Comparative Study on Linear Precoding Techniques for 5G Massive MIMO System

Zekarias Kahinu Ephrem

A Thesis Submitted to

The Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirements for the Degree of Master’s in Electronics and Communication Engineering

Office of Graduate Studies

Adama Science and Technology University

July, 2021

Adama, Ethiopia

Comparative Study on Linear Precoding Techniques for 5G Massive MIMO System

By: Zekarias Kahinu Ephrem

Advisor: Dr. Satyasis Mishra

Co-Advisor: Shanko Chura (PhD Candidate)

A Thesis Submitted to

The Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirements for the Degree of Master's in Electronics and Communication Engineering

Office of Graduate Studies

Adama Science and Technology University

July, 2021

Adama, Ethiopia

APPROVAL PAGE OF M.SC. THESIS

We, the advisors of the thesis entitled "Comparative Study on Linear Precoding Techniques for 5G Massive MIMO System" developed by Zekarias Kahinu Ephrem, hereby certify that the recommendation and suggestion made by the board of examiners are appropriately incorporated into final version of the thesis.

________________	________________	________________
Advisor	Signature	Date
________________	________________	________________
Co-Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Zekarias Kahinu Ephrem have read and evaluated his thesis entitled "Comparative Study on Linear Precoding Techniques for 5G Massive MIMO System" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted in partial fulfillment of the requirement of the Degree of Master science in Communication Engineering.

________________	________________	________________
Chairperson	Signature	Date
________________	________________	________________
Internal Examiner	Signature	Date
________________	________________	________________
External Examiner	Signature	Date

Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the office of postgraduate student (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC)

________________	____________	____________
Department Chair	Signature	Date
________________	____________	____________
School Dean	Signature	Date
________________	____________	____________
Office of Postgraduate, Dean	Signature	Date

DECLARATION

I hereby declare that this Master Thesis entitled “Comparative Study on Linear Precoding Techniques for 5G Massive MIMO System” is my original work. That is, it has not been submitted for award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for the thesis have been fully acknowledged through citation.

______________________	__________________	____________________
Name of the Student	Signature	Date

RECOMMENDATION

We, hereby certify that we have read the revised version of the thesis entitled "Comparative Study on Linear Precoding Techniques for 5G Massive MIMO System" prepared under our guidance by Zekarias Kahinu submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electronics and Communication Engineering. Therefore, we recommend the submission of the thesis to the department for further review and defense.

______________________	__________________	____________________
Advisor	Signature	Date
______________________	__________________	____________________
Co-Advisor	Signature	Date

ACKNOWLEDGMENT

Firstly, I would like to express my heartful thanks to Dr. Satyasis Mishra (Advisor) who has supported me throughout my thesis work and sacrifices his valuable times for encouraging me to work in my own way, and gave me the freedom to explore in deep for this study. It would not have been possible to achieve the objective of this study without his valuable helps. I would like to gratefully acknowledge Shanko Chura (PhD Candidate) for his continuous encouragement throughout the research work. He gave me valuable assistances whenever i have a problem with my thesis.

As well, I would like to thank all the member of School of Electrical and Computer Engineering especially to division of Communication Engineering coordinator for providing such an excellent education and research environment. I am thankful for all students in Division of Communication Engineering who gave me all knowledge. Finally, I am thankful for my family and friends for supporting me and standing beside me at every moment.

TABLE OF CONTENTS

APPROVAL PAGE OF M.SC. THESIS i

RECOMMENDATION ii

ACKNOWLEDGMENT iii

TABLE OF CONTENTS iv

LIST OF TABLES viii

LIST OF FIGURES ix

LIST OF ACRONYMS x

LIST OF ABBREVIATIONS xi

ABSTRACT xii

CHAPTER ONE 1

INTRODUCTION 1

1.1 Background 1

1.2 Statement of the Problem 2

1.3 Objectives of the Thesis 2

1.3.1 General Objective 2

1.3.2 Specific Objectives 2

1.4 Scope of the Study 3

1.5 Thesis Contributions 3

1.6 Organization of the Thesis 4

CHAPTER TWO 5

LITERATURE REVIEW 5

2.1 Related work 5

2.2 Multiuser MIMO Cellular Systems 7

2.3 Uplink Transmission 8

2.4 Downlink Transmission 8
2.5 Linear Processing 9
2.5.1 Linear Receivers (in the Uplink) 10
2.5.2 Linear Precoders 12
2.6 Channel State Information 14
2.6.1 Channel Estimation in TDD System 14
2.6.2 Channel Estimation Under FDD Systems 15
2.6.3 Perfect and Imperfect CSIT 16
2.7 Rayleigh Fading Channel 17
2.8 Achievable Rate 18
2.9 Some Details of M-MIMO 19
2.10 How Massive MIMO Works 21
2.10.1 Channel Estimation 22
2.10.2 Uplink Data Transmission 22
2.10.3 Downlink Data Transmission 22
2.11 Importance of Massive MIMO 22
2.12 Challenges in Massive MIMO 23
CHAPTER THREE 24
MATERIALS AND METHODS 24
3.1 System Design 24
3.2 System Model and Assumptions 25
3.3 Massive-MIMO 26
3.4 Massive MIMO Linear Precoding 26
3.4.1 MMSE Precoding 27
3.4.2 ZF Precoding 27

3.4.3 MRT Precoding....27

3.5 The Achievable Sum Rate....27

3.5.1 The Achievable Rate with MMSE Precoding....28

3.5.2 The Achievable Rate with ZF Precoding....29

3.5.3 The Achievable Rate with MRT precoding....30

3.6 Energy Efficiency....31

3.7 Implementation....33

3.7.1 Calculating Signal to Noise Ratio (SNR)....33

3.7.2 Calculating Achievable Rate....33

3.7.3 Calculating Spectral Efficiency....34

3.7.4 Calculating Energy Efficiency....34

CHAPTER FOUR....35

SIMULATION RESULTS AND DISCUSSION....35

4.1 Introduction....35

4.2 Simulation Parameters....36

4.3 Interpretation of the Numerical Result....36

4.3.1 Effect of Tranismit Power for Achivable Rate....36

4.3.2 Effect of SNR for Achivable Rate....37

4.3.3 Effect of Increasing Number of Antenna for Achievable Rate....38

4.3.4 Effect of Increasing Number of User for Achievable Rate....39

4.3.5 Effect of Transmit Power for Energy Efficiency....40

4.3.6 Effect of Increasing Number of Antennas for Energy Efficiency....40

4.3.7 Effect of Number of Active User on Fraction of Transmit Power....42

4.3.8 Effect of Number of Antennas on Fraction of Transmit Power....43

Conclusions 45

Future Work 46

REFERENCES..47

LIST OF TABLES

Table 3-1: Classical MU-MIMO versus M-MIMO [38] 26

Table 4-1: Simulation Parameter 36

LIST OF FIGURES

Figure 2-1: Block diagram of linear detection at the BS [30]. 10

Figure 2-2: Block diagram of the linear precoders [30]... 14

Figure 2-3: Downlink transmission phase 18

Figure 2-4: The regions of possible (M, K) in TDD and FDD system [30]. 20

Figure 2-5: Transmission protocol of M-MIMO time division duplex system [30]................ 21

Figure 3-1: Methodology 24

Figure 3-2: MU-MIMO Systems [30]... 25

Figure 4-1: Achievable sum rate Vs DL Transmit power... 37

Figure 4-2: Achievable rate Vs SINR 38

Figure 4-3: Achievable sum rate Vs Number of Antenna Array 39

Figure 4-4: Achievable sum rate Vs Number of user 40

Figure 4-5: Energy Efficiency Vs Transmit Power 41

Figure 4-6: Energy Efficiency Vs Number of Antenna array 42

Figure 4-7: Fraction of transmit power Vs Number of User (K) 43

Figure 4-8: Fraction of transmit power Vs Number of antenna at M>20 and K<20 44

LIST OF ACRONYMS

$\tau\rho$	Pilot coherence interval
h	Scalar h
H	Vector h
R	Set of real numbers
C	Set of complex numbers
$(.)*$	Complex conjugate
(.)T	Transpose of matrix
ρ_u	Average signal to noise ratio
tr (.)	Trace of square matrix
IN	Identity matrix with size N
E[.]	Mean of the random variable
‖.‖	Norm of vector
|.|	Absolute value
N (0, σ2)	Gaussian random variable with zero mean and varianceσ2

LIST OF ABBREVIATIONS

CSI	Channel State Information
DL	Downlink
EE	Energy Efficiency
i.i.d	Independent and identically distributed
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
M-MIMO	Massive Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MRT	Maximum Ratio Transmission
MSE	Mean Square Error
MU-MIMO	Multiuser Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
PDF	Probability Density Function
RZF	Regularized Zero Forcing
SDMA	Space Division Multiple Access
SE	Spectral Efficiency
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
UL	Uplink
ZF	Zero forcing

ABSTRACT

Massive multiple input multiple outputs (M-MIMO) are the most promising technology for 5th generation (5G) wireless communication system. Wireless throughput and communication reliability demand as well as the user density is always increase rapidly. Due to that wireless technology improvement is ongoing as the numbers of users and applications increase. M-MIMO system deploy a large number of antennas at the base station (BS) to transmit and receive signals using a Time Division Duplex (TDD) to or from users at the same time and the frequency. The performance analysis of massive MIMO DL system using linear precoding has been investigated in various methods. However, there is no more study on DL multi-user massive MIMO system. In this thesis, we have investigated the performance of a massive MIMO DL TDD system utilizing different linear precoding techniques (e.g. MMSE, ZF and MRT) under Rayleigh fading channel with perfect channel state information at the transmitter (CSIT) to alleviate the impact of multi-user interference. The simulation result indicates that as compared to ZF and MRT, MMSE linear precoding is optimal in all cases.

Key words*: Linear precoding, M-MIMO, Achievable rate, MRT, MMSE, ZF.*

CHAPTER ONE

INTRODUCTION

1.1 Background

One of the most essential techniques for fifth-generation (5G) wireless communication system is massive multiple input multiple outputs (MIMO). It pays an attention a great deal of research in recent years [1, 2]. The key ideas of M-MIMO are deploying large-scale number of antenna and employ a simple precoding scheme or detection technique at the base station (BS). This enables to significantly reduce the impact of noise and user interference. Hence, the performance metrics such as spectral efficiency (SE), energy efficiency (EE), transmission reliability, and quality of service (QoS) can be improved [3, 4]. M-MIMO system design faces a new challenge regarding to increasing number of BS antennas (may be up to dozens or even hundreds). Therefore, various possible techniques for M-MIMO system must be well defined before its roll-out [5, 6]. Performance limitation of wireless network at the physical layer is grasped. Since the spectrum available, electromagnetic propagation law and principles of data theory have an impact on the amount of data which will be routed between two locations.

There are three approaches to improve efficiency of a wireless network system [7]. These are: deploying more access points densely, using more spectrums and increasing the spectral efficiency, that is, the number of bits which will be sent per second per each band width unit. Maximizing the spectral efficiency for the definite band couldn't get to vanish while future wireless system and standards are likely to use an ever-increasing access point density and adapt new spectral band.

The use of multiple antennas, also referred to as MIMO technology, is ambitious for substantial improvement of spectral efficiency. MIMO technology is classified into three types: “Point to Point MIMO”, “Multiuser MIMO **(**MU-MIMO**)**”and “Massive MIMO (M-MIMO)”. This work is devoted on M-MIMO, which may be the key opening for the advancement of this research area.

M-MIMO is a 5G wireless communication system, which needs a large number of antenna array, on a range of few hundreds or thousands[8]. This system with single BS accesses a number of terminals using identical time-frequency resources. By breaking up the K-antenna terminal into multiple autonomous terminal M-MIMO scenarios is obtained efficiently from point-to-point MIMO setup.

1.2 Statement of the Problem

The fundamental performance metrics for wireless communication systems are spectral efficiency, link reliability, coverage and energy efficiency. The wireless channel is affected by dispersion time effects, Doppler and multipath fading. As a result, the spectral efficiency of the wireless system is degraded. So as to preserve the data rates offered, a simple method is to extend the allocated bandwidth. This technique is difficult due to scarce radio spectrum resource. So as to preserve higher data rates for the given bandwidth inter-user interference can be reduced while using precoding by focusing the energy on the desired user. Massive MIMO technology is now attracting many areas of research from both academia and industry. This reality also inspires me to devote on this area. This thesis work realized linear precoding comparative analysis under large number of antenna and user for downlink system.

1.3 Objectives of the Thesis

1.3.1 General Objective

The main objective of this thesis is comparative study of linear precoding algorithms for massive MIMO wireless systems.

1.3.2 Specific Objectives

The specific objectives of this work are highlighted as follows;

- Analyzing linear precoding techniques for massive MIMO system.
- Enumerate DL transmission power analytical expression for MMSE, MRT and ZF linear precoding.
- Compare and contrast linear precoders for massive MIMO under:
    - Wireless channel impairments and
    - Various number of transmitter antennas.

- Evaluate the effects of SE for DL M-MIMO system.
- Compare spectral efficiencies, energy efficiency and achievable sum rate to select efficient precoders among the three techniques.

1.4 Scope of the Study

This work emphasized on performance analysis of linear precoders techniques such as minimum mean square error, maximum ratio transmission and zero forcing for 5G M-MIMO system. It examines the typical 5G networks over Rayleigh fading channel and with Channel State Information at the Transmitter. Finally, the achievable rate, spectral efficiency, energy efficiency and performance of MMSE, ZF and MRT precoding under various SNR with large number of base station antenna, M and number of user, K will be analyzed.

1.5 Thesis Contributions

In all the literatures seen so far in Section 2.1 discussed below, linear precoding has been explored in different era. However, some of the differences from the previous work and this work are described as follow.

- M-MIMO system with perspective to linear precoding system is presented. The achievable sum rate of a user in relation to number of transmitter antennas, active user, and DL transmission power over Rayleigh fading channels is discussed.
- This work considered number of BS antenna is typically much larger than number of terminals for M-MIMO. Moreover, MMSE and ZF themselves tend to be optimal at high SINR conditions.
- Energy efficiency in relation to transmitter antenna, M and transmit power is also included as a contribution for this work.
- Enumerate DL transmission power analytical expression for MMSE, MRT and ZF linear precoding.

