Performance Analysis of Energy-Efficient Multi-Cell Massive MIMO System

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Performance Analysis of Energy-Efficient Multi-Cell Massive MIMO System

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Bachelor of Technology

by

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Abstract

Massive multiple-input-multiple-output (MIMO) is the key technology to provide higher spectral efficiency (SE) and data throughput in the fifth-generation (5G) wireless technology. Simultaneous wireless information and power transfer (SWIPT) makes the Massive MIMO system more efficient. Most of the research in this field evaluated the performance of SWIPT enabled Massive MIMO system under the assumption that the channel is reciprocal. But, the imperfection of the channel reciprocity affects the system performance due to RF mismatch in the transceiver at the base station. In this project, the performance of multi user Massive MIMO system is investigated considering channel reciprocity error. The performance like harvested energy, achievable spectral efficiency and optimization of data throughput by increasing spectral efficiency of Massive MIMO without increasing the bandwidth and cell density are analyzed. Various linear precoding techniques are used to maximize the SE of massive MIMO system. Pilot reuse technique is used to minimize the pilot contamination and co-channel interference. Bit error rate (BER) performance is evaluated and found to be negligible due to the large antenna array at the base station.

Keywords - Massive MIMO, Spectral Efficiency, Channel Reciprocity Error, Linear Precoding, Pilot Contamination.

Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources wherever required. I also declare that I have stuck on to all the principles of integrity and academic honesty and have not misrepresented or fabricated or falsified any data or sources in my submission. I understand that the violation of the above will be a cause for disciplinary action by the institute and can also evoke penal action from the sources which have thus not been properly cited or from proper permission has not been taken when needed.

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CERTIFICATE

This is to certify that the project report titled "Performance Analysis of Energy-Efficient Multi-Cell Massive MIMO System" submitted by Abhishek Thakur (15010213), a final year B.Tech. student in the Department of Electronics and Communication Engineering, Indian Institute of Information Technology Senapati, Manipur is a record of an original research work carried out by him under my supervision and guidance. The results embodied in this project report have not been submitted to any other University or Institute for the award of any degree or diploma.

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CERTIFICATE

This is to certify that the project report entitled **"Performance Analysis of Energy-Efficient Multi-Cell Massive MIMO System"** submitted by **Abhishek Thakur** (15010213), a final year B.Tech. student in the Department of Electronics and Communication Engineering, Indian Institute of Information Technology Senapati, Manipur is approved for the degree of Bachelor of Technology in Electronics & Communication Engineering Department.

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- Abhishek Thakur

Contents

List of Figures

List of Tables

List of acronyms

5G	5th Generation
BER	Bit Error Rate
BS	Base Station
EE	Energy Efficiency
FDD	Frequency Division Duplexing
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MRC	Maximal Ratio Combining
MRT	Maximum Ratio Transmission
SE	Spectral Efficiency
SWIPT	Simultaneous Wireless Information and Power Transfer
TDD	Time Division Duplexing
UT	User Terminal
ZF	Zero Forcing

Chapter 1

Introduction

Massive MIMO is one of the key technology for enabling the next 5th Generation wireless networks. In Massive MIMO large number of antenna arrays are present at the base station and as well as multi user antenna at user terminal. This multiple input and multiple output technology enhances the throughput of the previous network technology along with that high spectral efficiency is the key success of Massive MIMO. To develop a system, it requires RF chains for the large antenna arrays and low complexity. Decoding of received symbol vectors should be done optimally with efficient algorithms and precoding techniques. Channel estimation should be done carefully to understand the transmission process exactly. Users scheduling is simplified and also it is one of the important features in Massive MIMO. Most of the research field have assumed perfect channel reciprocity by assuming the time delay from the uplink channel estimation to the downlink transmission is lesser than the coherence time interval of the channel. One of the uplink and downlink radio frequency chains are the separate circuit which may or may not be reciprocal to each other. Due to which i.e, the RF mismatch the channel may not be perfectly reciprocal. The performance of Massive MIMO in the presence of channel reciprocity error is one of the major study of this project. Further the problem of pilot contamination or signal interference caused due to large number of users in Massive MIMO may degrade the quality of the channel estimation and signal recieved. But, the frequency reuse factor is one of the process of dividing frequency in the co-channel to remove this effect. Various Linear precoding techniques like zero-forcing(ZF), maximum ratio transmission (MRT), minimum mean square error (MMSE) have been extensively investigated in the context of massive MIMO systems to maximize and estimate the spectral efficiency and user capacity for energy efficient multi-cell Massive MIMO system. Along with that Massive MIMO is very profitable technology which provides high spectral efficiency, high speed or data rates to the users, faster communication, high throughput efficiency and excellent service through out the communication range. Due to high frequency it is not obstructed by blockage and buildings. Transmission range is short so major line of sight signal component is present in the Massive MIMO.

1.1 Literature Survey

Massive MIMO is one of the key enabling technology to establish the 5G wireless communication technology [1]. Simultaneous wireless information and power transfer between the BS and user terminal (UT) increases the efficiency of the system [2]- [3]. In downlink, BS charges the user by transferring energy to UT i.e, multi-user beam forming. The harvested energy is exploited by the users to communicate with the BS on the uplink. The downlink transmission is estimated by the uplink data transmission. But, due to the RF mismatch in the hardware chain at the BS transceivers, channel may not be reciprocal between the uplink and downlink [4]- [5]. The downlink pilot should be mutually orthogonal between the antennas, also the number of response of the channel estimated should be proportional to the number of BS antenna. So, the TDD mode is more optimistic in this situation which rely on the reciprocity between the uplink and downlink. TDD is considered as more spectrum efficient and reliable for growing data traffic. Harvested energy and achievable rate increases with the increment in BS antenna. But, in this finite world we can't use the infinite antenna at BS [6]. There is some limit which is decided by energy efficiency of the system [7]. If we increase the antenna at BS, circuitry power consumption, complexity and deploying cost of the system will increase, achievable rate gets constant after the energy efficient regime of massive MIMO, and the energy efficiency will decrease due to increase in the circuitry power consumption [8]. So, we have tried to quantify the massive MIMO. In the previous network technology SE has not seen the major improvement in it. As the global demand for wireless data traffic is increasing also new technology like internet of things (IOTs) are evolving and around 20 to 50 billion devices will be internetworked by 2020. Also wireless traffic is doubled every two year in last few decades, also the rate is increasing now a days. So, there is a improvement needed in area and data throughput [9]- [10] . The 5th generation network technology will also provide better addressing technique to billions of inter networked devices. Massive MIMO scale the SE by several tens and hundreds using different linear precoding process [11]. Zero forcing (ZF) precoding witness the higher performance in noiseless system while maximum ratio (MR) estimate efficiently with respect to channel state information (CSI). But there is a major drawback of ZF in previous network technologies, as it amplify the noise. But, the massive MIMO system is noise and error free, ZF will enhance the performance, as it is ideal for the noiseless system. Available resource bandwidth divided into different disjoint group of different frequency range i.e, pilot reuse factor or sub bands to reduce the pilot contamination [12]- [13]. Interference is more at the boundary of the cell. As per the user density different pilot reuse factor can be used to maximize SE [14]. In low user density, pilot reuse factor can be increased to minimize the interference while as it can be reduced in the high user density so that the full resource is available to the users [15].

1.2 Problem Formulation

From the available literature we observed that, most of the research in this field evaluated the performance of SWIPT enabled massive MIMO system under the assumption that the channel is reciprocal. Not much work is done to understand the impact of channel reciprocity error on the system performance. So, there is a need of future investigation on massive MIMO performance in estimation error i.e, channel reciprocity error.

Also, as the global demand for wireless data traffic is increasing. New technology like IOTs are evolving and around 23 billion device will be internetworked by 2020 also wireless traffic is doubled every two year, so there is an improvement needed in area and data throughput. Hence we considered the following problem for our research work: "Performance Analysis of Energy-Efficient Multi-Cell Massive MIMO System". Our Investigation includes:

- Performances of SWIPT enabled Massive MIMO system like harvested energy, achievable rate in channel reciprocity and channel reciprocity errorr.
- Optimization of area or data throughput by increasing the spectral efficiency of massive MIMO without increasing the bandwidth and cell density.
- Analysis of massive MIMO system performance in various linear precoding scheme like ZF and MR.
- We have also tried to quantify the meaning of massive by deriving the energy efficient regime of massive MIMO.
- Pilot reuse techniques to minimize the pilot contamination and co-channel interference.
- BER performance of Massive MIMO.

