characteristics in different SNR

4.4.1 Implementing using four antennas and two channels:

Four antennas are used at the transmitter side and the receiver side. The channels that were chosen to conduct this testing were:

1) Gaussian Channel:

One of the most common channels to use is the Additive White Gaussian Noise Channel. In real life, noise is much more complex than this model however, it is very efficient when simulating background noise or amplifier noise. In this section we will have a closer look on AWGN channels and their properties for different signal to noise ratio (SNR). In a communication system, data is often represented in a binary form which is discrete so we use digital to analog converter to accommodate them to analog signals that can be transmitted through physical channels. Within this channel model, the received signal can be expressed as:

$$Y = X(t) + N(t) \text{ [4]}$$

Where $X(t)$ is the modulated signal which is continuous and $N(t)$ is the noise which is added here $N(t)$ is AWGN Now we look into some properties of Gaussian channel

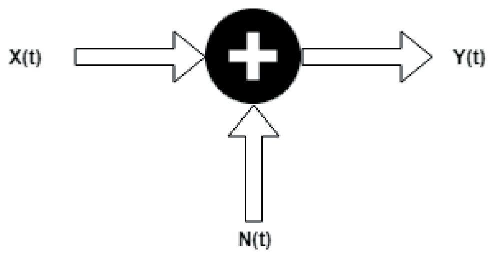

Figure 4.1: Digital signal representation

Generally it is denoted as $\boldsymbol{N}(0, \sqrt{N})$ which means Zero mean and $\sqrt{N}$ is the variance. A random variable is said to be Gaussian function if the distribution is having the following properties shown in the figure 4.2.

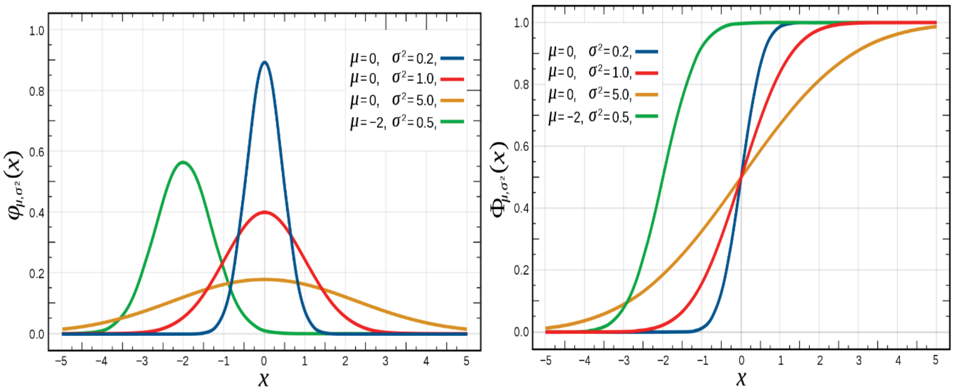

Figure 4.2: Properties of a Gaussian channel [5]

The parameters are described below:

- μ is the mean of the distribution
- σ is the standard deviation
- σ^2 is the variance

In a communication channel the signaling power is being constrained at the transmitter

$$E\,[X^2] \leq P$$

The power constraint is therefore defined to develop a realistic system otherwise we would choose as many signal alternative as far apart as one likes which means there is no limit in the information transmission for a single channel use.

In the case of massive MIMO, the channel between each transmitter antenna and receiver would have individual and independent channels. For simplicity purposes, perfect CSI is assumed. MIMO will use the true channel matrix without the need of correlations.

2) Rayleigh Channel:

In this section, Rayleigh channel is discussed. It is a channel model where fading follows a Rayleigh distribution. This type of channel is also called small scale fading. If the signal underwent multiple reflective paths that are large in number and there is no line of sight component, then from the statistical data we can say that the signal has undergone Rayleigh fading.