Finally, at large value of M and K DL transmit power in terms of antenna and user for MMSE linear precoding is derived and then compared with MRT and ZF linear precoding.

1.6 Organization of the Thesis

The rest of the thesis is organized as follow:

- Chapter 2: provides details on related work, basics of M-MIMO system, and a short formal explanation of perfect and imperfect CSIT and the achievable rate equation of a user for M-MIMO system.
- Chapter 3: discusses the proposed Methodology to accomplish the objective of the study.
- Chapter 4: presents various simulation result and discussions from M-MIMO perspective for different linear precoding techniques. Finally, concluding this work and summarizing the key ideas.

CHAPTER TWO

LITERATURE REVIEW

This chapter present that review (survey) of varied literature which has been close a proximity to this study. Also, the fundamental aspects of massive MIMO including basic network architecture and its advantage for wireless communication system are discussed.

2.1 Related work

The study and exploration of wireless access technology; MIMO has been motivated due to limited global bandwidth. Massive MU-MIMO technology is gaining traction in academics and industry and open an important research area that inauguration future research in massive MIMO system and beyond network. There are several researches that assess the performance of the precoding technique for enormous MIMO system. A number of studies which are related to this work are briefly highlighted below.

The first advance in “Massive MU-MIMO downlink TDD systems” with “linear precoding and downlink Pilots” was stated [9]. They formulate an efficient channel estimation scheme to obtain CSI at each user, so called beam forming training scheme. Real “M-MIMO channel model” during which BS is deployed a “cylindrical antenna array configuration” has been measured[10]. These measurements presented that, when the BS is deployed with finite number of antenna elements, channel vector between users weren't really pairwise orthogonal. The study in [8, 11] employed a consistent cylindrical array configuration equipped with many antenna elements. It results that the MIMO channel model illustrates that better correlation and without wide sense stationary properties compared with conventional MIMO systems. An identical research was channeled in [12].

Also, the probability of perfect CSI might be very difficult, when the amount of antenna becomes very large. This is often come to be another issue of M-MIMO systems [13]. By using “user preference and spatial locality”, the authors investigated the optimal cache policy to attenuate the typical file download time in “M-MIMO” system [14, 15]. In [16] the coordinated channel estimation for M-MIMO system is proposed by developing the second order statistical information. Channel estimation is contaminated by non-orthogonal pilot sequences from user’s located adjacent cells on the target cell, in multiple cell massive system. A time-shifted system was proposed in [17] which enable to recap the consequences of pilot contamination. And this suppresses effectively the pilot contamination. A pilot sequence coordination scheme proposed under the study of [18]. The pilot combinations can be eliminated by sharing various pilot sequences among each cell. In massive MU-MIMO systems, linear precoding scheme is of great importance. Since it's trendy for practical routine and allows significant increasing of their performance. The performance of M-MIMO system is realized the achievable spectral efficiency (SE) and energy efficiency (EE), respectively, where the BS adopts only MRT precoding and know in relation to an accurate CSI was considered [19].

Firstly, an accurate theoretical result for the achievable rate was derived. The mathematical expression of energy efficiency additionally obtained by allowing a sensible energy consumption model [20], the result of this work presented that massive antenna equipped within the BS can do boost system performance. Achievable rates for uplink under perfect or partial CSI were derived in [21]. Since the number of BS antenna increases in massive MIMO system, scaling laws were applied in terms of the facility savings. Moreover, for DL transmission, the achievable sum-rate of DL “massive MIMO” systems with respect to maximum ratio transmission and zero forcing precoders were investigated in [22]. Conversely, they didn't give precise expression. Moreover, the cumulative achievable rate was considered for M-MIMO system, where MRT and ZF precoding schemes are instigated [23].

BS precoders having beam forming training scheme broadcasts pilot sequences for all or any users. Then, based on the received pilots, each user estimates the nominal channel gain using minimum mean square error (MMSE) channel estimation. Then, they develop capacity boundary for MRT and ZF precoding techniques to gauge SE taking under consideration SE loss related with the transmission of the DL pilots. They also implied the potential benefits of massive MIMO system. BER performance of M-MIMO system with increasing number of BS antenna, users and SINR was examined [24]. They made a comparison of SE and BER performance of ZF, MMSE precoding under perfect CSIT and imperfect CSIT condition. It had been presented that performance of an M-MIMO system exploiting diverse precoding techniques (MMSE, ZF, and MRT) under Rayleigh fading channel for both complete and incomplete channel state information at the transmitter (CSIT) is inspected. The performance of M-MIMO DL including linear precoding is assessed [25]. The achievable sum rate and DL transmit power for ZF and MRT precoding techniques are derived, analyzed and compared under an equivalent condition and assumption. This scenario considers performance parameters to research when the ratios of BS antennas to number of users are so large. Here ZF is better than MRT. But at small ratio MRT is better than ZF under similar situations. The performance of massive MU-MIMO DL system in Rician distribution across a frequency selective fast fading channel is explored in terms of ZF, MMSE and MRT precoding schemes [26]. The performance has been explored in reference to BER and throughput. The performance analysis of linear precoding for MIMO system-based Imperfections CSI was studied [27].

The result of this showed that linear precoding provides significantly improvements even with imperfect CSI. The performance of multiple inputs multiple output orthogonal space time blocks coding MIMO-OSTBC over frequency selective fading channel using BER and SE as performance metrics parameters are analyzed [28]. The result shows that, as SNR increases, the spectral efficiency increases on the reverse the BER decreases for various antenna configuration.

Maximum energy efficiency of linear precoding methods specifically MRT, MMSE and ZF for M-MIMO technique in Wireless Communication system was investigated [29]. However, numerical expression for energy efficiency is complex.

The majority of massive MIMO based research has been concentrated on theoretical studies, with the assumption that the massive MIMO system experience i.i.d. Rayleigh fading channel. From the previous work point of view, it is often established that there is no more study to determine a comprehensive analysis on DL M-MIMO system in relation to achievable sum rate for MMSE, ZF and MRT precoding schemes that has been still needs a novelty on massive MIMO system research area.

2.2 Multiuser MIMO Cellular Systems

M-MIMO is a cellular system where the number of BS antennas and the number users are so large [30]. The section later here provides background of MU-MIMO cellular systems in terms of communication scheme and signal detection for both UL and DL. For the sake of simplicity, we limit our discussion on single-cell system.

2.3 Uplink Transmission

Reverse link (or uplink) transmission is the scenario where the K number of users sends the signal to BS. Let S_k with $E\{|S_k|^2\} = 1$, be the signal transmitted from the K^{th} user. Since K users share the same time-frequency resource, the $M \times 1$ received signal vector at BS is the resulting sum of all signals transmitted from all user.

$$y_{ul} = \sqrt{\rho_u} \sum_{k=1}^{K} h_k S_k + n \tag{2.1}$$

$$= \sqrt{\rho_u} \mathrm{Hs} + \mathrm{n} \tag{2.2}$$

Where ρ_u is average signal to noise ratio, $n \in C^{M\times 1}$ is the additive noise vector and

$S \triangleq [S_1 \ldots\ldots S_K]^T$.

We assume that the elements of n are i.i.d, Gaussian random variables (RVs) with zero mean and unit variance and independent with H.

The BS will coherently detect the transmitted signals from K users if the received signal vector,y_{ul} has CSI information. The channel model presented in equation (2.3) is the multiple access channels with sum-capacity [30].

$$C_{ul,Sum} = \log 2 \det\left(I_K + \rho_u H^H H\right) \tag{2.3}$$

2.4 Downlink Transmission

Downlink (or forward link) is the transmission scenario where the BS direct signals for all K users.

Let $x \in C^{M\times 1}$, where $E\{\| x \|^2\} = 1$, be the signal vector transmitted from BS antenna array. Then, the received signal at the k^{th} user is shown by;

$$y_{dl,k} = \sqrt{p_d} h_k{}^T + \mathcal{Z}_k \tag{2.4}$$

Where: p_d is the average SNR and $\mathcal{Z}_k$is the additive noise term at the k^{th} user.

$\mathcal{Z}_k$ is Gaussian distributed with (0,1). Cooperatively, the received signal vector of the K users can be written as;

$$y_{dl} = \sqrt{p_d} H^T \chi + \mathcal{Z} \tag{2.5}$$

Where $y_{dl} \triangleq [y_{dl,1}, y_{dl,2}, y_{dl,3} \dots \dots . y_{dl,K}]^T$ and $\mathcal{Z} \triangleq [\mathcal{Z}_1, \mathcal{Z}_2, \mathcal{Z}_3 \dots \dots . \mathcal{Z}_K]^T$.

The channel model in the above equation is the broadcast channel whose $\text{sum} - \text{capacity}$ is known to be;

$$C_{sum} = \max_{\substack{\{q_k\} \\ q_k \geq 0, \sum_{k=1}^{K} q_k \leq 1}} \log 2 \ \det\left(I_M + p_d H^H D_q H^T\right) \tag{2.6}$$

Where: D_q is the diagonal matrix, whose k^{th} diagonal element is q_k.

2.5 Linear Processing

For obtaining the target quality of service (QOS), we need to incorporate technique of complex signal processing. As an example, in UL, the maximum-likelihood (ML) MU detection can be used. The BS searching all probable transmitted signal vectors using ML MU detection and chooses the best one based on the following criteria:

$$\hat{S} = \arg \min_{s \in S^K} \left\| y_{ul} - \sqrt{\rho_u} H s \right\|^2 \tag{2.7}$$

Where S, is the finite alphabet of S_k, $k = 1, 2, \dots, K$.

The challenge behind this equation is a least square (LS) problem with a finite-alphabet constraint. The BS has to search over $|S|^K$ vectors, where $|S|$denotes the cardinality of the set S. Hence, ML has some complexity which is proportional to exponential increasing number of users. The BS adopt linear processing schemes (linear receivers in the UL and linear precoders in DL) to moderate the signal processing complexity. This is not an optimal scheme. Conversely, linear processing is nearly-optimal, when the number of BS antennas is as large as discussed in [9, 27]. That is why linear processing scheme is considered in this thesis. The following sections go into the details of linear processing technique.

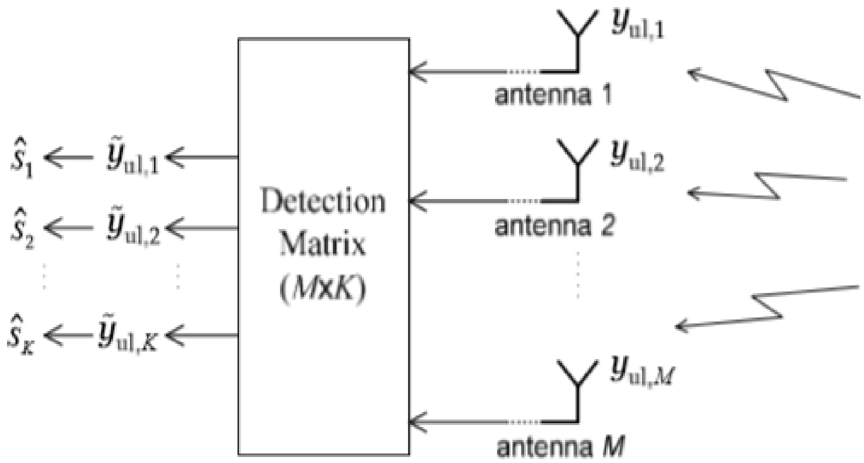

Figure 2-1: Block diagram of linear detection at the BS [30].

2.5.1 Linear Receivers (in the Uplink)

The received signal y_{ul} is decoded into K streams by multiplying it with a $\mathrm{M} \times \mathrm{K}$ linear detection matrix, **A** using linear detector scheme at the BS.

$$\tilde{y}_{ul} = A^H y_{ul} = \sqrt{\rho_u} A^H H s + A^H n \tag{2.8}$$

Each distinct stream is then interpreted independently. The complexity is on the order of $K|S|$, as seen in figure 2.2. From the above equation, the k^{th} stream of $\tilde{y}_{ul}$ which is used to decode S_k, is given by;

$$\tilde{y}_{ul,k} = \sqrt{\rho_u} a_k{}^H h_k s_k + \sqrt{\rho_u} \sum_{k' \neq k}^{K} a_k{}^H h_{k'} s_{k'} + a_k{}^H n \tag{2.9}$$

Note that:

- ✓ The first term signifies desired signal component.
- ✓ The second term is intra-cell(inter-user) interference.
- ✓ While the third term is termed as Noise.

Where: a_k denotes the k^{th} column of A.

The interference plus noise in other words does mean effective noise. Therefore, the received signal to interference plus noise ratio (SINR) of the k^{th} stream is given by:

$$\mathrm{SINR_k} = \frac{\rho_u |a_k{}^H h_k|^2}{\rho_u \sum_{k' \neq k}^{K} a_k{}^H h_{k'} + \|a_k\|^2} \tag{2.10}$$

Some of the highpoints on conventional linear MU receivers are discussed as follow;

a) Maximum Ratio Combining receiver: the received signal to noise ratio (SNR) of each stream can be maximized at the BS while using MRC. The effect of MU interference has no impact. From (2.9), the "k^{th} column of the MRC receiver matrix A" is:

$$\mathrm{a_{mrc,k}} = \underset{a_{k \in C^{M\times 1}}}{\operatorname{argmax}} \frac{\mathrm{Power(desired\ signal)}}{\mathrm{power(noise)}}$$

$$= \underset{a_{k \in C^{M\times 1}}}{\operatorname{argmax}} \frac{\rho_u |a_k{}^H h_k|^2}{\|a_k\|^2} \tag{2.11}$$

Then, the received SINR of the k^{th} stream of MRC is given by;

$$\mathrm{SINR_{mrc,k}} = \frac{\rho_u |h_k|^4}{\rho_u \sum_{k' \neq k}^{K} \left|h_k{}^H h_{k'}\right|^2 + \|h_k\|^2} \tag{2.12}$$

When $\rho_u \rightarrow \infty$

$$\mathrm{SINR_{mrc,k}} = \frac{\|h_k\|^4}{\sum_{k' \neq k}^{K} \left|h_k{}^H h_{k'}\right|^2} \tag{2.13}$$

Advantages:

- The signal processing is very humble.
- It can be implemented in a spread way.
- At low ρ_u, $\mathrm{SINR_{mrc,k}} \approx \rho_u \|h_k\|^2$.