We will perform our simulations in MATLAB and use tools from Probability theory and linear algebra to develop theory.

1.3 Organization of the Report

This report is organised as following parts.

- **Chapter ?? A Review on massive MIMO** In this chapter, we will discuss about the basics terminogy related to massive MIMO.
- **Chapter ?? Wireless Channel** In this chapter, we will study about different kind of wireless channel used in wireless communication.
- **Chapter ?? Harvested Energy and Downlink Achievable Rate in Channel Non-Reciprocity** In this chapter, we will discuss about the harvested energy and achievable rate and channel reciprocity error modelling.
- **Chapter ?? Linear Precoding Process** In this chapter we will discuss about the various linear Precoding scheme in the wireless communication and the performance of Massive MIMO system in respective precoding techniques.
- **Chapter ?? Energy Efficiency in Massive MIMO** In this chapter we will try to find the optimal region of massive MIMO which is most energy efficient.
- **Chapter ?? Spectral Efficiency and User Maximization** In this chapter, we will discuss about the various technique to maximize the spectral efficiency and user optimization.
- **Chapter ?? BER Performance of Massive MIMO** In this chapter, we will analyse the bit error rate (BER) performance of massive MIMO.
- **Chapter ?? Conclusion & Future Work** In this chapter, we will discuss about the summary of work done & future direction of this project.

Chapter 2

A Review on Massive MIMO

In this chapter we will briefly review on massive (large scale) MIMO (multiple-input multiple-output) and the basic terminology associated with it. It is a key technology in establishing the 5th Generation wireless communication system.

2.1 Massive MIMO

Massive MIMO system is just equivalent to very large MIMO system, there is hundreds of antennas at the terminals of communication system. Generally, MIMO system have two or four or eight antennas, but this technology is extending the previous MIMO system in vast way. This Massive MIMO also contributed in the area of developments in network technologies with exciting features and advantages. More degree of freedom can be achieved by using large antenna array which enables improvement in performance. The data rate requirement and complexity of device addressing is increasing day by days because of new technologies like Internet of Things (IOTs), For handling this complex and vast requirement of users Massive MIMO provides high reliability and better addressing techniques to the devices. The following advantage that can be achieved using Massive MIMO are as follows:

- High Data Rate: Increasing number of antennas at the terminal provides more number of path of transmission. Thus, a more number of path will provide a better data rate or rich data rate.

- Signal to Noise Ratio: Due to large number of antennas at the base station signal power achieved from the multi antenna system is high due to which Signal to Noise plus interference ratio (SINR) has increased. High SINR leads to the high spectral efficiency, which is one of the major goal of this project. This system is also termed as large diversity.

- Transmission Process: Transmission process in Massive MIMO consiste of uplink and downlink transmission. There is M number of antennas at base station while as

K number of users at user terminal. Simultaneous uplink and downlink transmission is happening. Users exploit energy recieved from the base station in order to do uplink transmission which is wireless informtion transmission to the base station, which is recieved by the receiver of the transceiver system at base station. After estimating the uplink process, downlink transmission is done by base station which is wireless power transfer. The energy received by the user is exploited to do uplink transmission. Beam forming technique is used to send the energy to user in downlink transmission by base station. Since, the transmission range is short, so line of sight signal component is dominant. Uplink transmission is also known as wireless information transfer while as downlink transmission is known as wireless energy transmission.

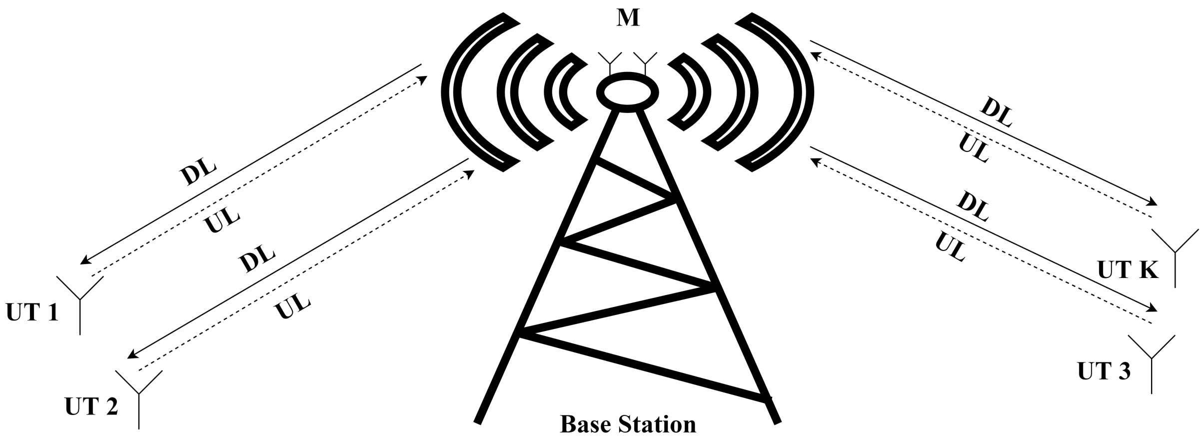

Figure 2.1: A generic Massive MIMO system having M antenna at BS and K UT.

2.2 SWIPT System

It stands for simultaneous wireless information and power transfer. It is the joint uplink and downlink transmission of information and power respectively. If transmission range is quite short, then SWIPT system is more efficient way of transmission. Also it is a multi casting system which can receive and transmit information and energy both simultaneously, which makes the system more efficient. Power splitting device is there in SWIPT systems which divide power efficiently in order to optimize for the decoding information and harvesting energy.

2.3 Channel Reciprocity

Channel Reciprocity: Downlink is estimated by uplink transmission. But the hardware chains in the base station and terminal transceivers may not be reciprocal between the uplink and the downlink. Time Division Duplex operation relies on channel reciprocity.

TDD refers to duplex communication in which uplink and downlink differs in allocation of different time slots in the same frequency band. There appears to be a reasonable that the propagation channel itself is essentially reciprocal, unless the propagation is affected by materials with strange magnetic properties. However, the hardware chains in the base station and terminal transceivers may not be reciprocal between the uplink and the downlink and this is termed as channel non-reciprocity.

Downlink is the wireless energy transfer from base station to user terminal. The users exploit the harvested energy to communicate with the base station on the uplink. Uplink is the wireless information transfer from users to base station. Base station charges the users on the downlink. When downlink is estimated via uplink then it is known as channel estimation i.e, channel is termed as reciprocal. But due to RF mismatch at the transmit and recieve antenna at the base station, there is estimation error that is know as channel reciprocity error.

2.4 Pilot Contamination

Each terminal in a Massive MIMO system is assigned with an orthogonal uplink pilot sequence. The maximum number of orthogonal pilot sequences that can exist is upper-bounded by the duration of the coherence interval divided by the channel delay-spread. For a typical operating scenario, the maximum number of orthogonal pilot sequences in one millisecond coherence interval is estimated to be about 200. It is easy to exhaust the available supply of orthogonal pilot sequences in a multi-cellular system. The effect of re-using pilots from one cell to another, and the associated negative consequences, is termed as “pilot contamination”.

Pilot contamination occurs when two terminals use the same pilot sequence (also known as reference signal). It can be suppressed by using different pilots in adjacent cells - for example, by having a large number of pilots sequences and switching randomly between them. Conventional systems can afford to have many more pilot sequences than active terminals, which makes the risk of pilot ”collision” rather small. In contrast, massive MIMO cannot afford that since it is supposed to have 20-40 times more active terminals on the same time/frequency resource than conventional systems. Simply speaking, if you have 30x more terminals the pilot contamination will be 30x more severe.

2.5 Time Division Duplexing

We need a pilot signal for Channel state information (CSI) estimation , but there are two problems : First, optimal downlink pilots should be mutually orthogonal between the antennas and Second, the number of channel responses that each terminal must estimate is also proportional to the number of base station antennas. The solution is to operate in TDD mode which rely on reciprocity between the uplink and downlink channels. Estimation lies in TDD mode only, as we get information in uplink in frequency band then you need to do downlink estimation in same frequency band. Here, uplink estimate is useful for downlink. TDD is typically considered as more spectrum-efficient and better suited for bursty data services.