The probability density formula of Rayleigh distribution is given as:

$$\frac{x}{\sigma^2} e^{-x^2/2\sigma^2} [8]$$

Where x has a Rayleigh distribution with parameter σ

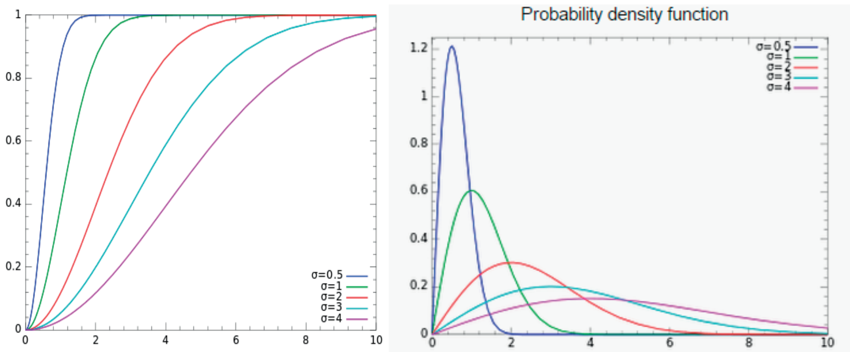

Figure 4.3: PDF & CDF [5]

As σ increases the distribution gets wider and wider.

The above graphs will closely look like Gaussian distribution as the number of elements in the random variable is increasing. This is explained by the central limit theorem.

Certain characteristics of MIMO transmission needs to be taken care of.

- Many incoming waves
- Many outgoing waves
- Correct antenna spacing
- Random incoming waves
- Random outgoing waves

These conditions leads to rich scattering occurring at both transmitter and receiver. Channel knowledge to the transmitter also plays a huge role in this implementation.

In most cases, the channel is unknown to the transmitter therefore the assumption made is that the channels are orthogonal and uncorrelated.

In the thesis, the entire channel is assumed to be Gaussian and it gives an array gain which can be shown using the capacity formula which is shown below

$$C = \sum_{K=1}^{k} \log_2(1 + \frac{E_s}{M_T N_0} \lambda_i) \text{ [8]}$$

For orthogonal case $\lambda_1 = \lambda_2 = \lambda_3 \dots \dots .. = \lambda_M = M$

The above formula changes to:

$$C = M \log_2(1 + \frac{E_s}{N_0}) \text{ [8]}$$

The expectation from this test is that the beam formed will have a slightly higher bit error rate but that could be ignored regarding the possible benefits that could be achieved.

Next, an observation of the signal characteristics with different channels was made. These channels have different characteristics at low SNR and high SNR and according to the theory we can say Gaussian is far better than Rayleigh which is expected to be shown in the result. All the above work is being simulated through Matlab.

Chapter 5: Results

After discussing in the previous chapters, the theoretical and implementation parts in the thesis, this chapter focuses on the results obtained from the implementation of codebook type II for a single user in single and multiple antenna transmission with different channel conditions between the UE and the base station.

5.1 Single antenna transmission

5.1.1 QPSK modulation

In order to assess the effect of beamforming with codebook, BER was calculated and compared for transmitted data with and without beamforming. Three samples were taken by randomly selecting wideband and sub-band indices assuming a (2,1) antenna port layout indicating the three states of the CSI.

- First CSI sample
  - Wideband indices: $pl_1^{(0)} = pl_1^{(1)} = \sqrt{1/64}\,;\, pl_1^{(2)} = pl_1^{(3)} = 0$
  - Sub-band indices: $pl_2^{(0)} = pl_2^{(1)} = pl_2^{(2)} = pl_2^{(3)} = \sqrt{1/2}$

  The constellation diagram below represents the data transmitted without beamforming and the beamformed data transmitted with the above indices.