Drawback:

- It performs poorly in interference-limited scenarios since MRC neglects the effect of multiuser interference.

b) Zero-Forcing Receiver: unlike MRC, zero-forcing (ZF) receivers preserve the inter-user interference into account on the other hand the impact of noise is neglected. Thus, the received SINR for k^{th} stream is defined as:

$$\mathrm{SINR}_{\mathrm{zf,k}} = \frac{\rho_u}{[(\mathrm{H^H H})^{-1}]_{kk}} \tag{2.14}$$

Advantage:

- Zero forcing (ZF) is consistent in interference-limited scenarios and signal processing is simple.
- Increasing transmit power results high SINR as desired.

Drawback:

- Since ZF ignores the effect of noise, it performs poorly under noise-limited scenarios.
- If the channel is not well conditioned, then the pseudo-inverse amplifies the noise term significantly.
- Due to pseudo inverse of the channel gain matrix computation implementation complexity is higher.

c) Minimum Mean-Square Error Receiver (MMSE): The linear minimum mean-square error receiver aims to mitigate the "mean-square error" between the estimate $\mathbf{A^H y_{ul}}$ and the transmitted signal **S**. More precisely,

$$\mathrm{A}_{\mathrm{mmse}} = \underset{\mathrm{A} \in \mathrm{C}^{M \times K}}{\operatorname{argmin}} \mathrm{E}\left\{\left\|\mathrm{A^H y_{ul}} - \mathrm{S}\right\|^2\right\}$$

$$= \underset{\mathrm{A} \in \mathrm{C}^{M \times K}}{\operatorname{argmin}} \sum_{k=1}^{K} \mathrm{E}\left\{\left|\mathrm{a}_k^H \mathrm{y_{ul}} - \mathrm{s}_k\right|^2\right\} \tag{2.15}$$

$$\mathrm{SINR}_{\mathrm{mmse,k}} = \rho_u h_k^H \left(\rho_u \sum_{i \neq k}^{K} h_i h_i^H + I_M\right)^{-1} h_k \tag{2.16}$$

2.5.2 Linear Precoders

By means of linear precoding techniques, the transmitted signal from M base station antenna, $\boldsymbol{x}$ is a linear combination of symbols designated for K users.

Let q_k, $\mathrm{E}\{|q_k|^2\} = 1$, be the symbol defined for the k^{th} user. Then, linearly precoded signal vector, $\boldsymbol{x}$**,** can be expressed as:

$$x = \sqrt{\alpha}\mathrm{Wq} \tag{2.17}$$

Where $q \triangleq [\ q_1, q_2, q_3 \ldots\ldots\ldots..q_k]^T$, $W \in C^{M\times K}$ is the precoding matrix and α is a normalization constant which can be chosen to satisfy the power constraint $E\{\|\boldsymbol{x}\|^2\} = 1$.

Thus,

$$\alpha = \frac{1}{E\{tr(WW^H)\}} \tag{2.18}$$

We obtain,

$$y_{dl,k} = \sqrt{\alpha\rho_d}\, h_k^T W q + \mathcal{Z}_k \tag{2.19}$$

$$y_{dl,k} = \sqrt{\alpha\rho_d}\, h_k^T w_k q_k + \sqrt{\alpha\rho_d} \sum_{k'\neq k}^{K} h_k^T w_{k'} q_{k'} + \mathcal{Z}_k \tag{2.20}$$

Therefore, from the BS to the k[th] user SINR of the transmission is expressed as;

$$SINR_k = \frac{\alpha\rho_d \left|h_k^T w_k\right|^2}{\alpha\rho_d \sum_{k'\neq k}^{K} \left|h_k^T w_{k'}\right|^2 + 1} \tag{2.21}$$

There are three conventional linear precoders techniques in massive MIMO systems which are shown in figure below. Those are maximum-ratio transmission (MRT) (also called conjugate beam forming), zero forcing (ZF) and minimum mean square error (MMSE) precoders. MRT, ZF and MRT receivers have the same functional meanings and properties with MRT, ZF, MMSE precoding. As a result, we only provide the precoding matrix formulas for three linear precoders as follows;

$$W = \begin{cases} H^H, & \text{for MRT} \\ H^H(H^T H^H)^{-1}, & \text{for ZF} \\ H^H\left(H^T H^H + \frac{K}{\rho_d} I_K\right)^{-1}, & \text{for MMSE} \end{cases} \tag{2.22}$$

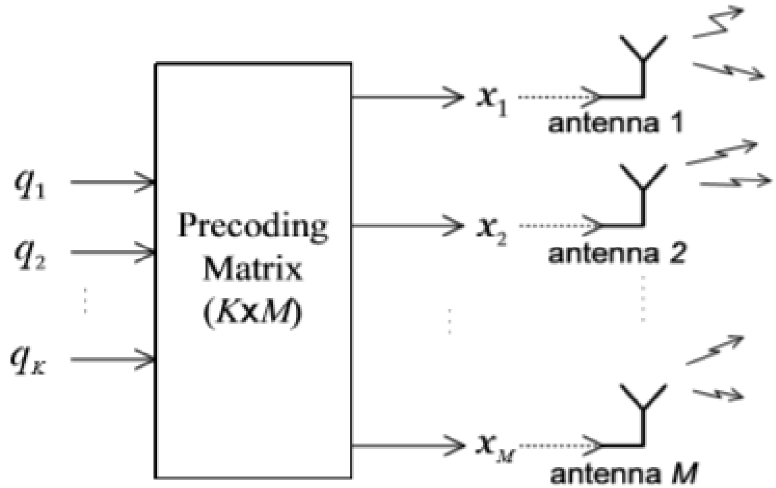

Figure 2-2: Block diagram of the linear precoders [30].

As we discussed in the section above, the achievable sum rate can be defined as:

$$R_k = \sum_{k=1}^{K} E\{\log2\ (1 + \mathrm{SINR_k})\} \qquad (2.23)$$

Where: $\mathrm{SINR_k}$is the k[th] user SINR.

2.6 Channel State Information

The channel state information at the transmitter (CSIT) is perfect under this assumption. Thus, it needs to perform any linear precoding techniques rather to traditional transmission techniques.

2.6.1 Channel Estimation in TDD System

It is also assumed that users and base station has perfect channel state information. Yet, in practice CSI has to be assessed. For TDD system, the reverse and forward link transmission uses the same radio spectrum in different time slots. The uplink and downlink channels guaranteed reciprocal properties. Thus, CSI can be obtained by the following scheme as of figure 2.4 [30]:

- For UL transmission case**:** the BS needs CSI to detect the signals transmitted from K users. Then, CSI is estimated at the BS. More precisely, K users send K orthogonal pilot sequences to their serving BS. At that time BS estimates the channels with respect to the received pilot signals. Such kind of process requires at least K channel.

- For downlink case: the BS needs CSI to process the transmitted signals, while each user needs an effective channel gain to detect the desired signals accurately. Having UL and DL channel reciprocity, an estimated channel at the BS for uplink is used to precode the transmitted symbol. To obtain an efficient knowledge of the effective channel gain, the BS should perform pilot beam forming, and then each user estimates the effective channel gains based on the received pilot signals. This requires a minimum of K channel uses.

As a result, the whole training process (UL+DL) needs a minimum of 2K channel uses. We assume that the channel stays constantly over T symbols. A brief description of channel estimation in TDD systems is clarified in [10].

2.6.2 Channel Estimation Under FDD Systems

Uplink and downlink transmission system utilize different frequency band for FDD system. Hence, UL and DL channels are not reciprocal, knowledge of channel at the BS and user terminal can be obtained by using the following training scheme:

- For downlink transmission**:** The BS with perfect CSI precode the symbol before sending to the K users. M number of BS antennas transmits M orthogonal pilot sequences for K user's terminal. Each user estimates the channel based on the received pilots. Then, it feeds back its channel estimates (M channel estimates) to the BS through the reverse radio link. This process requires at least M channel uses for DL and UL.
- For the case of uplink transmission: BS needs CSI to decode the signals transmitted from the K users. The simplest approach is that K users transmit K orthogonal pilot sequences to their respective BS. Then, based on the received pilot signals BS will estimate the channels. For the uplink this process requires at least K channel uses.

Advantages of M-MIMO system can be summarized as follow:

- Increased data rate: Because of a base station is equipped with large number of antennas, it can send the independent data stream for many users simultaneously (multiplexing gain).
- Link reliability: Having those antennas, multi-communication paths that radio signal can propagate over /diversity gain/.
- "Improving Energy efficiency": Due to BS is able to focus its transmission power into the "spatial direction" where each user is located /array gain/.

These three fundamental features solidify M-MIMO system scalable with respect to the M, number of BS antenna. Also,

- Only the BS acquires channel state information (CSI).
- K is usually much smaller than M.

Throughout all comparative analyses, we will assume that the small-scale fading is Rayleigh and independent between the antennas and the terminals, so that h_k^m is independent and identically distributedCN (0, 1) RV.

2.6.3 Perfect and Imperfect CSIT

Perfect CSIT does mean that transmitter knows all the components of H instantaneously and without errors ($\beta_k = \Upsilon_k$). In this scenario, the performance of the system can be increased very much while using CSIT.

In practice, it is impossible to achieve perfect CSIT because the transmission should be instantaneous, the precision of the electronics should be in finite. To be more accurate it can be considered that the CSI is incomplete. It does mean that only a part of the channel is indefinite. It can be caused for some user not knowing its channel. Then, a whole row of H is lost. Due to resource constraints are there in the system that doesn't let know a specific amount of information of the channel. It can also be instigated because an error on the CSI or a quantification error. An example of the imperfect CSIT could be like this [3].

$$H = \begin{bmatrix} h_1^1 & h_2^1 & h_3^1 & h_4^1 \\ \theta & \theta & h_3^2 & \theta \\ h_1^3 & h_2^3 & h_3^3 & h_4^3 \\ \theta & \theta & \theta & h_4^4 \end{bmatrix} \quad (2.24)$$

From (2.24), we can see that users 1 and 3 transmit all the CSI however users 2 and 4 just transmit the information only for the path from antenna 3 and 4 respectively.

2.7 Rayleigh Fading Channel

In the receiver side, the introduction of multiple signals of different phases induces multipath fading in wireless communication systems. The phase difference is produced in this received signal as a result of signals having traveled different distances on different paths of propagation through wireless communication. When the phases of the coming paths shift rapidly, the phase and amplitude of the obtained signal undergo rapid variations that are often modeled as a random variable with a particular distribution. Since it is quite difficult to find exact properties of channels Rayleigh fading channel, that cover more than one direction at the receiver is used for examining system performance. This model states that the summation of many statistically independent reflected and scattered paths with random amplitudes is $\mathrm{i.i.d}$ complex Gaussian RV. The element of the "channel matrix" can be written in a complex form as [31].

$$\mathrm{h_k^m} = \mathrm{c} + \mathrm{jd} \quad (2.25)$$

The joint pdf of (2.25) can be formulated as,

$$\mathrm{fc, d(c, d)} = \frac{1}{2\pi\delta^2} \mathrm{e}^{\frac{-(c^2+d^2)}{2\delta^2}} \quad (2.26)$$

Expressing h_k^m in polar form we obtain,

$$\mathrm{h_k^m} = \mathrm{re^{j\theta}} \quad (2.27)$$

Where $r = c^2 + d^2$, $\theta = \tan^{-1}\left(\frac{d}{c}\right)$.

From polar form, we can write the joint pdf of R and θ by;

$$fR,\theta(r,\theta) = \frac{r}{2\pi\delta^2} e^{\frac{-r^2}{2\delta^2}} \quad (2.28)$$

By integration with respect to **θ**, the PDF of R becomes;

$$PR(r) = \frac{r}{\delta^2} e^{\frac{-r^2}{2\delta^2}} \quad (2.29)$$

As a result, R is also Rayleigh distributed. Rayleigh fading channel can be designated in terms of amplitude and phase because of the above properties.

The "channel coefficient" of "complex Rayleigh fading" is generated by two Gaussian RV where each variable has $(\mathbf{0}, \boldsymbol{\sigma})$. Then, the "channel coefficient of Rayleigh fading channel" is given by;

$$h_{rayleigh} = c + jd \quad (2.30)$$

Where: $C \in N\ (0, \sigma)$, $d \in N\ (0, \sigma)$

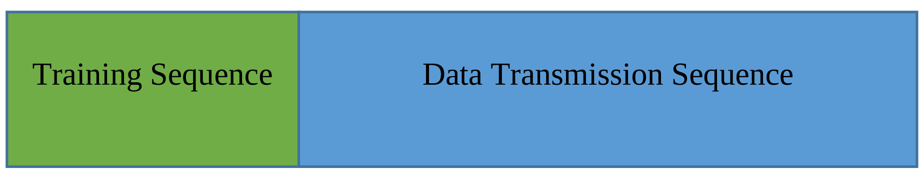

Figure 2-3: Downlink transmission phase

2.8 Achievable Rate

In M-MIMO system, after appropriate signal processing, the effective channel associated with each user terminal is a scalar point-to-point channel. The realization of the channel is characterized by the conditional probability distribution of **y** given **x**. The system performance can be defined by several approaches. Among them, achievable rate is a fundamental tool to enumerate the system performance. Achievable sum rate is an extension of classical Shannon theorem, which states "the maximum rate under which the transmitter can transmit more efficiently over the channel".

To communicate a message over a point-to-point scalar channel, the transmitter maps the message into a sequence distinct of symbols $\{\chi_n\}$, and then receiver recovers the message from the sequence of samples $\{y_n\}$. The rate, represented by R, is the effective number of bits conveyed per transmitted symbol, and is measured in bits per channel use (bpcu). Hence, transmitting a waveform with bandwidth BHz and time-duration T seconds does mean that transmitting BT symbols $\{\boldsymbol{x_n}\}$. Therefore, the rate R is measured in bits per second per Hertz (b/s/Hz). It is termed as spectral efficiency (SE).

Consideration of total SE in relation to the Shannon theory suggests that optimality of a rough parity between number of transmitter antenna (M) and number of receiver antenna (K).

In conventional MU-MIMO: further growth of M only yields logarithmically increasing throughput while experiencing linearly increasing amounts of time spent over training [11]**.** M-MIMO represents a clean break from conventional MU-MIMO. Measurement are taken such that one operates further from the Shannon limit, but inconsistently achieves much better performance than any conventional MU-MIMO system.