In frequency division duplex (FDD) mode the bandwidth is split into two separate parts: one for the uplink and one for the downlink. In time-division duplex mode where the whole bandwidth is used for both downlink and uplink transmission. Hence, TDD is the preferable mode since it not only requires shorter pilots than FDD, but is also highly scalable since the pilot length is independent of the number of BS antennas.

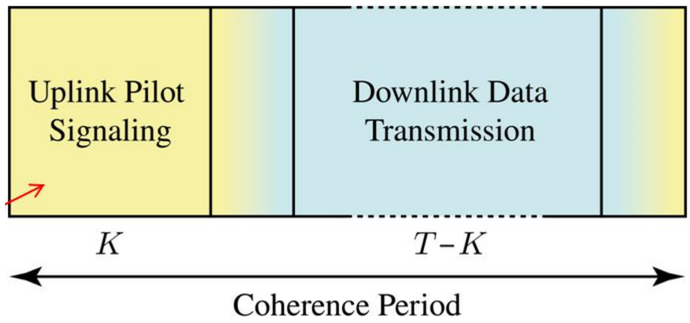

Figure 2.2: Time Division Duplex (TDD) protocol

2.6 Area Throughput

To keep up with the rapid increasing traffic growth, a key goal of the 5G technologies is to improve the area throughput by orders of magnitude 100 times and even 1000 times higher throughput, are regularly mentioned as 5G design goals.

$$AT(bits/s/km^2) = BW(Hz) * CD(cells/km^2) * SE(bits/s/Hz/Cell) \tag{2.1}$$

Here, area throughput is denoted as AT, bandwidth is denoted as BW and cell density is denoted as CD and spectral efficiency is denoted as SE. This simple formula reveals that there are three main components that can be improved to yield higher area throughput:

- More bandwidth can be allocated for 5G services.
- The network can be densified by adding more cells with independently operating access points.
- The efficiency of the data transmissions (per cell and for a given amount of bandwidth) can be improved.

The improvements in area throughput in previous network generations have greatly resulted from cell densification and allocation of more bandwidth. The spectral efficiency has not seen any major improvements in previous network generations. Hence, it might be a factor that can be greatly improved in the future and possibly become the primary way to achieve high area throughput in 5G networks. Spectral efficiency usually is expressed as “bits per second per hertz,” or bits/s/Hz. In other words, it can be defined as the net data rate in bits per second (bps) divided by the bandwidth in hertz. Net data rate and symbol rate are related to the raw data rate which includes the usable payload and all overhead. We will use diffrent precoding algoritm to increase the Spectral efficiency of the system.

2.7 Pilot Reuse Factor

Consider a classic cellular network topology with hexagonal cells as shown in Figure 2.4. a and b which is representing downlink and uplink respectively.

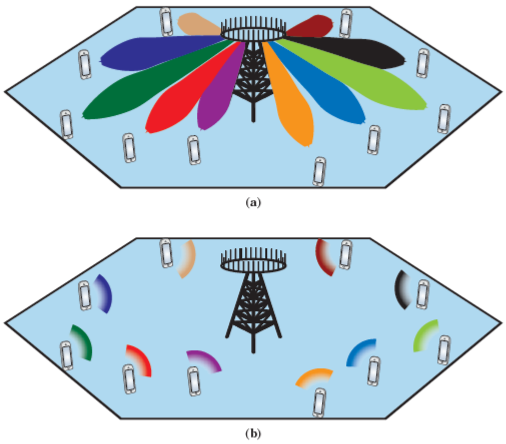

Figure 2.3: Hexagonal cells in Massive MIMO (a) Downlink in multiuser MIMO. (b) Uplink in multi-user MIMO

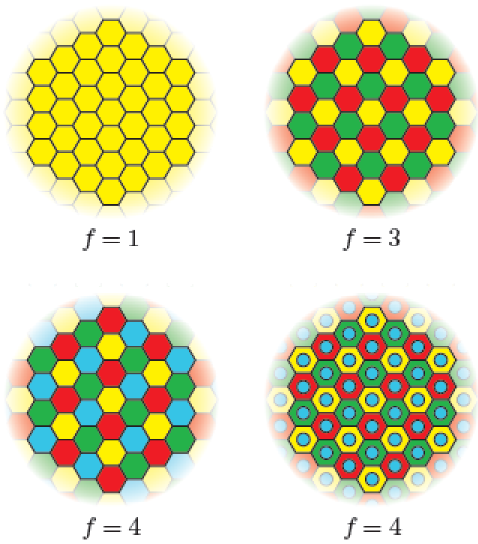

Figure 2.4: Reuse patterns created by three different pilot reuse factors and In the lower right case, each cell is divided into two sub-cells with different sets of pilots.

Only the cells with the same color use the same pilot sequences, and thereby cause pilot contaminated interference. In the lower right case, each cell is divided into two sub-cells with different sets of pilots. There is no contamination between cells with different colors.

2.8 Summary

In this chapter, we have discussed the basics of massive MIMO communication system. We can operate only in TDD mode if we are going to estimate the uplink via downlink. Joint information and power transfer simultaneously increase the spectral efficiency of the system. Data throughput is needed to be increased to fulfill the demand of growing wireless traffic.

Chapter 3

Wireless Channel

In this chapter, we will discuss about the wireless channels and we will see which channel is most suitable for SWIPT enabled massive MIMO system,

3.1 Rayleigh Fading Channel

The Rayleigh fading model uses a statistical approach to analyse the propagation, and can be used in a number of environments. The Rayleigh fading model is ideally suited to situations where there are large numbers of signal paths and reflections. Typical scenarios include cellular telecommunications where there are large number of reflections from buildings. Rayleigh fading is a reasonable model when there are many objects in the environment that scatter the radio signal before it arrives at the receiver. The central limit theorem holds that, if there is sufficiently much scatter, the channel impulse response will be well-modelled as a Gaussian process irrespective of the distribution of the individual components. If there is no dominant component to the scatter, then such a process will have zero mean and phase evenly distributed between 0 and 2π radians. The envelope of the channel response will therefore be Rayleigh distributed.

In mobile channels the Rayleigh distribution is commonly used to describe statistical time varying nature of the recieved envelope of a fading wireless channel. The probability density function of Rayleigh distribution can be expressed as [16]:

$$F_A(a) = \begin{cases} -2ae^{-a^2} & 0 \leq a < \infty \\ 0 & otherwise \end{cases} \tag{3.1}$$

i.e,

$$F_A(a) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} & 0 \leq r < \infty \\ 0 & otherwise \end{cases} \tag{3.2}$$

where σ^2 is the time average power of the recieved signal before the envelope detection. The probability that the envelope of Rayleigh distribution does not exceed a fixed amplitude ‘R’.

$$P(r \leq R) = 1 - e^{-\frac{R^2}{2\sigma^2}} \tag{3.3}$$

The mean value of the Rayleigh distribution is:

$$E[r] = \sigma\sqrt{\frac{\pi}{2}} = 1.2533\sigma \tag{3.4}$$

The variance of the Rayleigh distribution is:

$$E[r^2] = 0.4292\sigma^2 \tag{3.5}$$

But Rayleigh fading channel is used mainly when non line of sight path transmission is more.

3.2 Rician Fading Channel

When there is dominant line of sight propagation path present, the small scale fading envelope distribution is Rician. In this case random multipath component arriving at different angle superimposed on a stationary dominant signal. If the dominant signal becomes weaker the composite signal has an envelope that is Rayleigh. Thus, the Rician distribution degenerates to a Rayleigh distribution when the dominant component fades away. The model behind Rician fading is similar to that for Rayleigh fading, except that in Rician fading a strong dominant component is present. This dominant component can for instance be the line-of-sight signal.
The probability density function of the Rician fading distribution can be expressed as [16]:

$$F_R(r) = \begin{cases} \frac{r}{\sigma^2} e^{-(\frac{r^2+A^2}{2\sigma^2}) I_o(\frac{Ar}{\sigma^2})} & 0 \leq r < \infty, A \geq 0 \\ 0 & otherwise \end{cases} \tag{3.6}$$

Where A is the peak amplitude of the dominant signal. $I_o()$ is the modified bessel function of the first kind and zeroth order.
The Rician distribution can also be described in terms of parameter 'K' which is called as Rician factor.

$$K = \frac{Deterministic \quad signal \quad power}{Variance \quad of \quad the \quad multipath \quad envelope} \tag{3.7}$$

$$K = \frac{A^2}{2\sigma^2} \tag{3.8}$$

$$K_{dB} = 10log(\frac{A^2}{2\sigma^2}) \tag{3.9}$$

As the Rician factor K becomes 0 then Rician distribution degenerates to a Rayleigh distribution. In this project transmission range is very short in SWIPT system, thus the line of sigh propagation is dominant. Hence, we will use Rician fading channel.