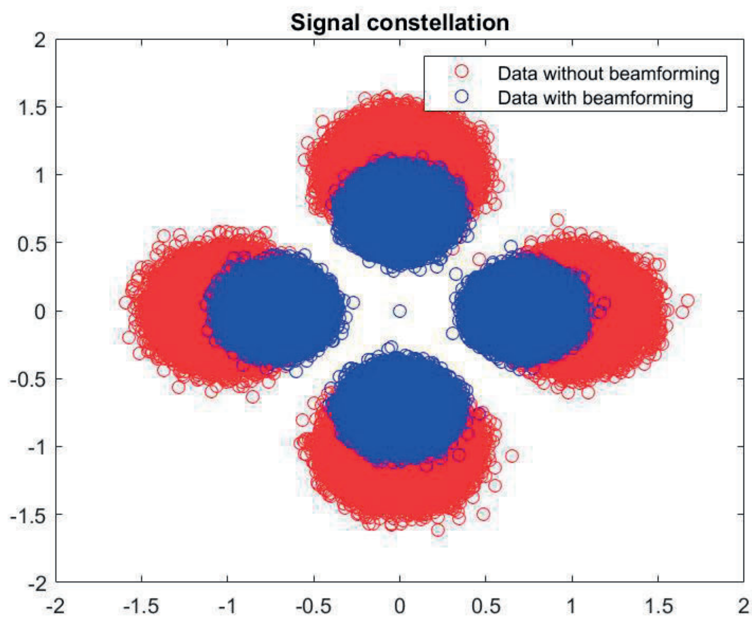

Figure 5.1: QPSK signal constellation with perfect CSI

- Second CSI sample
    - Wideband indices: $pl_1^{(0)} = pl_1^{(1)} = pl_1^{(2)} = \sqrt{1/16}; pl_1^{(3)} = 0$
    - Sub-band indices: $pl_2^{(0)} = pl_2^{(1)} = pl_2^{(2)} = pl_2^{(3)} = \sqrt{1/2}$

The constellation diagram below represents the data transmitted without beamforming and the beamformed data transmitted with the above indices.

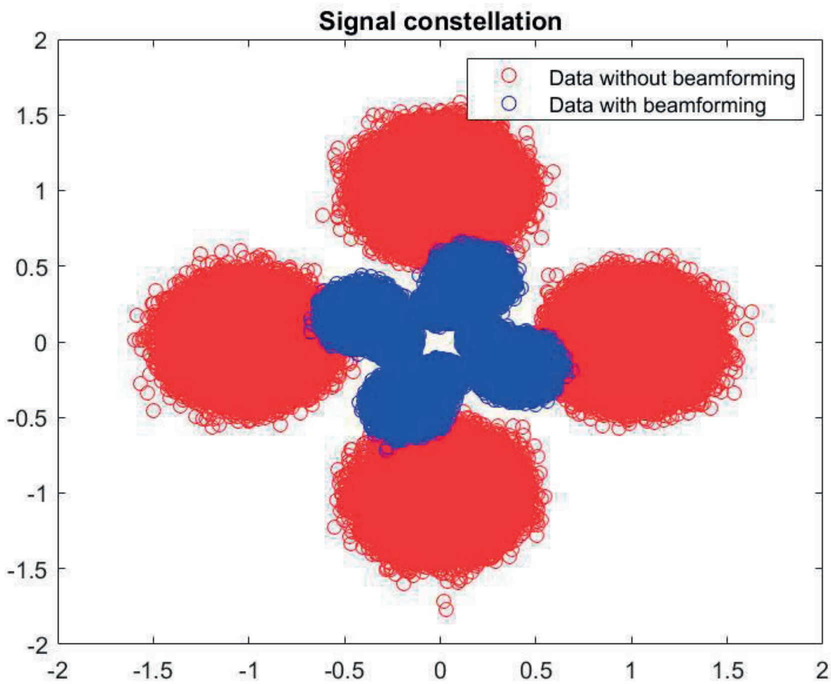

Figure 5.2: QPSK signal constellation with medium CSI

- Third CSI sample
    - Wideband indices: $pl_1^{(0)} = pl_1^{(1)} = pl_1^{(2)} = pl_1^{(3)} = 1;$
    - Sub-band indices: $pl_2^{(0)} = pl_2^{(1)} = pl_2^{(2)} = pl_2^{(3)} = 1$
- The constellation diagram below represents the data transmitted without beamforming and the beamformed data transmitted with the above indices.