2.9 Some Details of M-MIMO

Time division duplex (TDD) operation: As it is discussed in Section 2.4 with frequency division duplex(FDD), the channel estimation overhead depends on the amount of BS antennas, M. Contrarily, for time division duplex the channel estimation is independent of the base station antenna, M. Since base station antenna, M is large in Massive MIMO system,TDD operation is preferable. For instance, assume coherence interval is T=200symbols. The amount of BS antennas, M and users K, are governed by $\mathrm{M} + \mathrm{K} < 200$ for FDD systems, whereas the constraint on M and K is formulated as $2\mathrm{K} < 200$ in TDD systems. The figure as shown below clearly illustrates the feasible regions of function of(M, K) in FDD and TDD systems. So that, it validates that the “FDD region” is much smaller than the “TDD region”. Also, with TDD, adding more antennas does not affect the resources needed for the channel estimation as shown in figure 2-4.

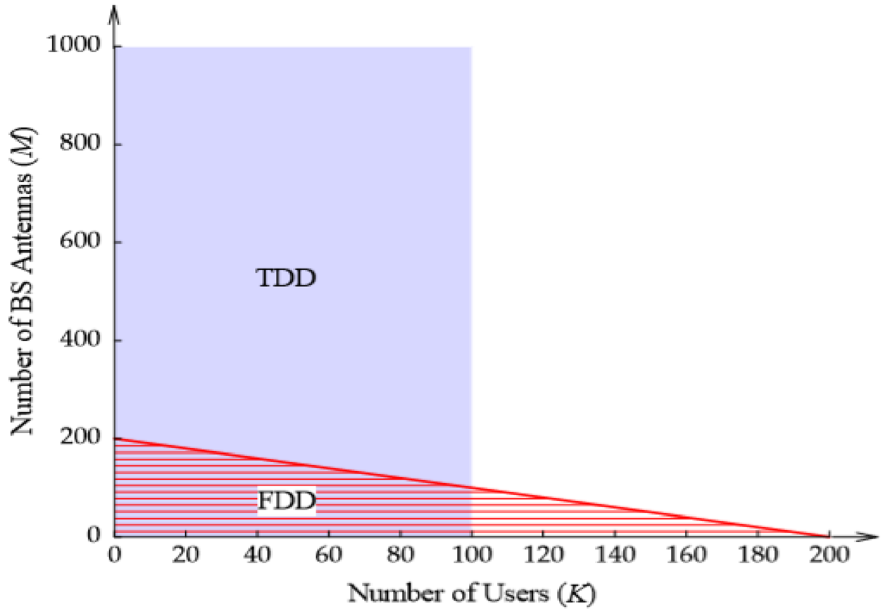

Figure 2-4: The regions of possible (M, K) in TDD and FDD system [30].

Linear precoding (processing): Since M and K are so large, simple signal processing is desirable. In Massive MIMO, linear processing (linear combing schemes within the UL and linear precoding schemes within the DL) are nearly optimal.

Favorable propagation: It means that the "channel matrix between the BS antenna array and the users" is well-conditioned. The favorable propagation property holds true in "M-MIMO" under certain conditions.

A M-MIMO BS antenna array does not need to be physically large. For instance, consider a cylindrical array with 128 antennas, having four circles of 16 dual-polarized antenna elements. The space between adjacent antennas is about 6 cm, which is half wavelength at 2.6 GHz. Hence, this array occupies only a physical size of 28cm×29cm [32].

Massive MIMO is scalable: In M-MIMO, the BS acquires the channel via uplink training, for TDD operation. For channel estimation the time required is independent of the number of BS antennas. Consequently, without increasing the channel estimation overhead the amount of BS antennas is often made as large as desired. Furthermore, the signal processing, doesn't depend upon other users' activity. Other user's activities can't suffer from Adding or dropping some users from service.

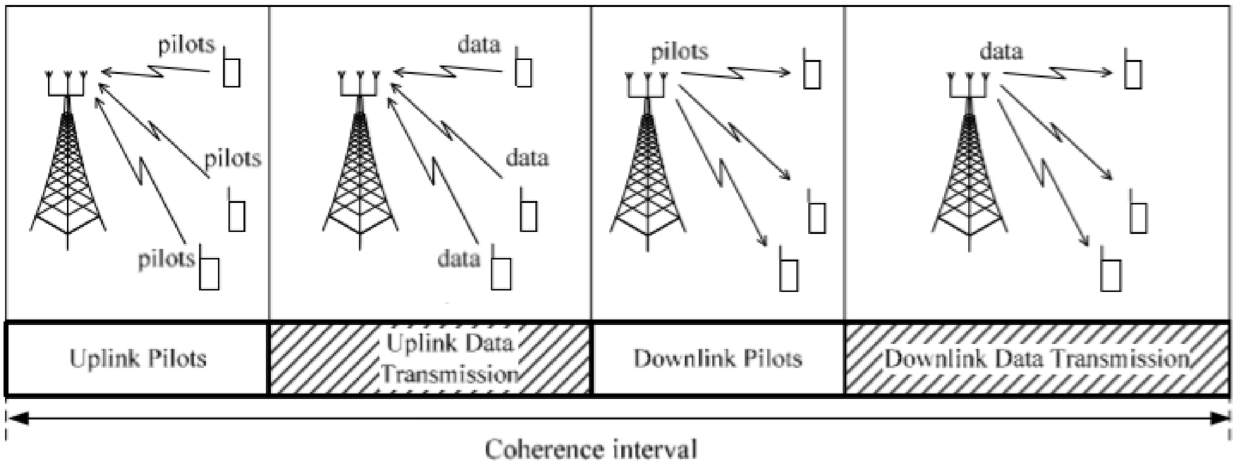

Figure 2-5: Transmission protocol of M-MIMO time division duplex system [30].

2.10 How Massive MIMO Works

In Massive MIMO there are three basic operations:

- ✓ Channel estimation (including the uplink and downlink training),
- ✓ Uplink data transmission and
- ✓ Downlink data transmission through a coherence interval.

Transmitter precoding (beam forming) is a valuable technique for signal transmission from an array of M antennas for one or multiple users. In wireless communication system, the crucial issue is:

- Increasing the signal power at the intended user and
- Reducing interference to non-intended users.

Transmitter precoding is focused on the signal energy at certain places and it results less energy arrives on the other places. This aids for so-called space-division multiple accesses (SDMA), where K is spatially separated users served simultaneously. One beam forming vector per user is assigned and matched to its channel. Basically, there are two precoding techniques: linear types, e.g., ZF, MMSE, MF and non-linear precoding, e.g., THP, VP, etc.

2.10.1 Channel Estimation

BS needs CSI to detect the signals transmitted from user in uplink, and to precode the signals within the downlink. Through the uplink training the specified CSI is obtained. An orthogonal pilot sequence is assigned for every user, and sends it to BS. The BS acknowledges pilot's sequences transmitted from all users, and then estimates the channels based on the received pilot signals. Moreover, for coherent detection transmitted signals from BS each user may have partial CSI knowledge. This information is often attained through "DL training" or some "blind channel estimation" algorithm. The BS uses linear precoding techniques for beam forming signals to the users, the user needs only the effective channel gain (which may be a scalar constant) to detect its desired signals. As a result, in the downlink to CSI acquisition, the BS will spend more time for pilot beam forming than the users.

2.10.2 Uplink Data Transmission

A fragment of the coherence interval is used for uplink data transmission. For uplink, all K, active users transmit their data to their BS within the same time-frequency resource. To detect signals transmitted from all users, BS uses channel estimation with linear combining techniques.

2.10.3 Downlink Data Transmission

In DL, the BS broadcast signal for all K users within the same $\mathrm{time} - \mathrm{frequency}$ resource. More specifically, the BS uses its channel estimates together with the symbols intended for the K users to make M precoded signals which are then fed to M antennas.

2.11 Importance of Massive MIMO

Wireless throughput demand and communication reliability as well as the user density are always escalating. Future wireless communication system requires new technologies during which many users are often simultaneously served with a very high throughput. M-MIMO guarantees this demand. Consider the UL transmission, (The same arguments are often used for the DL transmission). From (2.3), under favorable propagation condition (the channel vectors between user and BS are pair wisely orthogonal), the sum-capacity of UL transmission is:

$$\mathrm{C_{sum}} = \log 2\ \det\left(\mathrm{I_K} + \rho_u \mathrm{M I_K}\right) = \mathrm{K} \log 2\left(1 + \mathrm{M}\rho_u\right) \tag{2.31}$$

In (2.31), K is “multiplexing gain” and M is also an “array gain”. Huge spectral efficiency and energy efficiency can be attained when M and K are large. More users can be served in the same frequency band with no increase in transmission power per terminal and by rising K and M. The desired throughput per user also increases at the same time. Also, by maintaining the original quality of service, doubling the “number of BS antennas” consequences decreasing the transmit power by 3dB.

At the BS multiplexing and array gain are assured under favorable propagation condition and optimal processing. In “Massive MIMO”, when the amount of BS antennas is large, thanks to “the law of huge numbers”, the channels become favorable. As a result, linear processing is almost optimal. Also, the throughput will always increase by increasing the amount of BS antennas and number of users.

2.12 Challenges in Massive MIMO

Despite of numerous advantages of M-MIMO, many issues has been still tackled. The most identified challenging issue of Massive MIMO is mentioned as follow:

- Pilot Contamination.
- Unfavorable Propagation.
- New Standard and Design specification are required.

CHAPTER THREE

MATERIALS AND METHODS

The performance metrics parameter namely the achievable rate, as well as the energy efficiency, and downlink transmission power mathematical approach will be discussed in this chapter.

In this thesis, various related sources of data such as several books in LTE, 3GPP standardization documents, previous researcher's studies, Institute of Electrical and Electronics Engineers (IEEE) articles, development in 5G cellular technology in general and basics of massive MIMO in particular are inspected. Based on the inputs retrieved from review of related literatures and the statement of the problem in mind, the methodology of this study is proposed as follows;

3.1 System Design

The system in which the number of antennas, "M" deployed at base station serves "K**"** number of users for single cell downlink MIMO system are considered.

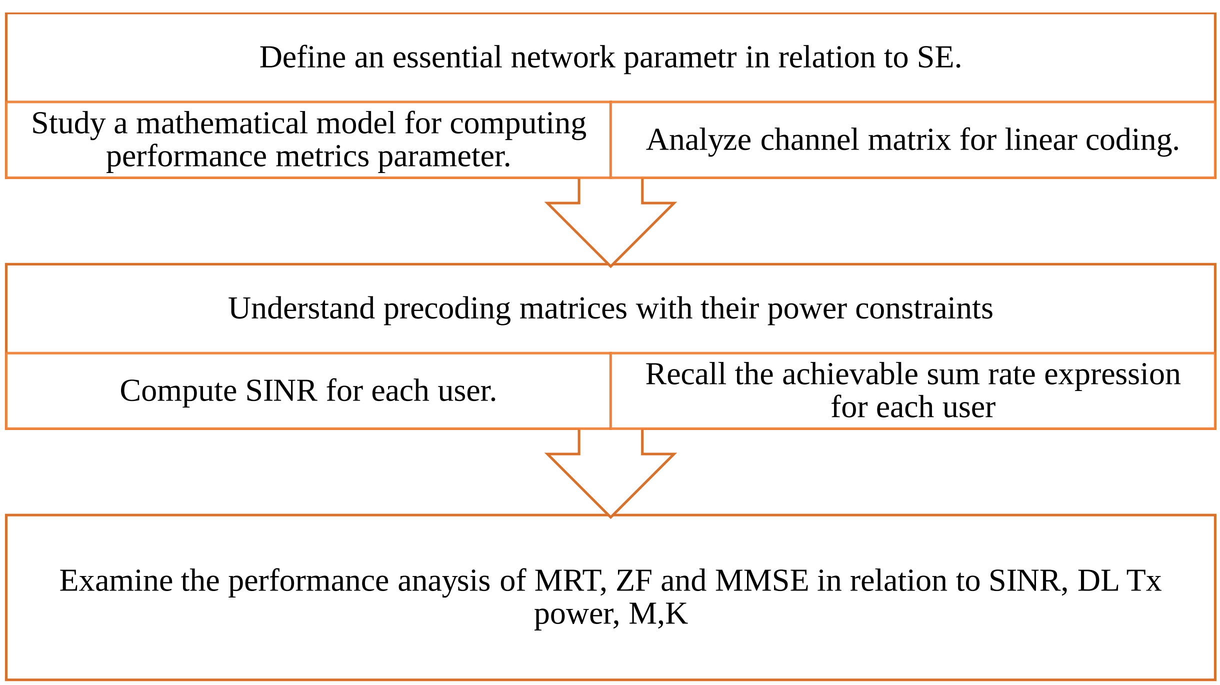

Figure 3-1: Methodology

Hence, the total capacity of the system and finally taking an average of all realization to find the final system capacity.

- Identify all fundamental input parameters for simulation.
- Outline simulation work flow.
- Perform target network capacity prediction simulations.
- Simulate the proposed network system to estimate the capacity.
- Perform SE evaluation analysis whether the target network requirement achieved or not.

3.2 System Model and Assumptions

Multiple antennas can be equipped for each user. However, the system with single-antenna users for simplicity of the analysis is realized. Furthermore, under this situation a perfect CSI is available for BS and users. During the training phase channels are acquired at the users and BS. The training scheme also depends on system protocols (FDD or TDD) and later, this as we discussed in detail in section 2.6.1.

Let $\mathrm{H} \in \mathrm{C}^{\mathrm{M}\times\mathrm{K}}$ is the channel matrix between K user and M BS antenna array, where h_k, denotes kth column of H, represents the $\mathrm{M} \times 1$ channel vector between kth user and M BS. "Large-scale fading" and "small-scale fading" have been used for the propagation channel model. But in this chapter, "large-scale fading" is out of the scope of this study. We considered that channel matrix elements are identically distributed with zero mean and unit variance (0, 1).