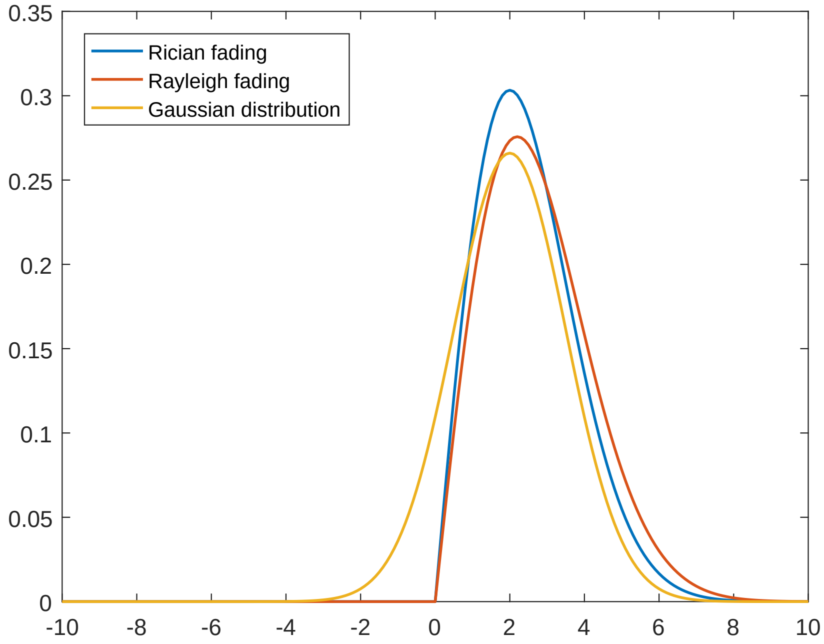

Figure 3.1: Rician, Rayleigh and Gaussian distribution

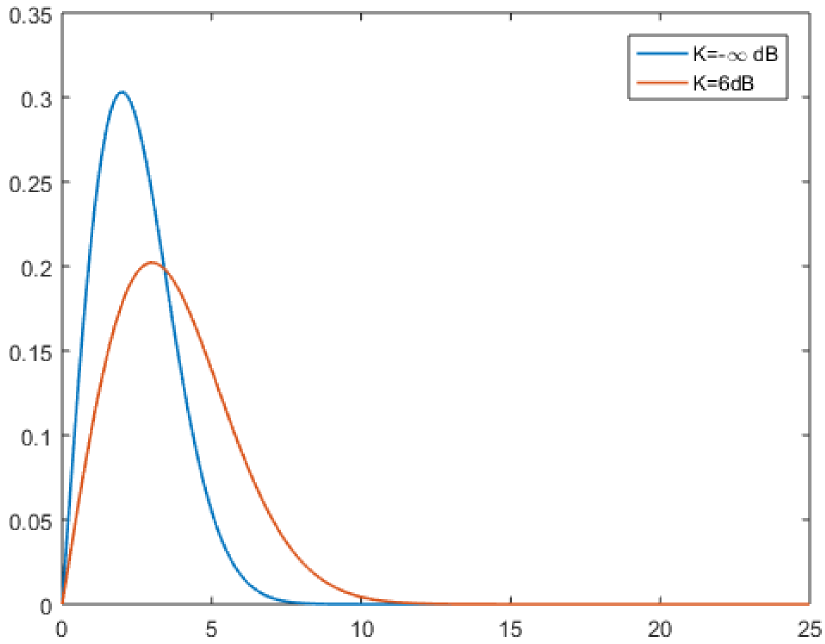

Figure 3.2: Rician distribution for different value of rician factor K

In Figure 3.1, probability distribution function of Gaussian distribution, Rayleigh distribution, Rician distribution is shown. Rayleigh and Rician starts after zero. In Figure 3.2, Rician distribution is plotted for different Rician factors for $K = \infty dB$ and $K = 6dB$. when K vanishes means equal to zero then Rician distribution degenerates to Rayleigh distribution.

3.3 Summary

We have seen important types of channels used in wireless communication. For short range LOS signal component, Rician fading channel is more efficient than Rayleigh fading channel.

Chapter 4

Harvested Energy and Downlink Achievable Rate in Channel Non-Reciprocity

In this chapter, we will derive the harvested energy and achievable rate and channel reciprocity error modelling.

4.1 Introduction

Massive MIMO is a multiple input multiple output technology for enabling the 5th generation wireless communication system. A very large number of antenna array is present at the base station and the user terminal.

4.2 System Model

We considered a multi user massive MIMO system having M number of BS antenna and K users at user terminal ($M >> K$). The total area of coverage is divided into number of cells. Hexagonal cells which is very near to a circle is used to distribute the users. In a coherrent interval time T, τT ($\tau < 1$) of time is used for training of channel and remaining $(1 - \tau T)$ is used for information and power transmission. In FDD downlink and uplink is simultaneously happening with having a extra guard bandwidth separated in between which results in loss of bandwidth. TDD mode is acceptable because of the reciprocity of the system. In TDD the whole bandwidth is used for downlink and uplink transmission. Hence, TDD is the preferable mode since it not only requires the shorter pilot than FDD but also highly scalable as the pilot length is independent of M.

Channel Matrix: Since, the transmission range is quite short in massive MIMO system, there is dominant line of sight propagation present, the small scale fading envelope distribution is Rician. The pdf of Rician fading can be expressed as:

$$F_R(r) = \begin{cases} \frac{r}{\sigma^2} e^{-(\frac{r^2+A^2}{2\sigma^2}) I_o(\frac{Ar}{\sigma^2})} & 0 \leq r < \infty, A \geq 0 \\ 0 & otherwise \end{cases} \tag{4.1}$$

Where A is the peak amplitude of the dominant signal. $I_o()$ is the modified bessel function of the first kind and zeroth order.
The Rician distribution can also be described in terms of parameter 'K' which is called as Rician factor which is the ratio of deterministic signal power and variance of the multipath envelope.

$$K_{dB} = 10log(\frac{A^2}{2\sigma^2}) \tag{4.2}$$

The channel vector between BS and k-th user is given as:

$$\vec{h}_k = \sqrt{\frac{\beta K}{K+1}}\vec{A} + \sqrt{\frac{\beta}{K+1}}\vec{Z} \tag{4.3}$$

Here, $\beta = Cd^{-\alpha}$ is the large scale fading depend on the distance d between BS and user. $\vec{A}$ denotes the deterministic signal component, $\vec{Z} \sim \mathcal{N}(0_M, I_M)$ denotes the random component of the k-th user.