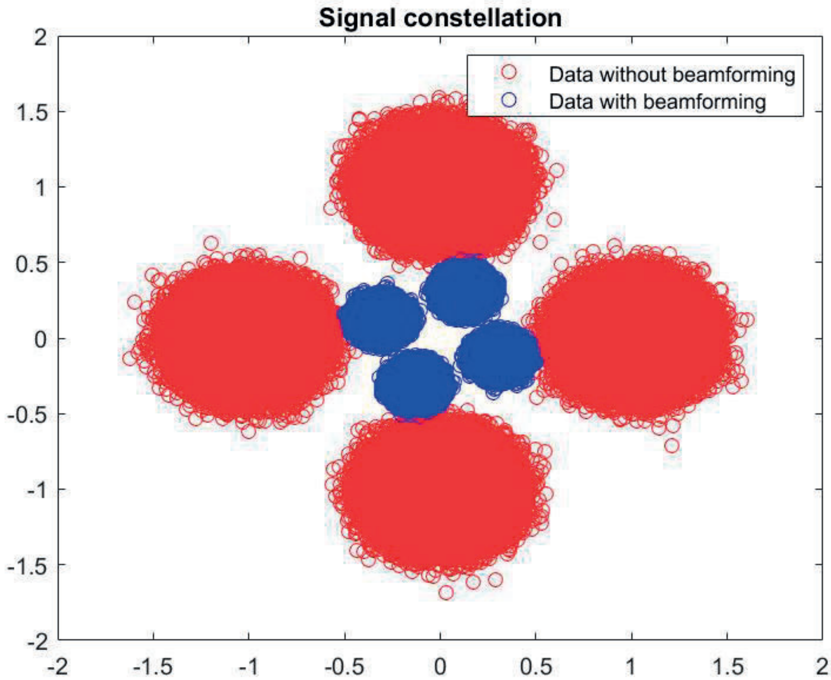

Figure 5.3: QPSK signal constellation with poor CSI

The three samples of CSI represent the good, the bad and the worst. The first CSI sample had a BER of 0.01% indicating that the beamformed signal is demodulated perfectly for a given SNR. The second CSI sample had a BER of 45% indicating that the data received was poorly demodulated. The third and final CSI sample had a BER of 99% indicating that the receiver was not capable of decoding the message sent correctly due to the bad CSI report. The reason for that fluctuation in the results is the wideband indices reported by the UE that are closer to one. Sub-Band indices do not affect as much in CSI report.

5.1.2 8-PSK modulation

Similarly, for 8-PSK modulation, the above result is also applicable. Having a perfect CSI with wideband indices relatively low, the BER is roughly 0.1%.
The constellation diagram below represents the data transmitted without beamforming and the beamformed data transmitted with the following indices:

- Wideband indices: $pl_1^{(0)} = pl_1^{(1)} = \sqrt{1/64}\,; pl_1^{(2)} = pl_1^{(3)} = 0$
- Sub-band indices: $pl_2^{(0)} = pl_2^{(1)} = pl_2^{(2)} = pl_2^{(3)} = \sqrt{1/2}$