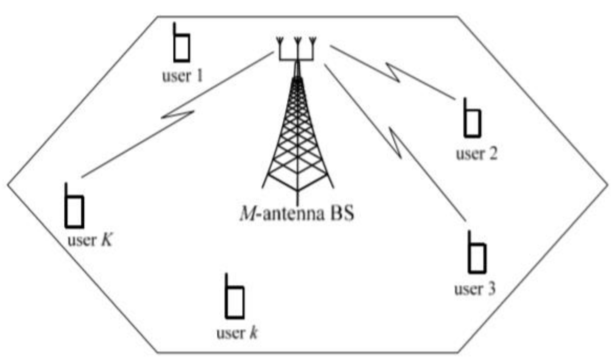

Figure 3-2: MU-MIMO Systems [30].

Here, in the same time frequency resource, K user with single antenna is served by M BS antenna.

3.3 Massive-MIMO

Massive MIMO is a type of MU-MIMO systems in which the number of BS antennas and users are both excessively large. In Massive MIMO, BS antennas in the range of hundreds or thousands simultaneously serve tens or hundreds of users at the same frequency resource. The fundamental features of massive MIMO over classical MIMO are summarized in table 3.1.

Table 3-1: Classical MU-MIMO versus M-MIMO [38]

Comparative parameters	Classical MIMO	Massive MIMO
Antennas and users K	$M \approx K$	$M \gg K$
Signal processing	Nonlinear is favored	Linear is near optimal
Duplexing mode	TDD and FDD	TDD with reciprocity
Instantaneous channel	Known at the BS and user	Only needed at the BS
Channel quality	Limited by frequency selective and fast fading	Almost no channel quality variations (hardening)
Variations in users load	Scheduling required if $K>M$	Scheduling seldom used
Resource allocation	Rapid due to fading	Only on a slow time scale
Cell edge performance	Only noble if BS cooperate	Improved by array gain, M
BS cooperation	Highly rapid if useful	Only long-term coordination

3.4 Massive MIMO Linear Precoding

Linear precoding may be a transmitter-based precoding scheme for compensating multi-path interfering channel effect. By means of linear precoding techniques within the forward link, the

BS transmits linearly precoded information data with signal vector X, which is based for the K users[33].

3.4.1 MMSE Precoding

MMSE precoding is the optimal linear precoding for massive MIMO DL system. This system is triggered by the mean square error (MSE) method. Due to average power at each transmitted antenna is constrained. Lagrangian optimization method is employed for obtaining these precoders [34].

3.4.2 ZF Precoding

The ZF precoding may be a well-known MIMO precoding method. Thanks to its low complexity nature, it is often implemented without having any prior knowledge of noise statistics. By projecting each stream onto the orthogonal complement of the inter-user interference for ZF MU interference can be totally nulled out. ZF approaches to MMSE when $\rho_d \to \infty$.

3.4.3 MRT Precoding

To maximize the received SNR at the user mobile terminal MRT is the one among the oldest precoding techniques applied. It is consistent for the MIMO system where, the BS radiates low signal power to the users. MRT approaches to MMSE when $\rho_d \to 0$.

3.5 The Achievable Sum Rate

There are several metohds to describe the system performance. Achievable sum rate is one of them to quantify the system performance. It is followed by "Shannon theorem". This theory tells us the maximum rate, which the transmittercantransmitoverthechannel. This sectionadresses a comprehensive discussion on the achievable rate. It is assumed that the channel isergodic and the system posses Gaussian random processes. From (2.6), let y_k andx_k be the k^{th}elements of the K ×1 vectors **y** and **x** respectively. Then, y_k is written as

$$y_k = {h_k}^T a_k x_k + \sum_{i=1, i\neq k}^{K} {h_k}^T a_i x_i + n_k \tag{3.1}$$

The desired signal energy is expressed as;

$$\mathrm{E}\left[\left|{h_k}^T a_k x_k\right|^2\right] = \left|{h_k}^T a_k\right|^2 \mathrm{E}[|x_k|^2] = \left|{h_k}^T a_k\right|^2 \quad (3.2)$$

The interuser interference plus noise power precisely is expressed as follow:

$$\mathrm{E}\left[\left|\sum_{i=1,i\neq k}^{K} {h_k}^T a_i x_i + n_k\right|^2\right] = \sum_{i=1,i\neq k}^{K} \left|{h_k}^T a_i\right|^2 \mathrm{E}[|x_i|^2] + \mathrm{E}[|n_k|^2]$$

$$= \sum_{i=1,i\neq k}^{K} \left|{h_k}^T a_i\right|^2 + 1 \quad (3.3)$$

From “Shannon theorem”, the channel capacity over “Additive White Gaussian Noise” (AWGN) channel is derived by [35].

$$\mathrm{R} = \log2(1 + \mathrm{SNR})\ (\mathrm{bits/s/Hz}) \quad (3.4)$$

MU MIMO transmitter for DL systeminvolves channel state information, which is a key issue of MU communication system. As stated in section 2.3, receiver feedback to the transmitter on the reverse link just before to send channel estimation. Then, the transmitter gets CSI. In MU-MIMO system the interference consists of additive white noise and interference between the users.Then, the achievable rate of k^{th} user for MU-MIMO downlink system can be expressed as;

$$R_k = \mathrm{E}[\log_2(1 + \mathrm{SINR}_k)] \qquad (\mathrm{bits/s/Hz}) \quad (3.5)$$

Recall (3.2),(3.3)and (3.4) the approximate achievable rate in terms of the desired and interferance signal is defined as;

$$\mathrm{R_k} = \mathrm{E}\left[\log_2\left(1 + \frac{\left|\mathrm{h_k}^{\mathrm{T}} \mathrm{a_k}\right|^2}{1 + \sum_{\mathrm{i=1,i\neq k}}^{\mathrm{K}} \left|\mathrm{h_k}^{\mathrm{T}} \mathrm{a_i}\right|^2}\right)\right] \quad (3.6)$$

3.5.1 The Achievable Rate with MMSE Precoding

As we enumarate equation (2.10), thenMMSE received vector can be formulatedas:

$$\mathrm{y} = \frac{1}{\beta} \mathrm{H^T} \left[\mathrm{H}^* \left(\mathrm{H^T H^*} + \frac{\mathrm{K}}{\mathrm{P_{tr}}} \mathrm{I_K}\right)^{-1}\right] \mathrm{x} + \mathrm{n} \quad (3.7)$$

Where, $\beta = \sqrt{\frac{\mathrm{tr}\left(\mathrm{H^T H^*}\left(\mathrm{H^T H^*} + \frac{\mathrm{K}}{\mathrm{P_{tr}}} \mathrm{I_K}\right)^{-2}\right)}{\mathrm{P_{tr}}}}$

Let y_k, x_k, and n_k, be the k^th^ elementsof $K \times 1$ vector y, x and n respectively and we define the k^th^ column of A_{MMSE} as;

$$a_k = H^* \Lambda k \tag{3.8}$$

where Λk is the k^th^ column of $\left(H^T H^* + \frac{K}{P_{tr}} I_K\right)^{-1}$. From (3.7), k^th^ user received vector for MMSE is reformed as;

$$y_{k=} \frac{1}{\beta} {h_k}^T H^* \Lambda k \, x_k + \frac{1}{\beta} \sum_{i=1, i \neq k}^{K} {h_k}^T H^* \, \Lambda k \, x_i + n_k \tag{3.9}$$

The k^th^ user achievable rate with MMSE is assumed by;

$$R_K^{MMSE} = E\left[\log_2\left(1 + \frac{\frac{1}{\beta^2}\left|{h_k}^T H^* \Lambda k\right|^2}{1 + \frac{1}{\beta^2}\sum_{i=1, i \neq k}^{K} \left|{h_k}^T H^* \, \Lambda k\,\right|^2}\right)\right] \tag{3.10}$$

Interpretation of the Effective SE expressions:

- From the formulation the channel is frequency independenct.
- The coherent beamforming gain for the signal designated for the k^th^ terminal is numerator of equation(3.11) where as denominator includes noise and intra-cell interference.

3.5.2 The Achievable Rate with ZF Precoding

The received vector with ZF is as follow, from (2.12)

$$y = \frac{1}{\beta} H^T [H^* (H^T H^*)^{-1}] x + n \tag{3.11}$$

Where, $\beta = \sqrt{\frac{tr(H^T H^* (H^T H^*)^{-2})}{P_{tr}}}$

Let y_k, x_k, and n_k, be the k^th^ elements of $K \times 1$ vectors y, x,and n respectively and we define the k^th^ column of A_{ZF} as;

$$a_k = H^* g_k \tag{3.12}$$

where g_k is the k[th] column of $(\mathrm{H^T H^*})^{-1}$. From (3.11), the received vector of k[th] user with ZF is given by;

$$\mathrm{y_k} = \frac{1}{\beta}\mathrm{h_k}^{\mathrm{T}}\mathrm{H^* g_k x_k} + \frac{1}{\beta}\sum_{\mathrm{i=1,i\neq k}}^{\mathrm{K}}\mathrm{h_k}^{\mathrm{T}}\mathrm{H^* g_k x_i} + \mathrm{n_k} \tag{3.13}$$

The k[th] user with ZF achievable rate is given by;

$$\mathrm{R_K^{ZF}} = \mathrm{E}\left[\log_2\left(1 + \frac{\frac{1}{\beta^2}\left|h_k{}^T H^* g_k\right|^2}{1+\frac{1}{\beta^2}\sum_{\mathrm{i=1,i\neq k}}^{\mathrm{K}}\left|h_k{}^T H^* g_i\right|^2}\right)\right] \tag{3.14}$$

Interpretation of the Effective SE expressions:

- From the formulation the frequency dependence of the channels disappears. As a result only the large-scale fading coefficient is considered as major factor.
- The numerator is the coherent beamforming gain.
- The denominator signifies noise and interference commonly known as effective Noise, whose magnitude is independent of M:
    - The term "1" resembles to receiver noise.
    - The remaining term,which is convenient to think of as intra-cell interference, represents the effects of channel estimation errors.

3.5.3 The Achievable Rate with MRT precoding

Having equation (2.14), the received vector with MRT can be derived as

$$\mathrm{y} = \frac{1}{\beta}(\mathrm{H^T H^*})\mathrm{x} + \mathrm{n} \tag{3.15}$$

Where, $\beta = \sqrt{\frac{\mathrm{tr(H^T H^*)}}{\mathrm{P_{tr}}}}$

Let $\mathbf{y_k}$**,** $\mathbf{x_k}$ and $\mathbf{n_k}$ be the k[th] elementsof $\mathrm{K} \times 1$ vectors **y, x** and **n** respectively and we define the k[th] column of MRT as;

$$a_k = h_k^* \tag{3.16}$$

The received vector of k[th] user with MRT as of equation (3.15) is adapted into

$$y_k = \frac{1}{\beta} h_k{}^T h_k^* x_k + \frac{1}{\beta} \sum_{i=1, i\neq k}^{K} h_k{}^T h_k^* x_i + n_k \tag{3.17}$$

Then, k^{th} user achievable rate with MRT is given by

$$R_K^{MRT} = E\left[\log_2\left(1 + \frac{\frac{1}{\beta^2}||h_k||^4}{1 + \frac{1}{\beta^2}\sum_{i=1,i\neq k}^{K} |h_k{}^T h_k^*|^2}\right)\right] \tag{3.18}$$

Interpretation of Effective SE expressions:

- The channel is frquency independent from the formulation. This is reliable with the coherent beamforming gain and effects of intra-cell interference arise from the jointachievement of many antennas.
- The numerator is the coherent beamforming gain for the the k^{th} terminal designated signal.
  - The factors $\frac{\mathbf{1}}{\boldsymbol{\beta}^2}\|\boldsymbol{h_k}\|^4$represent the effective strengths of the channel between the base station and the k^{th} terminal.
  - The gain is affected by Only the k^{th} power control coefficient,$\boldsymbol{\eta k}$.
- Noise and intra-cell interference is the denominator of equation (3.18)
  - The term "1" is receiver noise.
  - The remaining term is treated as intra-cell interference that represents the effects of channel estimation errors, channel non-orthogonality and beamforming gain uncertainty.
  - The interference arrives only by the path to the k^{th} terminal, and is proportional only to the total radiated power,i.e.,the sum of the power control coefficients.

3.6 Energy Efficiency

The EE of a system is defined as the “sum-rate” (the spectral effciency) divided by the “transmit power”. Generally, the sum rate increase while increasing transmit power. However, EE will reduce. Having perfect CSI with a single cell “massive MIMO system”, the spectral efficiency(SE) is defined as;

$$R_P = \sum_{k=1}^{K} R_k \tag{3.19}$$

where R_k is the achievable rate of user k and Rp is the SE in bits/s/Hz. EE is modified as;

$$\eta = \frac{R_P}{P_{tr}} \qquad \text{(bits/J/Hz)} \tag{3.20}$$

Where P_{tr} : BS average transmission power.

Obviously thisdemonstrate that a tradeoff betweenenergy and SE in "massive MU-MIMO DL system" is essential.

For large value of M and K, the related $SINR_k$ of MRT precoding is given as [36].

$$\mathrm{SINR}_K^{mrt} = \frac{P_d M}{K(P_d+1)} \tag{3.21}$$

From [37] the achievable data rate with MRT can be deduced as;

$$R_{sum}^{mrt} = K\log_2(1 + \mathrm{SINR}_K^{mrt}) \tag{3.22}$$

Substituting (3.22) in to (3.23), then it gives;

$$R_{sum}^{mrt} = K\log_2\left(1 + \frac{P_d M}{K(P_d+1)}\right) \tag{3.23}$$

Taking exponential of both sides we have;

$$P_d{}^{mrt} = \frac{K\left(e^{\frac{R_{sum}\ln 2}{k}} - 1\right)}{M - K\left(e^{\frac{R_{sum}\ln 2}{k}} - 1\right)} \tag{3.24}$$

For large values of M and K, the related $SINR_k$ of k_{th}user is given by [28].

$$\mathrm{SINR}_K^{zf} = \frac{P_d(M-K)}{K} \tag{3.25}$$

The achievable data rate that can be achieved with ZF can be calculated as;

$$R_{sum}^{zf} = K\log_2(1 + \mathrm{SINR}_K^{zf}) \tag{3.26}$$

Substituting (3.26) into (3.27) gives;

$$R_{sum}^{zf} = K\log_2\left(1 + \frac{P_d(M-K)}{K}\right) \tag{3.27}$$

Taking exponenetial of both sides we have;

$$P_d{}^{zf} = \frac{K\left(e^{\frac{R_{sum}\ln 2}{k}}-1\right)}{M-K} \tag{3.28}$$

For large values of M and K, the related $SINR_K$ of k_{th}user is given as [28]

$$SINR_K^{mmse} = \frac{P_d(M-K)}{K} + \frac{K}{P_d} \tag{3.29}$$

The achievable data rate that can be achieved with ZF is as follows:

$$R_{sum}^{mmse} = K\log_2(1 + SINR_K^{mmse}) \tag{3.30}$$

Substituting (3.30) into (3.31), gives

$$R_{sum}^{mmse} = K\log_2\left(1 + \frac{P_d mmse(M-K)}{K} + \frac{K}{P_d mmse}\right) \tag{3.31}$$

Equation (3.31) can be rearranged as;

$$P_d{}^2 mmse\left(\frac{M}{K}+1\right) \text{-} P_d mmse\left(e^{\frac{R_{sum}\ln 2}{k}} - 1\right) + K = 0 \tag{3.32}$$

3.7 Implementation

MATLAB-2019a is used to generate all scenarios. Each simulation result is conducted on 500 “channel realization” to confirm the results are smooth and correct.