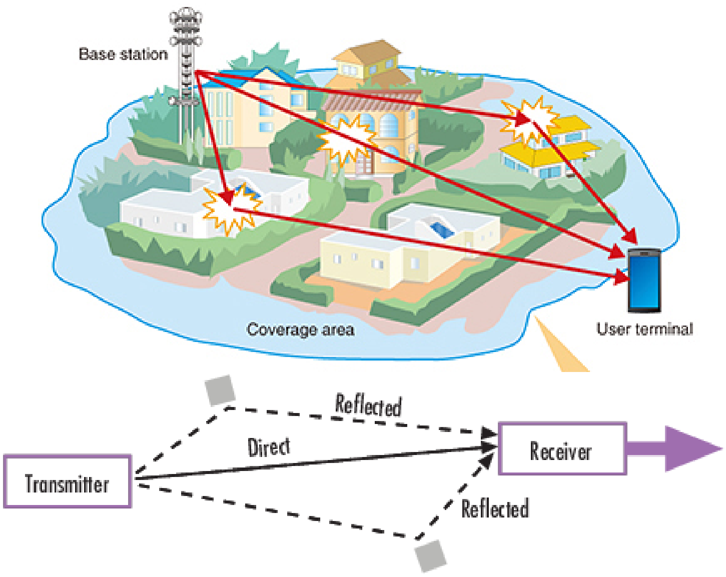

Figure 4.1: Rician channel having LOS dominant component and NLOS as scattered component

4.3 Channel Reciprocity Error Modelling

Due to the fact that the imperfection of the channel reciprocity affect the system performance which occurs due to the RF mismatch in the transceiver at the BS, we focus on the reciprocity error at the BS. The effective response of the transmit antenna at the BS is given by H_t as follows:

$$\vec{H}_t = diag(h_{t,1}, h_{t,2}, h_{t,3}, \dots, h_{t,m}, \dots, h_{t,M}) \tag{4.4}$$

where, $h_{t,m}$ represents the effective response of the m_{th} transmit antenna at the BS. (The subscript t is for the transmitter end of the transceiver at the BS). Mathematically,

$$h_{t,m} = A_{t,m}e^{j\phi_{t,m}} \tag{4.5}$$

$A_{t,m}$ represents the amplitude response and $\phi_{t,m}$ represents the phase response of the m_{th} transmitt antenna at the BS. $A_{t,m}$ and $\phi_{t,m}$ are truncated Gaussian distribution, since it is more realistic in comparision to the uniformly distributed model and the negligible power component is ignored. The amplitude and phase error is given by truncated gaussian as:

$$A_{t,m} \sim \mathcal{NT}(0, \sigma^2)\ , A_{t,m} \in [a, b]$$

$$\phi_{t,m} \sim \mathcal{NT}(0, \sigma^2)\ , \phi_{t,m} \in [\theta_1, \theta_2]$$

The effective response of the receive antenna of the transceiver at the BS is given by H_r as follows:

$$\vec{H}_r = diag(h_{r,1}, h_{r,2}, h_{r,3}, \dots, h_{r,m}, \dots, h_{r,M}) \tag{4.6}$$

where, $h_{r,m}$ represents the response of the m_{th} receive antenna of the transceiver at the BS. (The subscript r is for the receiver end of the transceiver at the BS). Mathematically,

$$h_{r,m} = A_{r,m}e^{j\phi_{i,m}} \tag{4.7}$$

$A_{r,m}$ represents the amplitude response and $\phi_{r,m}$ represents the phase response of the m_{th} receive antenna at the BS. We have taken $A_{r,m}$ and $\phi_{r,m}$ as truncated Gaussian distribution and ignored the negligible power component. The amplitude and phase error of receiver of the transceiver at the BS is given by truncated gaussian distribution as:

$$A_{r,m} \sim \mathcal{NT}(0, \sigma^2)\ , A_{r,m} \in [a, b]$$

$$\phi_{r,m} \sim \mathcal{NT}(0, \sigma^2)\ , \phi_{r,m} \in [\theta_1, \theta_2]$$

Thus, the reciprocity error matrix is given as:

$$\vec{E}_r = \vec{H}_t\vec{H}_r^{-1} = diag(\frac{h_{t,1}}{h_{r,1}} \dots \frac{h_{t,m}}{h_{r,m}} \dots \frac{h_{t,M}}{h_{r,M}}) \tag{4.8}$$

The channel matrix after considering the reciprocity error i.e, effective channel response is given as:

$$\vec{H}_{ij} = [diag(\vec{h}_k)]\vec{E}_r = [\vec{H}_k]\vec{E}_r \tag{4.9}$$

When, $\vec{E}_r = 1$ i.e, ($\vec{H}_{it} = \vec{H}_{ir}$) then the channel is completely reciprocal i.e, downlink is estimated via uplink transmission.

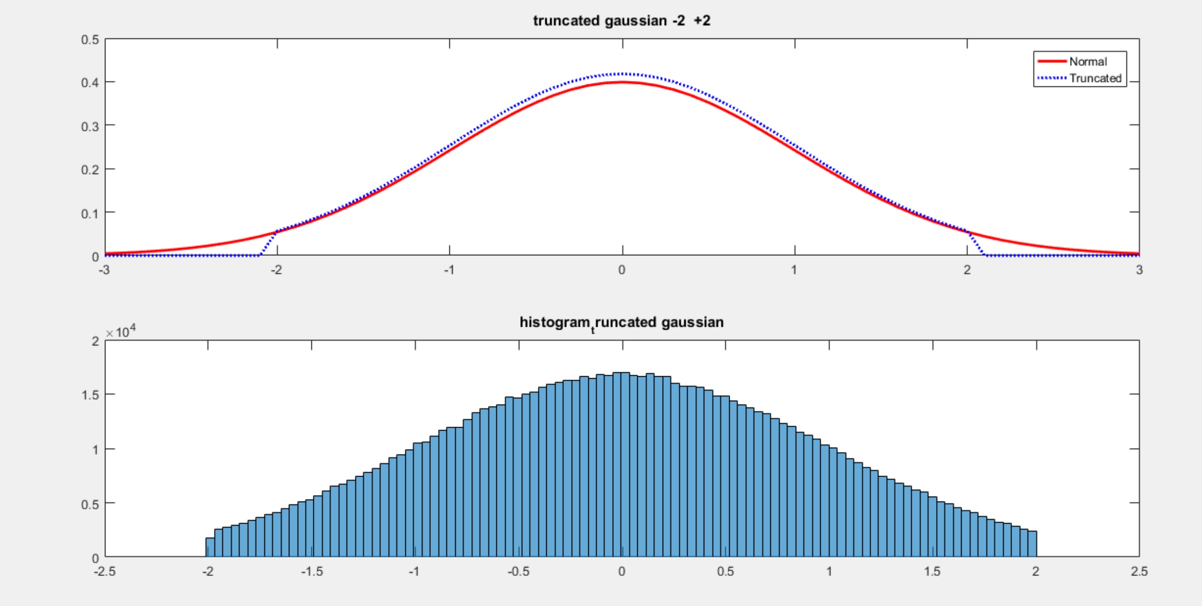

Figure 4.2: The truncated Gaussian distribution model of the phase and amplitude error

4.4 Uplink Channel Estimation

A mutually orthogonal pilot sequence vector each of length L_p, is assigned randomly to all the users for uplink pilot transmission to the BS. The pilot sequence matrix is of the size $L_p \times K$. The estimated channel of $\vec{h}_k$ after the minimum mean square error (MMSE) estimation is $\hat{\vec{h}}_k$ that minimizes the mean square error (MSE) i.e, $\vec{E}||\ \vec{h}_k - \hat{\vec{h}}_k\ ||^2$ is minimum. The uplink estimated channel vector is represented as:

$$\hat{\vec{h}}_k = \sqrt{zK}\vec{A} + \left(\frac{z\sqrt{p_L L_p}}{zp_L L_p + \sigma^2}\right)(\sqrt{zp_L L_p}\vec{Z} + \vec{n_k}\phi_k) \tag{4.10}$$

where, $z = \frac{\beta}{K+1}$, $\vec{n}_k \sim \mathcal{CN}(\mu, \sigma^2)$ is a independent and identical complex gaussain noise, $\phi_k \sim \mathcal{CN}(\mu, \sigma^2)$ represent the pilot signal transmitted in uplink by the k_{th} user and p_L represent the power of the transmitted pilot signal by k_{th} user.