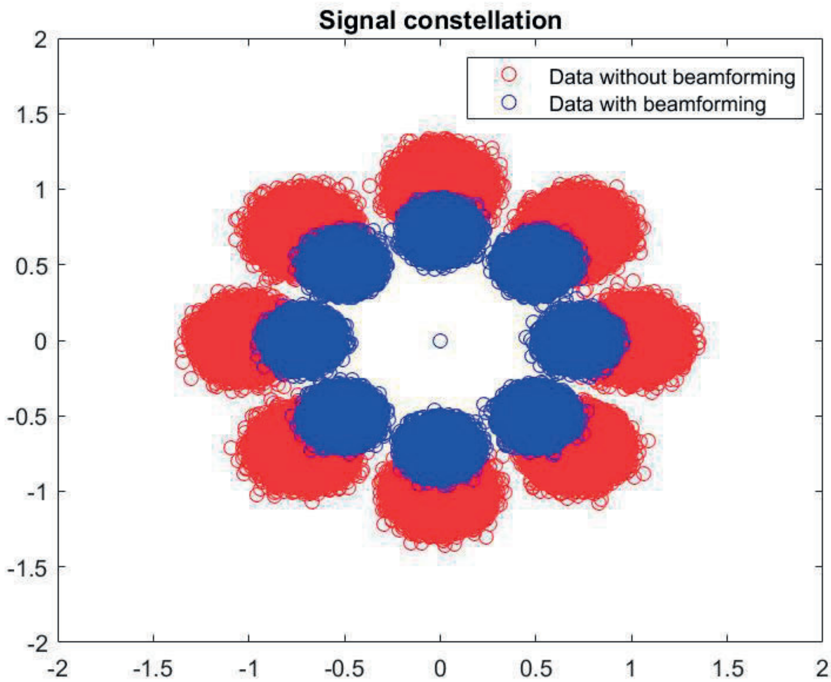

Figure 5.4: 8-PSK signal constellation with perfect CSI

As we look into these plots, there are no major difference in terms of constellation except overall amplitude gets smaller through the precoding block. But having a much better CSI due to the pre-coded signal can compensate for this disadvantage and will reduce the corrupted effect of the communication channel as shown in the following sections.

5.2 2x2 MIMO transmission

As mentioned in chapter 4, in order to increase the spectral efficiency, diversity is needed. Therefore, increasing the number of antennas at the UE and the base station will provide the necessary gain without too much complexity.

For this part, a plot of the BER vs SNR will pinpoint the gain attained from implementing codebook type II for 2x2 MIMO transmission vs single user transmission vs non-beamformed transmission.

These plots were generated using the $Q(x)$ function. The Q-function is the tail distribution function of the standard normal distribution or in other words, it is the probability that a normal random variable will obtain a value larger than x standard deviations. This function was used to determine the BER as follows:

$$Pb = Q(\sqrt{x \times 2 \times snr})$$

Where x is the ratio of the energy of the beamformed signal to the non-beamformed signal and snr is the signal to noise ratio in linear format.