3.7.1 Calculating Signal to Noise Ratio (SNR)

The SNR is defined as the “ratio of desired signal power and noise power”. In this work, we assume that the desired signal vector **x** and the noise vector **n** are i.i.d. complex Gaussian RV (with zero mean and unit variance$(0,\sigma)$). Then, the SNR is given by:

$$\frac{S}{N} = P_{tr} = 10\log P_{tr} \;\; dB \tag{3.33}$$

3.7.2 Calculating Achievable Rate

As we discussed above, the MU-MIMO system performance is enumerated by the achievable rate. The achievable sum rate which is proportional to linear sum of achievable rate of each user is considered. Once we obtain these achievable rate, we average them. Since, the average value is used to realize M-MIMO DL system performance.

3.7.3 Calculating Spectral Efficiency

After we calculate the achievable rate of user 1, we calculate the spectral efficiency by multiplication between the achievable rate of user 1 and the number of users in the system [27]. The spectral efficiency is defined by equation 3.19. Preserving this parameter is essential to study the "performance of massive MU-MIMO DL" system.

$$R_P = K \times R_k = \text{(bits/s/Hz)} \tag{3.34}$$

3.7.4 Calculating Energy Efficiency

Recall equation 3.20 to calculate the EE. After we obtain the spectral efficiency, this parameter is divided by SNR. We obtain the EE which is important to analyze the system performance under Rayleigh fading channel.

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSION

4.1 Introduction

Here we present and discuss the results of the simulations and the realization of practical massive MU-MIMO system.

Case 1. Change in Achievable sum rate with growing downlink transmission power.

Case 2. Change in Achievable sum rate by means of increasing SNR.

Case 3. Change in Achievable sum rate through increasing the number of base station antenna.

Case 4. Change in Achievable sum rate with increasing number of active users.

Case 5. Change in Energy efficiencywith increasing number of antenna at the base station.

Case 6. Change in Energy efficiency in reference to increasing number of user. Lastly,

Case 7. Change in DL Transmit power with the increasing of number active user for large value of M and K.

Case 8. Change in DL transmit power with the increasing of number of antenna at the base station for large value of M and K.

However, the limitation of model is the number of users,K is not largely greater than from the number of antennas,M. The results are interpreted in terms of;

- The achievable sum-rate versus Signal-to-Interference Ratio (SINR).
- The achievable sum rate versus the number of antenna.
- The achievable sum rate that can be achieved vs. the number of users.
- The Energy efficiency versus number of antenna.
- The Energy efficiency versus number of users.
- Downlink trasmssion power (ρ_d) versus number of antenna.

4.2 Simulation Parameters

All simulation parameter that has been used extensively in this thesis are defined form 3GGP standards and regulation. It is a global wireless communications organization that collaboratively develops standards or specifications for radio, core network and service architecture.

Table 4-1: Simulation Parameter

S. No	**Parameters**	**Value**	**Remark**
1	SNR (fixed)	10dB	LTE signal strength range
2	SNR(Varied)	-20 to 20 dB	LTE signal strength range
3	No of Antennas (fixed)	90	Variable
4	No of Antennas (Varied)	10 to 200	Variable
5	No of User (fixed)	10	Variable
6	No of User (Varied)	5 to 100	Variable
7	DL Transmission power	-20 to 20dBmw	Variable

4.3 Interpretation of the Numerical Result

4.3.1 Effect of Tranismit Power for Achivable Rate

In wireless communication system the two fundamental scare resources are trasmission power and channel bandwidth(BW). Thus, the QOS (system performance) strongly dependent on downlink trasmission power. It does mean that the capacity of the system can be governed by trasmisssion power. An increase in trasmission power signify that QOS is improved.

Figure 4.1 illustrates that an increase achievable rate is revealed whenever transmission power(Pd) increase from 10mw to 15mw. At low trasmssion power the achievable rate of MMSE and ZF are quite approximable. Both MMSE and ZF outperform MRT precoding. At high transmission power the achievable rate of MMSE and ZF performance gap increase. In Fig 4.1, it is often seen that the MMSE linear precoding scheme achieves a high sum rate and provides a far better result compared to ZF and MRT.

The channel aging at high SINR causes a siginificant reduction in the data rate. Consequently, we can suppress a high SINR at increased trasmited power because MMSE is able to mitigate inter-cell interference. While, the linear decoding ZF has low complexity and the performance is very close to that of a maximum likelihood multi-user when the number of antenna increases. Moreover, the achivable high rate are often obtained when transmission power is much higher than circuit power consumption. However, when the trasnmission power is reasonble, the consumption circuit power will be less than tasnmission power and achieving the high data rate.

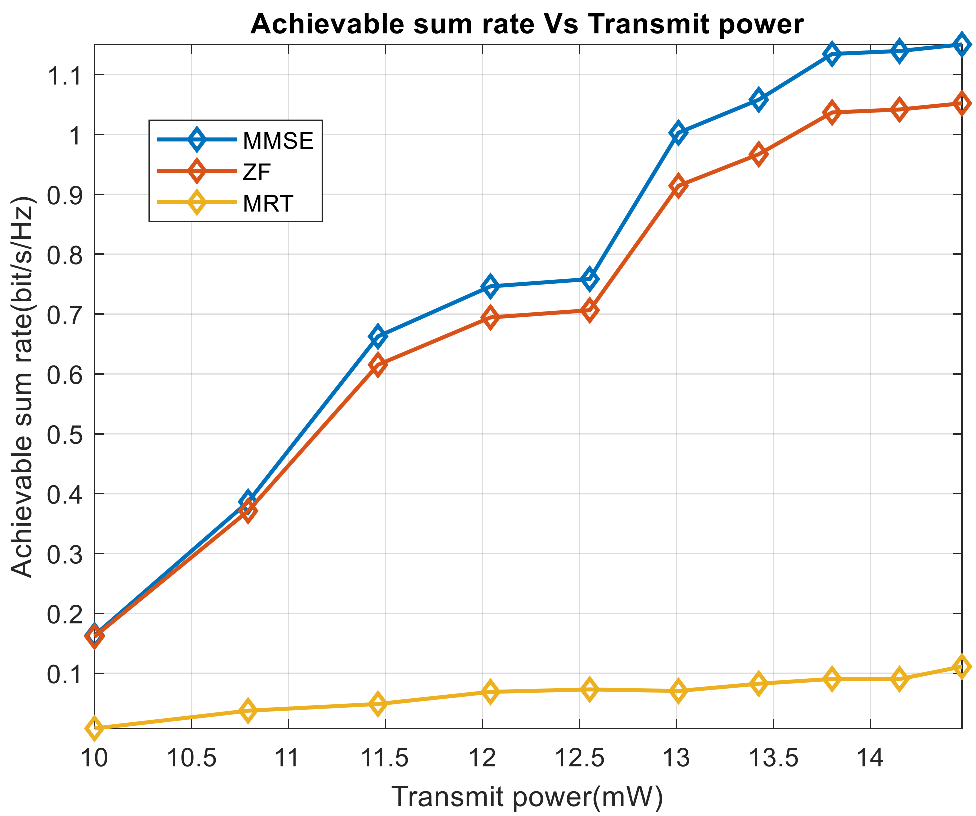

Figure 4-1: Achievable sum rate Vs DL Transmit power

4.3.2 Effect of SNR for Achivable Rate

Figure 4.2 shows the achievable rate versus SNR for MRT, ZF, and MMSE precoding schemes, respectively. In our simulations, the number of users is set to $K = 10$, the number of BS antennas is $M = 90$ and the input SNR vary from (−20 to 20 dB).

The signal to intreference plus noise ratio(SINR) is the performance metrics parameter of communication system. The effect of linear precoding(processing) for DL M-MIMO system can be viewed interms of SNR. Under this condition at low SNR ZF and MMSE precoding performance is limited. We can see that throughout the entire SINR range MMSE outperforms MRT and ZF. It is known that the MMSE receiver exploits the received SINR. As a result, among the MMSE, ZF, and MRT receivers, MMSE is the optimum. We can see from (2.22) that, at low and high MRT performance is limited because of less immune capability to suppress intra and inter-cell interference. Here MMSE performs strictly better than both ZF and MRT over the entire range of SNRs. In the low SNR regime, ZF follows MMSE, and MMSE faraway ZF in the high SNR regime.

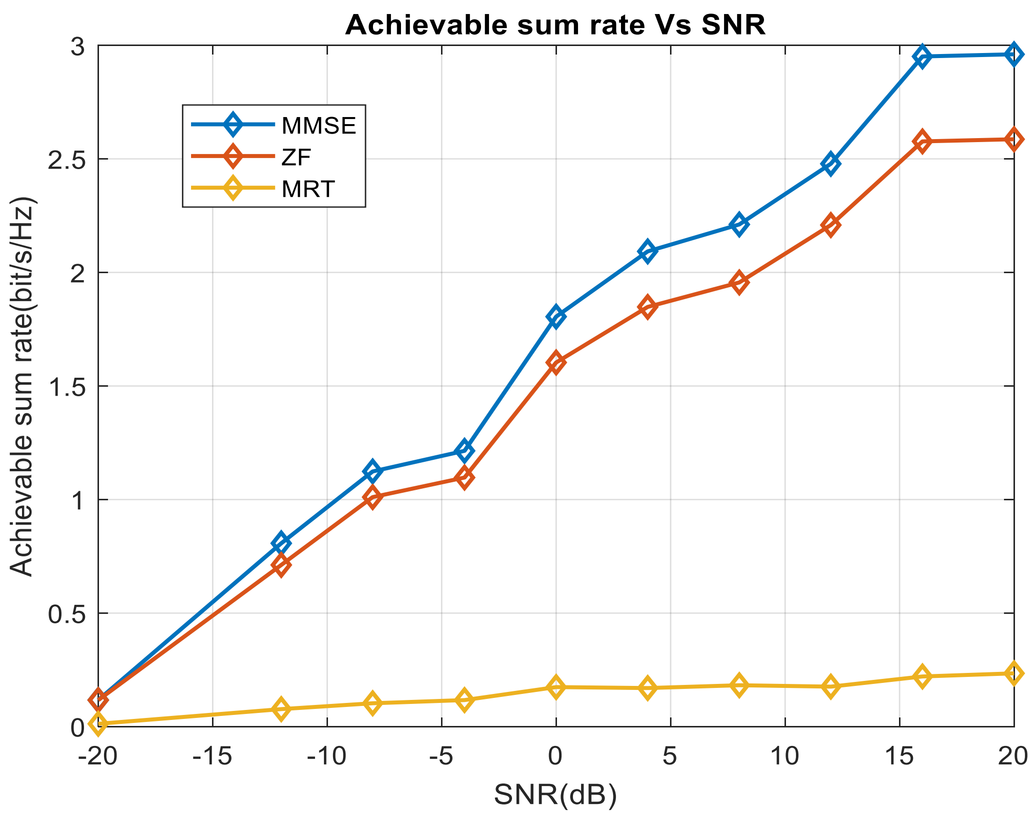

Figure 4-2: Achievable rate Vs SINR

4.3.3 Effect of Increasing Number of Antenna for Achievable Rate

The unique feature of Mu M-MIMO system is beamforming techniques. This anables to enhance the effeiciency of 5G system by linearly increasing the number of anteenna array. Because of this figure 4.3 clearly demonstsrtes that increasing the number of antenna for M-MIMO TDD system greatly adavance the performance. as we discussed above in the first range of antenna MMSE outperms from the contrary precoding scheme viz MRT and ZF have no large difference. The performance variation gap in between them largely increase. It is evident that at higher number of antenna array using MMSE precoding scheme mitigate the inter-user intreference dramitically. From fig 4.3 increased number of antenna array, M at BS from 10 to 200 directly increase the achievable data rate when the number of active user, K=10.