4.5 Downlink Information and Energy Transmission

In downlink transmission, information signal and power is transmitted to the user k. The information signal transmitted to k_{th} user is denoted as x_k. The signal $\vec{y}_k$ received at k_{th} user is denoted as:

$$\vec{y}_k = \underbrace{\sqrt{p_k}\vec{h}_k^H\vec{w}_{lk}x_k}_{\text{desired signal}} + \underbrace{\sum_{j\neq k}^{K}\sqrt{p_j}\vec{h}_k^H\vec{w}_{lk}x_j}_{\text{interference signal}} + \underbrace{\vec{n}_k}_{\text{noise signal}} \tag{4.11}$$

where p_k represent the transmitted power and $\vec{w}_{lk}$represents the linear precoding vector of the k_{th} user. While using ZF precoding matrix $(\vec{w}_{lkZF}) = \vec{H}^{\dagger} = \vec{H}^{\dagger} = (\vec{H}^H\vec{H})^{-1}\vec{H}^H$ for the received signal $(\vec{w}_{lkZF})\vec{y} = x + \vec{w}_{lkZF}\vec{n}_k$. Thus, the ZF precoding amplify noise and it is ideal for the noiseless system. Precoding vector for ZF is given as:

$$\vec{w}_{lkZF} = \frac{\hat{\vec{H}}^{\dagger}}{\sqrt{\vec{E} || \ \vec{H}^{\dagger} \ ||^2}} \tag{4.12}$$

Precoding vector for MR is given as:

$$\vec{w}_{lkMR} = \frac{\hat{h_k}}{\sqrt{\vec{E} || \ \hat{h_k} \ ||^2}} \tag{4.13}$$

n_k is complex additive white Gaussian noise $\vec{n}_k \sim \mathcal{N}(0,1)$. ρ_k fraction of received power is used for the decoding information while as remaining fraction $(1 - \rho_k)$ is used for harvesting energy. The energy harvested by the k_{th} user is given as:

$$E_k = \eta_k \vec{E}[| \ h_k^H \sum_{t=1}^{K} p_t w_{lk} \ |^2] \tag{4.14}$$

Here, η_k is the conversion efficiency at the UT.

4.6 SINR and Achievable Rate

Achievable rate depends on the signal-to-interference-plus-noise ratio (SINR). Spectrum efficiency is the efficient use of bandwidth so that the maximum amount of data can be transmitted with minimize errors. Spectral efficiency which is measured in bits/s/Hz per unit area or bits/s/Hz/cell is upper bounded by the Shanon capacity or achievable rate i.e, $(1 - \tau) \times log_2(1 + SINR)$. ρ_k is the fraction of power used for the decoding information. SINR is given as:

$$SINR = \frac{\rho_k p_k \vec{E}(| \ \vec{h}_k^H \vec{w}_{lk} x_k \ |^2)}{\vec{E} \ | \sum_{j \neq k}^{K} \sqrt{p}_j \vec{h}_k^H \vec{w}_{lk} x_j) \ |^2 + \sigma_n^2} \tag{4.15}$$

The Achievable Rate (bits/s/Hz) of the k_{th} user is given as:

$$R = (1 - \tau) log_2 \left(1 + \frac{\rho_k p_k \vec{E}(| \ \vec{h}_k^H \vec{w}_{lk} x_k \ |^2)}{\vec{E} \ | \sum_{j \neq k}^{K} \sqrt{p}_j \vec{h}_k^H \vec{w}_{lk} x_j) \ |^2 + \sigma_n^2} \right) \tag{4.16}$$

4.7 Simulation Results and Discussion

We have evaluated the performance of massive MIMO system like harvested energy and achievable rate by our simulated results in MATLAB. In our system we varied the number of antenna at BS and user upto few hundreds in order to quantify the efficient number of BS antennas and multi users at UT. The SINR is taken as 20dB, coherence time $\tau_c = 600ms$. The pilot length L_p equals to K. Power splitter coefficient (ρ_k) is taken in between 0.4 to 0.6.

4.7.1 Harvested Energy

The average harvested energy result also indicate that the amount of the harvested energy increases with the number of antennas at BS as shown in Figure 4.3. The harvested energy is simulated for different values of amplitude error in channel estimation with having power 1dB, 4dB, 6dB and 8dB and it is seen that the energy exploited by user is decreasing with the increase in the power of the amplitude of the channel reciprocity error modelling.

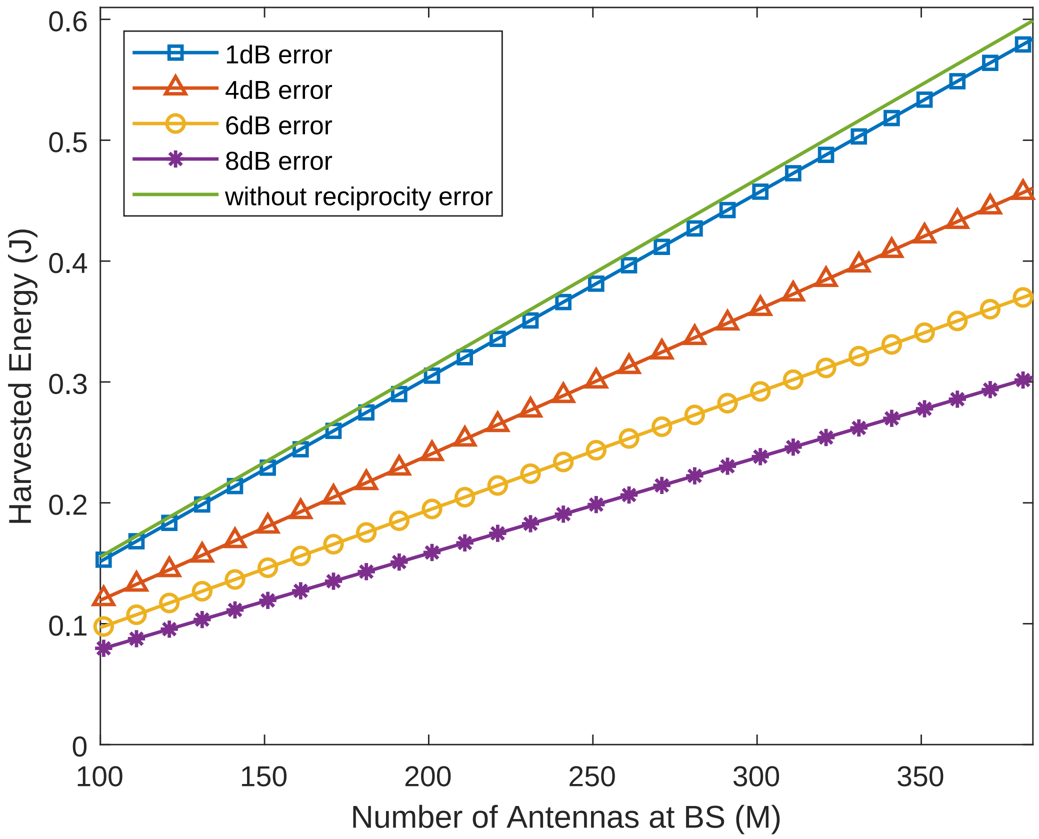

Figure 4.3: Average harvested energy versus number of antennas at BS for different values of reciprocity error amplitude.

4.7.2 Achievable Rate

It is seen in Figure 4.4, that the achievable rate is increasing with increase in number of antennas at BS and the curve getting constant after some instant. So, increasing the number of antenna too much also is not efficient as the rate getting constant after $M = 350$. Also the rate performance is affected due to reciprocity error and it is decreased.

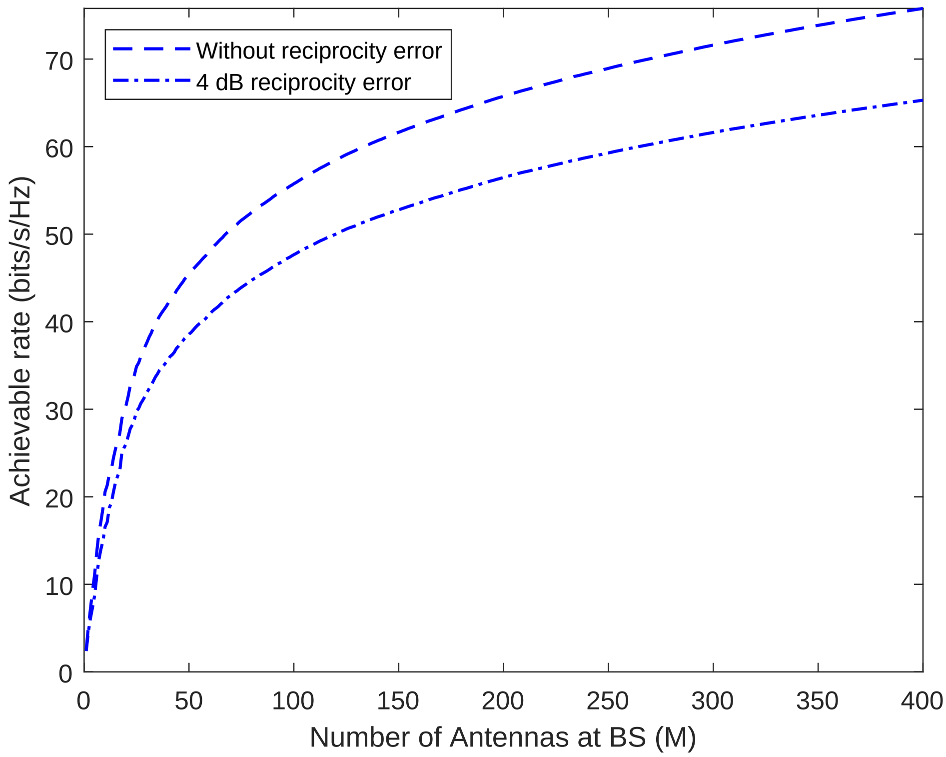

Figure 4.4: Average achievable rate versus number of antennas at BS.