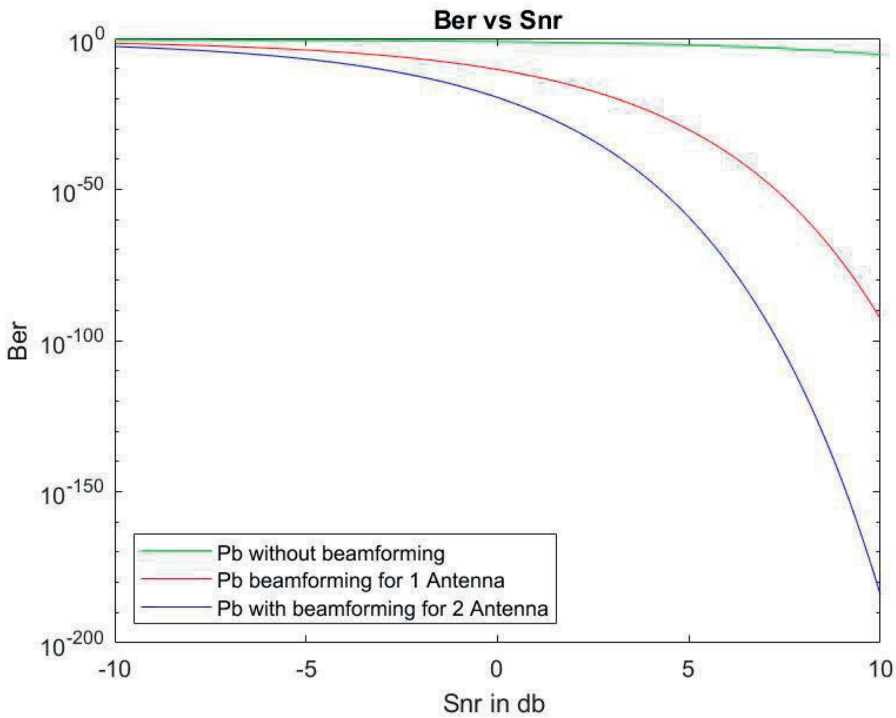

Figure 5.5: BER vs SNR for 2x2 MIMO transmission

So, from above the graph at low SNR, the BER is almost the same since the noise signal power is dominating. But, at high SNR, signal power is dominating over noise power, meaning lower BER is expected as the number of antennas is increasing, the gain is also increasing. This gain can be measured along the x axis at any given value, which is roughly 2dB gain.

5.3 4x4 MIMO transmission

Going into higher number of antennas at the UE and the base station means higher complexity yet more diversity and gain is achievable. The plot below represents the gain attained from implementing codebook type II for a 4x4 MIMO transmission compared to previously tested schemes.

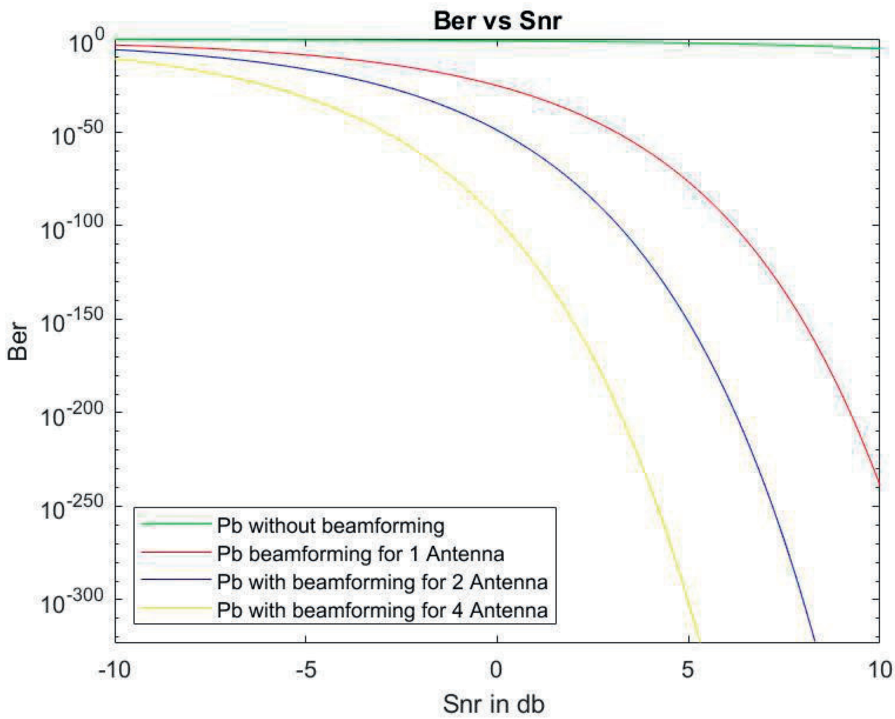

Figure 5.6: BER vs SNR for a 4x4 MIMO transmission

As seen in the figure above, implementing codebook type II for 4x4 MIMO transmission is achieving a higher diversity and attainable gain than the 2x2 MIMO transmission and single antenna transmission. Combining the different multipath components has led to a better scattering, higher data rate and capacity.