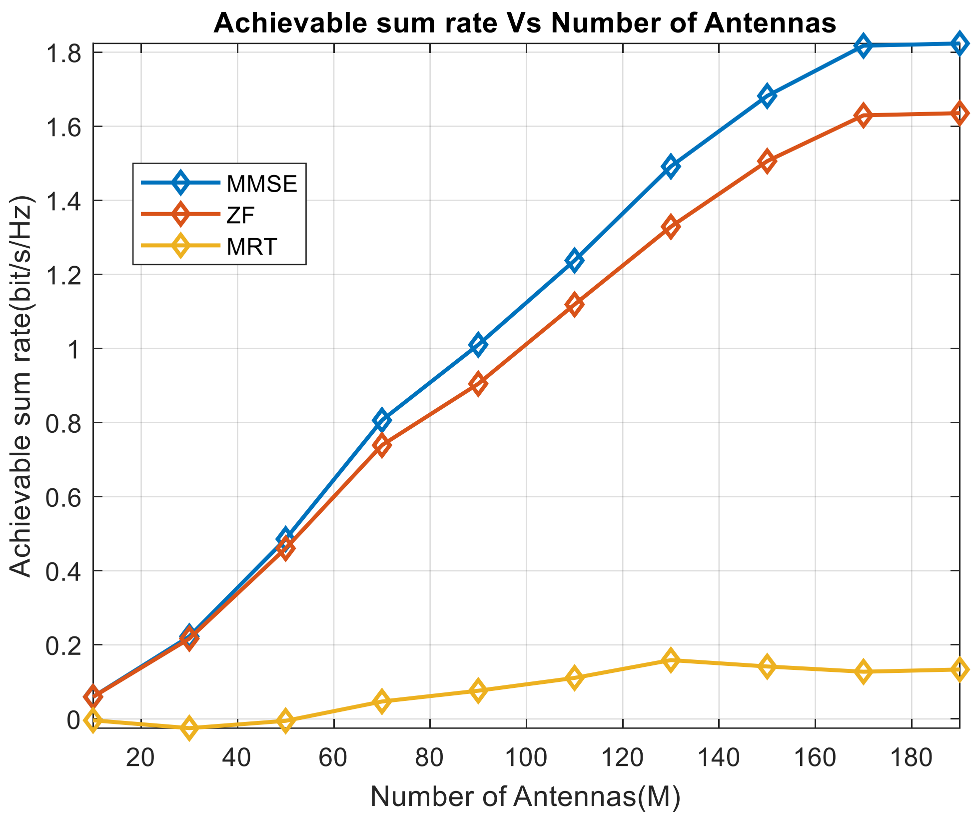

Figure 4-3: Achievable sum rate Vs Number of Antenna Array

4.3.4 Effect of Increasing Number of User for Achievable Rate

One of the main challenge of 4G and prior is large number of active user draws high inter-user interference. This issue can be handled by while using linear processing of M-MIMO system. Accordingly, in fig 4.4 at low number of user K the achievable rate of MMSE, MRT and ZF increases linearly at the middle region of active user. Spectral effeciency of MMSE and ZF becomes saturate. Then, the achievable rate of MMSE and ZF decreaes slowly. Since higher number of active user increase inter-user interference. Conversly, the system performance decreases.

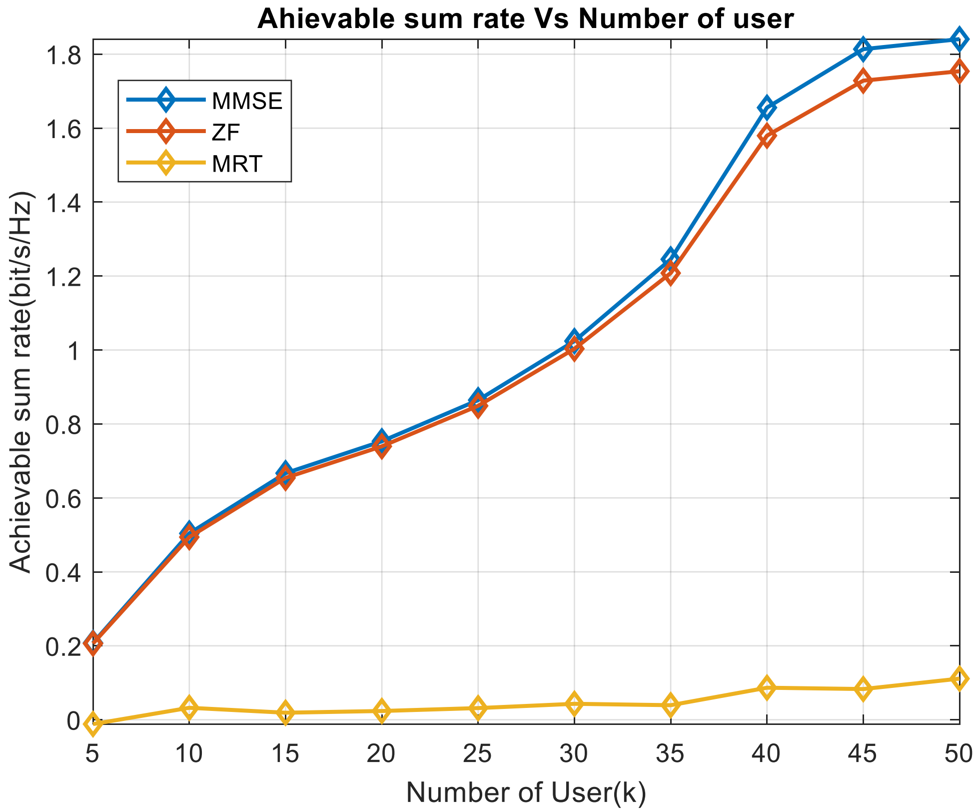

Figure 4-4: Achievable sum rate Vs Number of user

4.3.5 Effect of Transmit Power for Energy Efficiency

From fig 4.5 it is reveal that the increasing the DL transmit power at the BS progressively decrease energy efficieny (EE).

4.3.6 Effect of Increasing Number of Antennas for Energy Efficiency

Maximizing the data rate or system throughput in M-MIMO system can be accomplished by uysing conventional linear precoding schemes such as MMSE,MRT and ZF. So that, fig 4.6 evident that troughput for MMSE precoding scheme is high as compared to MRT and ZF precoding troughout overall SE region.

Figure 4.5 and 4.6 shows thata the energy efficiency value are also related to the average transmit power and Number of Antennas. Comparativly,among the three well known precoding technique the performance of MRT scheme is worst where as the performance of ZF and

MMSE is quite proportional. It becomes an optimal scheme when the average transmission power is 20dB in particular.

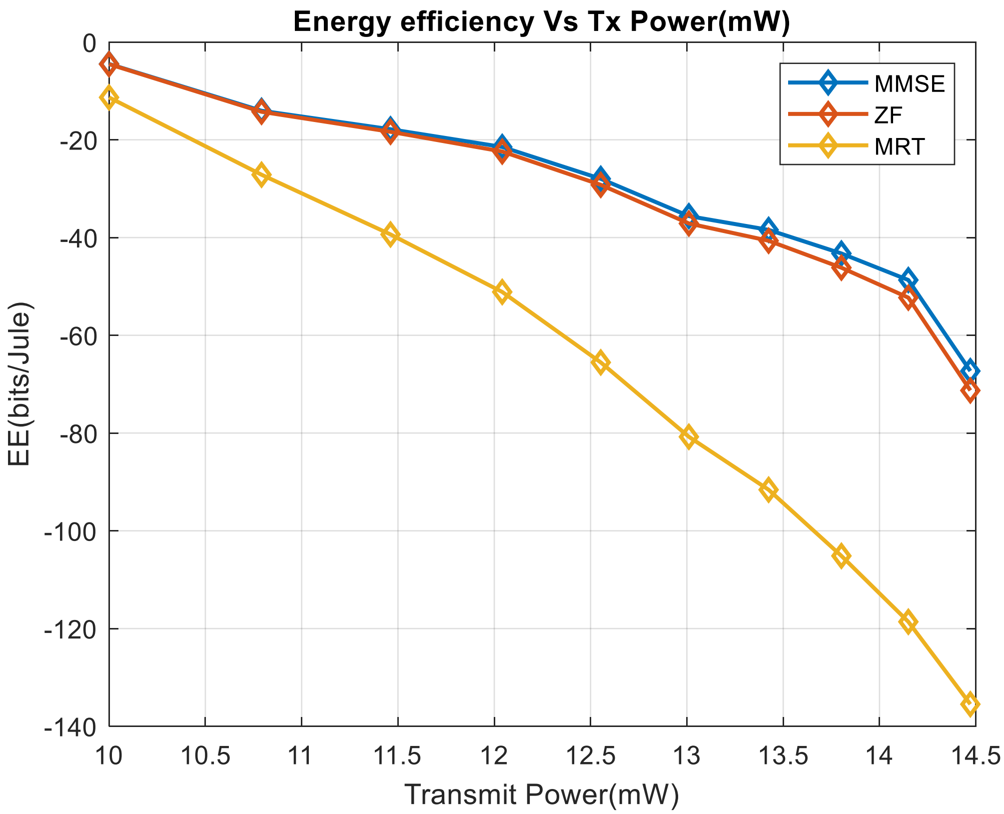

Figure 4-5: Energy Efficiency Vs Transmit Power

Fig 4-6 shows energy efficiency and its relation with the Number of Antennas under perfect CSI. Accordingly, as the number of antennas increases gradually from 20 to 180 the energy efficiency also increases exponentially which maximizes the area throughput and produces high data rate with low latency. Just similar to the above deduction, the superiority of MMSE precoding scheme is also preserved under energy efficiency versus downlink transmission power scenario.

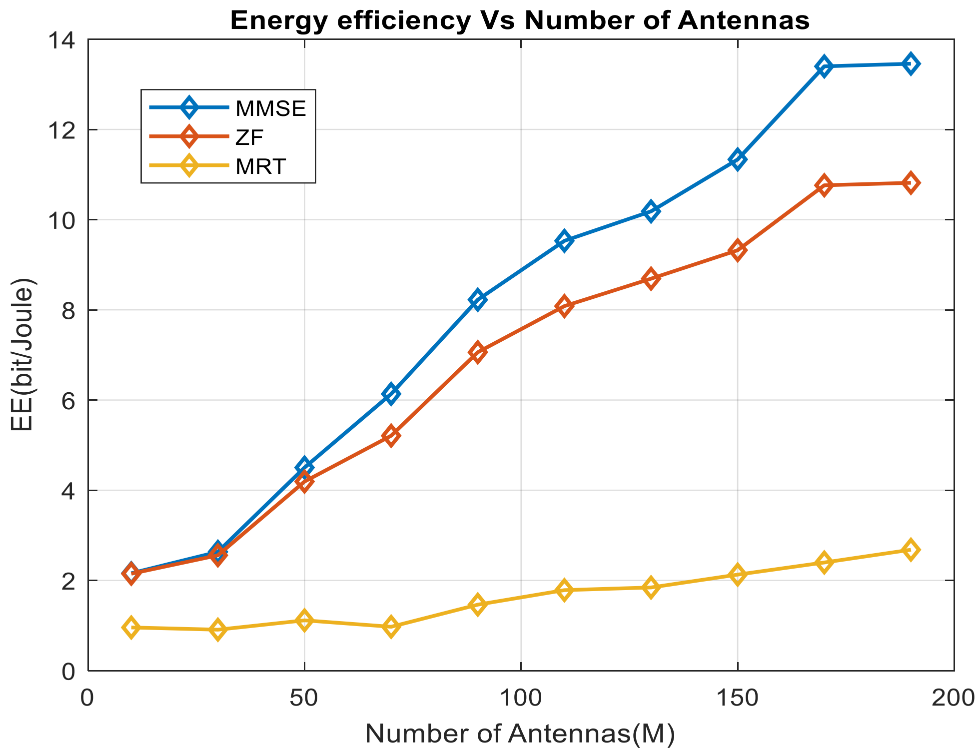

Figure 4-6: Energy Efficiency Vs Number of Antenna array

4.3.7 Effect of Number of Active User on Fraction of Transmit Power

Figure 4.7 shows fraction of transmits power versus Active number of user. In the same scenario we try to examine the performance of linear precoding (MMSE, MRT, ZF) in relation to the effect of number of user on the transmission power. For single cell multiuser massive MIMO system at low and large number of active user is considered. For a very small number of user, fraction of transmit power is optimum. Because interference power that will introduce by inter-user interference is quite insignificant as a result fraction of transmit power is high. Besides, linear precoding also increases the system capacity rather than no precoding processing. Until the middle all linear precoding technique that we have considered in this thesis outperforms the theoretical result. In the right side of middle regime only MMSE has better result rather than ZF and MRT.

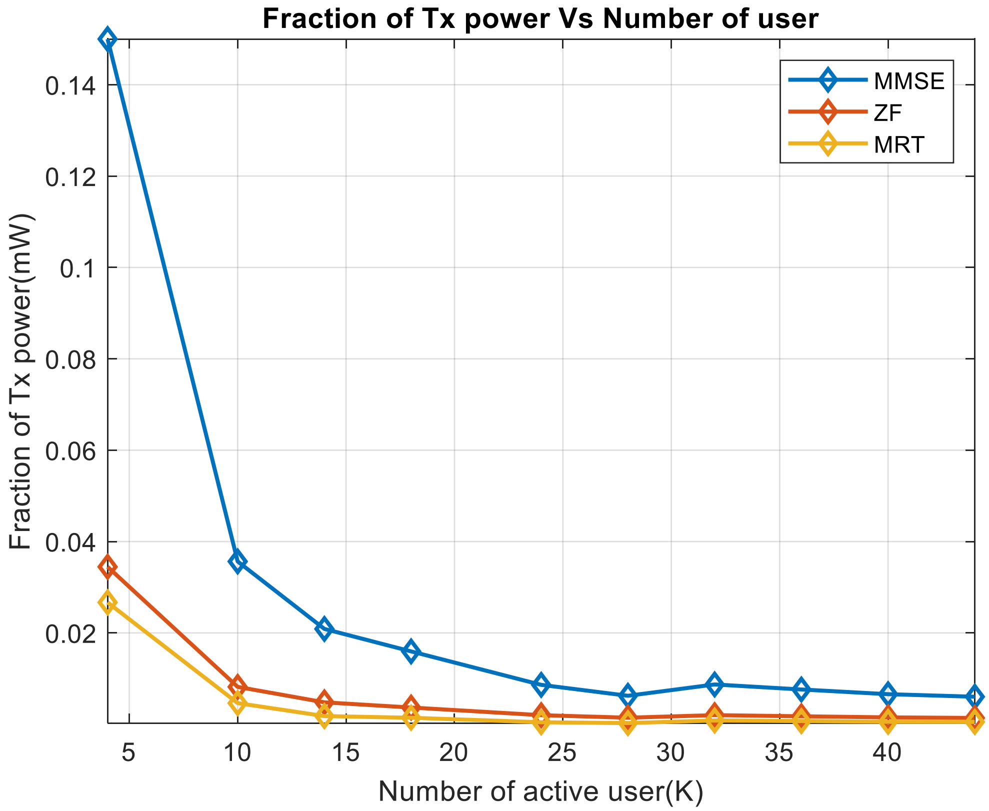

Figure 4-7: Fraction of transmit power Vs Number of User (K)

4.3.8 Effect of Number of Antennas on Fraction of Transmit Power

Figure 4.8 shows the fraction transmission power versus number of antennas for perfect CSI. These figures apparently reveal that as the number of antennas increases gradually from 10 to 140 the average power consumption for theoretical and simulation that results an increase the system capacity. Under small number of Antenna, the theoretical numerical result curve lower than MRT, ZF and MMSE precoding simulation result. It validates that when 'M' vary from 10 to 25 an improved performance can be achieved while employing linear precoding namely ZF, MRT and MMSE rather to the theoretical result. For limited number of antennas, the fraction of transmit power is drastically high. Hence, the quality of service for massive MIMO system is limited. Contrarily, for large number of antennas the fraction of transmit power gradually decreases. As a result, the capacity of the system is increased for all linear precoding schemes (MMSE, ZF, and MRT). On the other hand, MMSE precoding scheme outperform ZF and MRT since high transmission power draws high system capacity. In the middle range at

M≈ 40 to 100, the numeric value of fraction of transmits power for ZF and MRT less than to the theoretical value. Not only in this have regime but also at large number of antenna MMSE fraction of transmitted power exceeds from the contrary precoding scheme and theoretical result. It implies that under the condition the system quality of service can be improved if and only if the precoding type is MMSE.