4.8 Summary

In this chapter, we discussed about the Massive MIMO system model and the Rician fading channel in the reciprocity error. Rician channel having line of sight dominant component and non-LOS as scattered component. The phase and amplitude errors in channel estimation is modelled by the truncated Gaussian distribution. We found the harvested energy, signal to interference and noise ratio and achievable rate for different amplitude error in channel reciprocity error and simulated the same in matlab. It is noted that channel reciprocity error reduced the performance of the system.

Chapter 5

Linear Precoding Process

In this chapter we will discuss about the various linear precoding scheme in the wireless communication and the performance of Massive MIMO system in respective precoding techniques.

5.1 Zero-Forcing

Zero-forcing precoding is a method of spatial signal processing by which the multiple antenna transmitter can null multiuser interference signals in wireless communications. Regularized zero-forcing precoding is enhanced processing to consider the impact on a background noise and unknown user interference, where the background noise and the unknown user interference can be emphasized in the result of known interference signal nulling. Zero Forcing Equalizer refers to a form of linear equalization algorithm used in communication systems which applies the inverse of the frequency response of the channel. However, when the channel is noisy, the zero-forcing will amplify the noise greatly.The zero-forcing is ideal when the channel is noiseless.
The recieved signal is represented as:

$$Y = HX + n \tag{5.1}$$

Here, Y is the recieved signal, X is the desired signal, H is the channel matrix and n is the noise signal. When the number of base station antenna M is different than the number of user K, then we need to obtain the pseudo inverse of channel matrix H, which is given as:

$$Pinv(H) = H^{\dagger} = (H^H H)^{-1} H^H \tag{5.2}$$

$$H^{\dagger} Y = X + H^{\dagger} n \tag{5.3}$$

5.2 Maximum Ratio Transmission

Maximal ratio transmission only maximizes the signal gain at the intended user. MRT is close-to-optimal in noise-limited systems, where the inter-user interference is negligible compared to the noise. Maximal ratio combining (MRC) is a type of receive diversity technique where multiple received signals are combined, thus improving sensitivity. The optimal combining weight vector is used to effectively raise the SNR level of the recieved signal is given as:

$$\bar{w} = \frac{\bar{h}}{\|\bar{h}\|} \tag{5.4}$$

Here, $\bar{w}$ is the optimal combining weight vector, h is the channel vector and this technique of maximizing SNR is maxmimal ratio combiner.

5.3 Minimum Mean Square Error

Minimum mean square error (MMSE) estimator is an estimation method which minimizes the mean square error. it doesn't enhance noise. The desired signal in MMSE with respect to estimated signal is given as:

$$\hat{X} = \bar{E}^T \hat{Y} \tag{5.5}$$

minimize:

$$E\|(\hat{x} - x)^2\| \tag{5.6}$$

Here, $\hat{x}$ is the estimation of desired signal and E is the minimum mean square error of estimated signal with respect to the desired signal.

5.4 Simulation Results and Discussion:

We have evaluated the spectral efficiency versus number of base station antennas in different linear precoding process i.e, maximum ratio precoding and zero forcing precoding.

5.4.1 Spectral Efficiency in MR Precoding

In Figure 5.1, spectral efficiency for different number of base station antenna is plotted by using MR precoding algorithm. MR precoding estimates better with respect to perfect CSI. Simulation result shows that TDD mode is having better performance than FDD mode. In TDD, pilot sequence is independent of the number of antenna at BS and all the available resource is used in communication process divided in time slots. In FDD, frequency is divided in between different users at the same time, so by increasing more number of BS antenna will not improve the spectral efficiency of the system, as there will be simultaneous communication between transmitter and receiver. So, after the minimum of pilot length sequence (L_p) and BS antenna (M), the spectral efficiency gets constant in FDD.

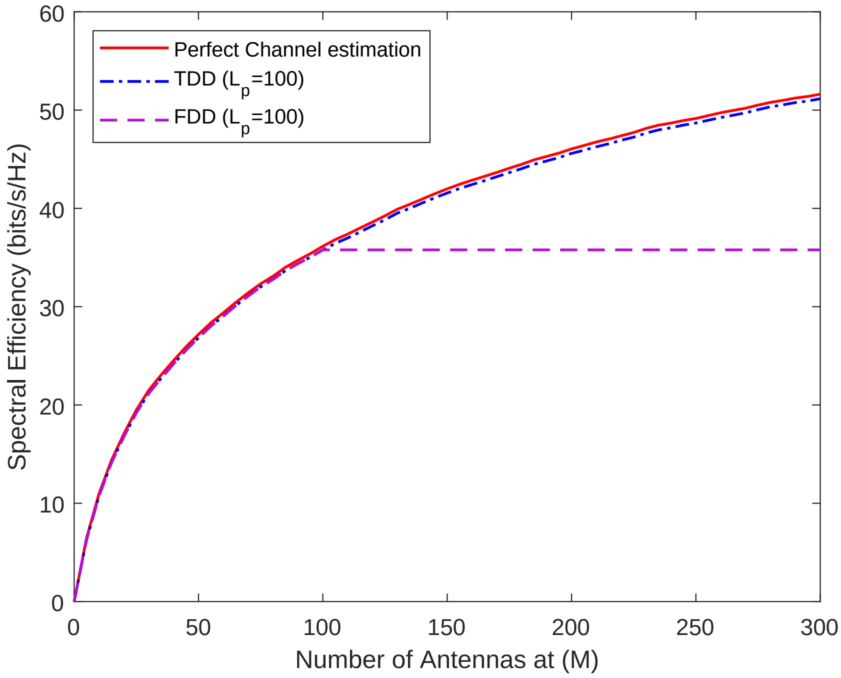

Figure 5.1: Average downlink spectral efficiency versus number of BS antennas is plotted with maximum ratio precoding ($L_p = 100$).

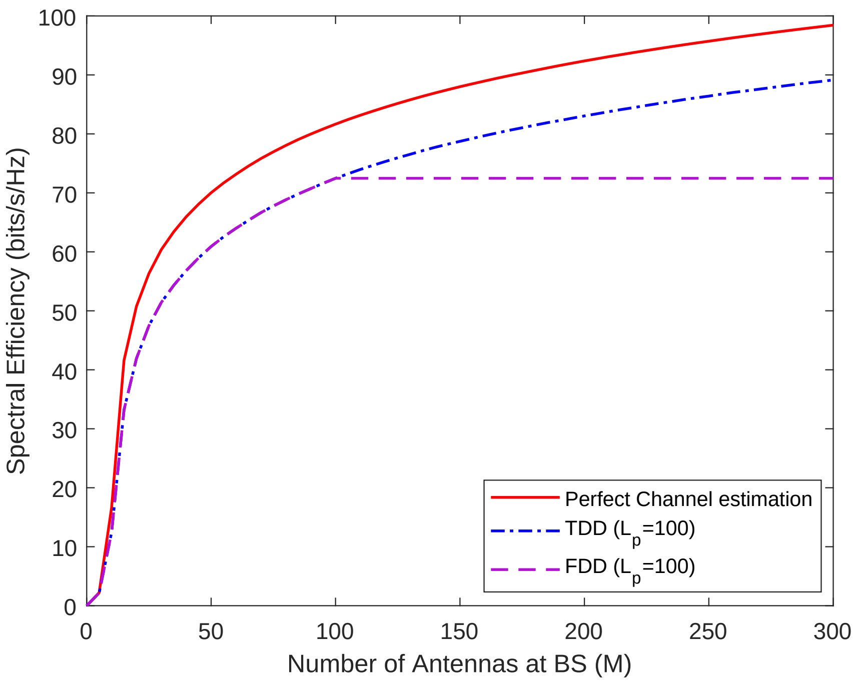

Figure 5.2: Average downlink spectral efficiency versus number of BS antennas is plotted with zero forcing precoding ($L_p = 100$).