5.4 Rayleigh

Figure 5.7 represents a plot of the BER vs SNR in the case of Rayleigh Channel considering the different MIMO cases:

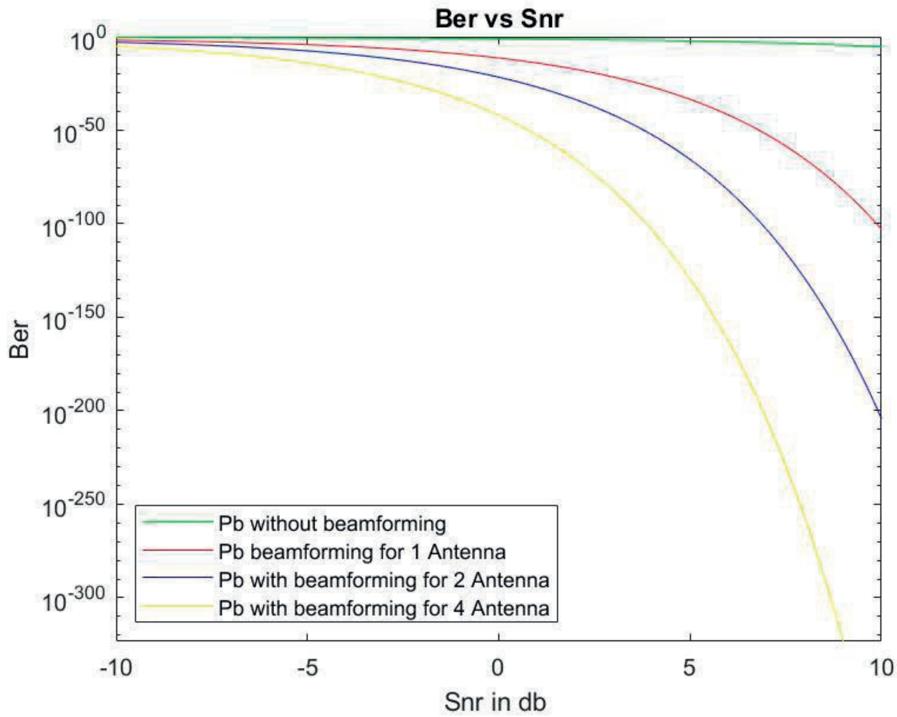

Figure 5.7: BER vs SNR for a 4x4 MIMO transmission with a Rayleigh Channel

Differences between Rayleigh and Gaussian channel:

As from above graphs comparing 5.6 and 5.7 the following observations are made. The BER at a given SNR for a given signal in Gaussian medium has a better BER than the Rayleigh Medium. According to the central limit theorem, the sum of a set of random variables with any distribution will converge to the Gaussian distribution. Hence, the Rayleigh distribution will converge to Gaussian. At low SNR, the BER of the signal is almost close or same whether it is Gaussian or Rayleigh. But at high SNR there is a noticeable difference between the channels and also the gain.

Chapter 6: Conclusion

The implementation of Codebook type II in NR systems was covered during this project. The thesis covered the evolution of Codebook from LTE to NR. The thesis discusses the main components of Codebook Type II and the parameters involved in making it the basis for NR. Then the implementation was structured for a different scenario ranging from changing the number of antennas both at the transmitter and the receiver, getting different UE reports affecting the codebook, changing the channel conditions and observing its characteristics and behavior of the transmitted signal.

These studies were a proof of concept since no previous attempt was made in NR, leading the way to great potentials in implementing the work done for multi-user MIMO achieving high spectral efficiency, reduction in BER due to advanced signal processing and achieving extension of cell coverage.

Chapter 7: Future Work

The main purpose of the thesis was to simulate precoding using codebook type II and explore using it for multi user MIMO. Hence, the future work should be based on the outcomes of this thesis and attempt to implement it for multi user MIMO. The main issue with MU-MIMO is having a perfect CSI. Through the implementation of codebook type II, the CSI has improved drastically. Hence, implementing MU-MIMO in the future will enable direct gain to be obtained due to MU-multiplexing. Also, the propagation issues such as antenna correlation and channel rank loss that affects single user MIMO will not have the same effect on MU-MIMO. Finally, spatial multiplexing gain could be achieved at the base station without the need for some expensive antennas at the UE side. All these advantages can be accomplished since we already established a proof of concept that can be used as the basis for future work.

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