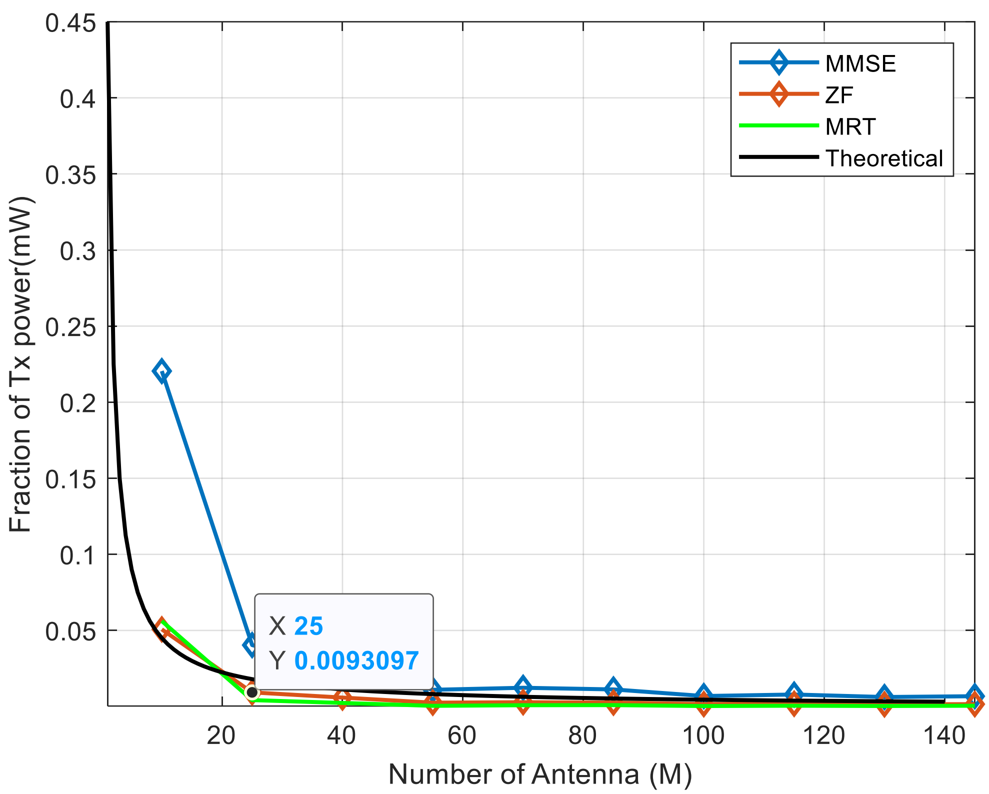

Figure 4-8: Fraction of transmit power Vs Number of antenna at M>20 and K<20

As we see from the below figure 4.8, at 20 number of antenna and below that all precoding techniques performs good comparing with the theoretical one. And MRT and ZF are not transmitting good power above 20 number antenna, but MMSE transmitting good power at that number of antenna. So we can conclude that MMSE transmit good power throughout the figure and it performs well.

Conclusions

This work examined that comparative anaysis of linear precoding for 5G (M-MIMO) system. At large number of base station (transmitter) anennas, M and active users, K this research provides a fundamental conclussion on the downlink transmission capacity of M-MIMO wireless systems for three linear precoding scheme MRT, MMSE and ZF. The simulation result indicates that the achievable sum rate of MRT decreases at higher SNR system while the attainable sum rate of the MMSE receiver is better than MRT because MMSE can able to supress both inter and intra-cell interference. The data rate increases with the average SNR, which depends on an increase in terms of number of antenna and limited users inside the given cell. The energy efficiency of DL M-MIMO in relation to transmitter antenna, M and downlink transmit power for three linear precoding is studied. It reveal that increasing the number of transmitter antenna improve the energy efficieny for MRT, ZF and MMSE precoder. How ever rising in DL Tx power evident that decreasing energy efficiency i.e directly conform to the theortical expresstion. Generally, ZF gives better performances at high transmission power while MRT gives better performance at the low transmission power. However, MMSE gives the best performance at low and high transmission power.

However, the optimal choosing of linear precoding ready to mitigate multi-user interference, which enhance the system performance and increase the achievable sum rate. Massive MIMO is the foremost promising technology for 5th generation. It gives high spectral efficiency and communication reliability. In this thesis, a pre-coder has been considered for downlink massive MIMO TDD system. The achievable rate also gives a better performance as the number of antennas increased. Therefore, a massive MIMO system is a key in next wireless system. It presents advantages in terms of the achievable rate, the spectral efficiency, and the energy efficiency.

Future Work

Further investigations need to be carried out to find out the optimal precoding technique for downlink massive MIMO system without more reducing the standard achievable sum rate. The tactic that has been utilized during this thesis assumes that the users are located at the cell edges. However, in practice this situation is rarely occurred as users are randomly distributed within a cell. Further investigations shall be administered to assess the effect of random user location on the event of the achievable sum rates. During this work, also the effect of an antenna structure isn't considered for DL M-MIMO channel estimation. The effect of an antennas structure can be studied further on the improvement of the achievable rate of the system. It would be better if this work include the performance analysis of linear precoding with non-linear precoding thechnique.

REFERENCES

[1] Y. Fang *et al.*, (2016). "A survey on DCSK-based communication systems and their application to UWB scenarios," vol. 18, no. 3, pp. 1804-1837.

[2] K. Zheng *et al.*, (2015). "Survey of large-scale MIMO systems," vol. 17, no. 3, pp. 1738-1760.

[3] C. Li, K. Song, D. Wang, F.-C. Zheng, and L. J. S. C. I. S. Yang, (2016). "Optimal remote radio head selection for cloud radio access networks," vol. 59, no. 10, pp. 1-12.

[4] M. Zhao, D. Deng, W. Zhou, and L. J. P. C. Fan, (2018). "Non-renewable energy efficiency optimization in energy harvesting relay-assisted system," vol. 29, pp. 183-190.

[5] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. J. I. c. m. Popovski, (2014). "Five disruptive technology directions for 5G," vol. 52, no. 2, pp. 74-80.

[6] J. Yuan, S. Jin, W. Xu, W. Tan, M. Matthaiou, and K.-K. J. I. T. o. C. Wong, (2017). "User-centric networking for dense C-RANs: High-SNR capacity analysis and antenna selection," vol. 65, no. 11, pp. 5067-5080.

[7] T. L. Marzetta, (2016). *Fundamentals of massive MIMO*. Cambridge University Press.

[8] X. Gao, O. Edfors, F. Rusek, and F. Tufvesson, (2011). "Linear pre-coding performance in measured very-large MIMO channels," in *2011 IEEE Vehicular Technology Conference (VTC Fall)*, pp. 1-5: IEEE.

[9] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. J. I. c. m. Marzetta, (2014). "Massive MIMO for next generation wireless systems," vol. 52, no. 2, pp. 186-195.

[10] S. Payami and F. Tufvesson, (2012). "Channel measurements and analysis for very large array systems at 2.6 GHz," in *2012 6th European Conference on Antennas and Propagation (EUCAP)*, pp. 433-437: IEEE.

[11] B. Liu, Q. Zhu, W. Tan, H. J. W. C. Zhu, and M. Computing, (2018). "Congestion-optimal WIFI offloading with user mobility management in smart communications," vol. 2018.

[12] J. Hoydis, C. Hoek, T. Wild, and S. ten Brink, (2012). "Channel measurements for large antenna arrays," in *2012 International Symposium on Wireless Communication Systems (ISWCS)*, pp. 811-815: IEEE.

[13] X. Lai, J. Xia, M. Tang, H. Zhang, and J. J. I. A. Zhao, (2018). "Cache-aided multiuser cognitive relay networks with outdated channel state information," vol. 6, pp. 21879-21887.

[14] X. Liu, M. Jia, X. Gu, F. Kong, and Q. J. J. o. S. Jing, (2014). "Optimal joint allocation of multislot spectrum sensing and transfer power in multichannel cognitive radio," vol. 2014.

[15] F. Zhou, L. Fan, X. Lei, G. Luo, H. Zhang, and J. J. I. C. L. Zhao, (2018). "Edge caching with transmission schedule for multiuser multirelay networks," vol. 22, no. 4, pp. 776-779.

[16] H. Yin, D. Gesbert, M. Filippou, and Y. J. I. J. o. s. a. i. c. Liu, (2013). "A coordinated approach to channel estimation in large-scale multiple-antenna systems," vol. 31, no. 2, pp. 264-273.

[17] S. Jin, X. Wang, Z. Li, and K.-K. Wong, (2014). "Zero-forcing beamforming in massive MIMO systems with time-shifted pilots," in *2014 IEEE International Conference on Communications (ICC)* pp. 4801-4806: IEEE.

[18] C. Li, S. Zhang, P. Liu, F. Sun, J. M. Cioffi, and L. J. I. T. o. V. T. Yang, (2015). "Overhearing protocol design exploiting intercell interference in cooperative green networks," vol. 65, no. 1, pp. 441-446.

[19] W. Tan, S. Jin, C.-K. Wen, T. J. E. J. o. W. C. Jiang, and Networking, (2017). "Spectral efficiency of multi-user millimeter wave systems under single path with uniform rectangular arrays," vol. 2017, no. 1, pp. 1-13.

[20] C. Li, Y. Li, K. Song, and L. J. S. C. I. S. Yang, (2016). "Energy efficient design for multiuser downlink energy and uplink information transfer in 5G," vol. 59, no. 2, pp. 1-8.

[21] H. Q. Ngo, E. G. Larsson, and T. L. J. I. T. o. C. Marzetta, (2013). "Energy and spectral efficiency of very large multiuser MIMO systems," vol. 61, no. 4, pp. 1436-1449.

[22] H. Yang and T. L. J. I. J. o. S. A. i. C. Marzetta, (2013). "Performance of conjugate and zero-forcing beamforming in large-scale antenna systems," vol. 31, no. 2, pp. 172-179.

[23] Y.-G. Lim, C.-B. Chae, and G. J. I. T. o. W. C. Caire, (2015). "Performance analysis of massive MIMO for cell-boundary users," vol. 14, no. 12, pp. 6827-6842.

[24] M. M. Rahman and D. M. A. B. Siddiqui, "Performance Analysis of Massive MIMO with Different Precoders under Perfect and Imperfect CSIT Condition," ed: American International University-Bangladesh Dhaka, Bangladesh.

[25] A. Israr, Z. Rauf, J. Muhammad, and F. J. W. P. C. Khan, (2017). "Performance analysis of downlink linear precoding in massive MIMO systems under imperfect CSI," vol. 96, no. 2, pp. 2603-2619.

[26] V. Selvan, M. Iqbal, and H. Al-Raweshidy, (2014). "Performance analysis of linear precoding schemes for very large multi-user MIMO downlink system," in *Fourth edition of the International Conference on the Innovative Computing Technology (INTECH 2014)*, pp. 219-224: IEEE.

[27] F. Rusek *et al.*, (2012). "Scaling up MIMO: Opportunities and challenges with very large arrays," vol. 30, no. 1, pp. 40-60.

[28] L. Zhao, K. Zheng, H. Long, and H. J. T. o. E. T. T. Zhao, (2014). "Performance analysis for downlink massive MIMO system with ZF precoding," vol. 25, no. 12, pp. 1219-1230.

[29] M. H. Kabir, S. Z. Rashid, A. Gafur, M. N. Islam, and M. J. Hoque, (2019). "Maximum energy efficiency of three precoding methods for massive MIMO technique in wireless communication system," in *2019 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, pp. 1-5: IEEE.

[30] H. Q. Ngo, (2015). *Massive MIMO: Fundamentals and system designs*. Linköping University Electronic Press.

[31] F. Edition, A. Papoulis, and S. U. Pillai, (2002). "PROBABILITY, RANDOM VARIABLES, AND STOCHASTIC PROCESSES".

[32] E. Björnson, L. Sanguinetti, J. Hoydis, and M. J. I. T. o. w. c. Debbah, (2015). "Optimal design of energy-efficient multi-user MIMO systems: Is massive MIMO the answer?," vol. 14, no. 6, pp. 3059-3075.

[33] M. Zourob, R. J. M. N. Rao, and Applications, (2018). "Hybrid Lower-Complexity Wiener Filter for Pilot-Based Channel Estimation for C-RS in LTE-A DL System," vol. 23, no. 4, pp. 921-939.

[34] H. Q. Ngo, T. L. Marzetta, and E. G. Larsson, (2011). "Analysis of the pilot contamination effect in very large multicell multiuser MIMO systems for physical

channel models," in *2011 IEEE international conference on acoustics, speech and signal processing (ICASSP)*, pp. 3464-3467: IEEE.

[35] M. Wen, E. Basar, Q. Li, B. Zheng, and M. J. I. T. o. C. Zhang, (2017). "Multiple-mode orthogonal frequency division multiplexing with index modulation," vol. 65, no. 9, pp. 3892-3906.

[36] S. J. A. l. p. o. M. M. Choi, Yonsei University, (2012). "Special topics: massive MIMO".

[37] J. Isabona and V. M. J. W. P. C. Srivastava, (2017). "Downlink massive MIMO systems: Achievable sum rates and energy efficiency perspective for future 5G systems," vol. 96, no. 2, pp. 2779-2796.

[38] Emil Bjornson, “Introduction to Massive MIMO”,

https://mammoet-project.technikon.com /downloads/massive-MIMO-workshop-

Lausanne2016/02-MAMMOET_Slides-communication-syste-concept-LIU.pdf