5.4.2 Spectral Efficiency in ZF Precoding

In Figure 5.2, spectral efficiency for different number of base station antenna is plotted for ZF precoding algorithm. It is seen that spectral efficiency performance has increased in ZF than MR precoding because Massive MIMO is noiseless communication system. Thus, the noise amplification in zero-forcing is negligible. But, ZF precoding is not the better estimate with respect to perfect channel state information. Hence, ZF precoding is preferred over MR precoding in noiseless communication system for the enhanced performance.

5.5 Summary

The performance of Massive MIMO in various linear precoding algorithm were analyzed. It is observed in the simulated results that zero-forcing give better performance and maximum ratio precoding gives better estimate with respect to perfect channel state information. TDD mode is preferred over FDD mode as the pilot length sequence in TDD mode doesn't depends on the number of base station antenna.

Chapter 6

Energy Efficiency in Massive MIMO

In this chapter we will try to find the optimal region of massive MIMO which is most energy efficient.

6.1 Circuitry Power Consumption

the required transmit power to support a target achievable rate is inversely proportional to the number of antennas in massive multiple-input multiple-output (MIMO) systems..

Circuitry power consumption is the power consumed by the antenna circuit at the base station. However, the consumed power of the massive MIMO systems should not include only the transmit power but also the circuit power consumption which is the fundamental power for operating the circuit at the transmitter, because the effect of circuit power consumption is more serious when the transmitter is equipped with massive number of antennas. For the exact power consumption of massive MIMO systems, we need to investigate the energy efficiency for multiple cellular systems with large-scale antenna arrays under a consideration of circuit power consumption of each antenna. As the number of antenna increases power consumption will increase. Circuitry power consumption is directly proportional to the number of antenna at BS. The equation of circuitry power consumption is given as:

$$P = P_{TX} + P_c \tag{6.1}$$

Here P_{TX} represent the transmit power consumption while as P_c represent the circuit power consumption.

$$P_{TX} = \frac{P_{dl}}{\eta_{BS}} = \frac{\alpha_{WET}\rho_{dl}B}{\eta_{BS}} \tag{6.2}$$

where, $\eta_{BS} \in (0, 1)$ denotes the BS PA efficiency. Note that the uplink transmit power, which is a fraction of the average harvested power, only appears in the numerator (via the expression for the achievable rate R). This is because the energy harvesting users do not have any power source except for the wireless energy delivered by the BS.
we allow the circuit power consumption P_c to scale with the key parameters such as M

and K: P_{FIX} lumps the fixed power spent on running the BS.
P_{BS} models the circuit power consumed by the antenna circuitry. Let us use δ_{BS} to denote the BS computational efficiency in flops/watt, and recall that there are $\frac{B}{S}$ coherence blocks per second.
Then, $P_{CE} = \frac{2MK^2B}{S\delta_{BS}}$ models the power consumed while computing the channel estimates on the uplink during each coherence block (includes the power consumed in multiplying an $M \times K$ received pilot signal with a length K pilot sequence for each of the K users.
P_{LP} accounts for the power consumption due to linear processing at the BS, i.e., for computing the downlink energy beamformer ($\frac{3MKB}{S\delta_{BS}}$) once per coherence block, and for evaluating a matrix-vector multiplication for each data symbol ($\frac{2\alpha_{WIT}MKB}{\delta_{BS}}$).
Finally, $P_{DEC}KR$ models the power consumed in decoding the received data, where P_{DEC} parameterizes the decoder power consumption (in W/bit/s) at the BS. We note that the computational power consumption is usually negligible compared to the antenna power consumption in the large-antenna regime.

$$where, \quad P_{TX} + P_c = P_{TX} + P_{FIX} + MP_{BS} + P_{CE} + P_{LP} + P_{DEC}KR \tag{6.3}$$

where P_{TX} and P_c respectively denote the total average transmit power consumption (in watts) and the total average circuit power consumption (in watts) at the BS. In particular,

6.2 Energy Efficiency

Energy efficiency has been a key consideration in the system-level analysis of massive MIMO systems. Energy efficiency is simply achievable rate per unit power consumption at the base station. Its unit is bits/sec/joule. The power consumed is in the form of circuitry power consumption and transmitted power. The circuit power consumption includes, the computational power, $P_c = \frac{2MK^2B}{S\eta_{BS}}$. η_{BS} is the computational efficiency, it is measured is flops/watt and $\frac{B}{S}$ is coherence block per second. KRP_d is the power consumed in decoding the received data, R is an user average achievable rate and P_d is the power consumption by the decoder. P_l is the power consumed in the linear precoding process at BS for ZF processing power consumed is $\left(\frac{B(\frac{K^3}{3}+3MK^2+MK)}{S\eta_{BS}}\right)$. Energy efficiency is given as:

$$EE = \frac{(1-\tau)log_2\left(1 + \frac{\rho_k p_k \vec{E}(|\vec{h}_k^H \vec{w}_{lk} x_k|^2)}{\vec{E}|\sum_{t\neq k}^{K} \sqrt{p}_j \vec{h}_k^H \vec{w}_{lk} x_j)|^2 + \sigma_n^2}\right)}{KRP_d + \frac{2MK^2B}{S\eta_{BS}} + \left(\frac{B(\frac{K^3}{3}+3MK^2+MK)}{S\eta_{BS}}\right) + P_f} \tag{6.4}$$

Here, P_f is the fixed power consumption in deploying antenna at BS. In [6] marzetta tried to analyse the performance of massive MIMO in unlimited number of antennas, anywat unlimited number of antenna is not possible in this finite world. With the increase of antenna at BS power transmitted and energy harvested will increase linearly. But, the cost of deploying such base antenna and circuit power will increase which will give less energy efficient system. Here we tried to find the meaning of Massinve in Figure 5.1, we concluded that massive MIMO regime is around 300-400 antenna array at base station.

After that increasing more numbber of antennas at BS will lead to less energy efficient and complex system. By inceasing number of antenna at BS, massive MIMO performance can be enhanced but there is some limit which is bounded by energy efficiency. By increasing the number of antenna at BS, the deploying cost and circuit power consumption will increase which will give less energy efficient system as the achievable rate getting constant after some instant. Here we tried to quantify the meaning of massive.

6.3 Power Splitter

In SWIPT system franction of recieved power P_s is used for decoding information and remaining $(1 - P_s)$ is for harvesting energy. So, as P_s will increase harvesting energy will decrease at $P_s = 1$, harvesting energy will become zero and achievable rate will be maximum and at $P_s = 0$, HE will be maximum and Achievable rate will become zero. At around $P_s = 0.50 - 0.60$ system is more efficient and joint transfer of power and information is maximum. Hence, the power splitter coefficient P_s is directly proportional to the information transfer or achievable rate and it is inversely proportional to the harvested energy.

$$P_s \propto Information \quad transfer \tag{6.5}$$

$$P_s \propto \frac{1}{HE} \tag{6.6}$$

6.4 Simulation Results and Discussion

We have simulated the energy efficiency curve for the Massive MIMO vs number of antennas at the base station. Also, the variation of power splitter with respect to harvested energy and achievable rate.

6.4.1 Energy Efficiency

In Figure 6.1, we concluded that massive MIMO regime is around few hundreds (300-400) of antenna array at base station. After that by increasing more number of antennas at BS will lead to the less energy efficient and complex system. As achievable rate getting constant after Massive MIMO regime and power consumption increases which is dependent on the number of antennas at base station. Hence, the energy efficiency decreases after that.

6.4.2 Power Splitter

In Figure 6.4, to get the efficient fraction of power recieved used for harvesting energy and decoding information. It is seen that at $P_s = 0.53$ curve is intersecting, i.e, the optimal value of P_s. Generally P_s is taken in between 0.4 and 0.6. As P_s will increase, harvested energy will decrease and achievable rate increase. So efficient value of P_s come around in between 0.4 to 0.6, In this case it is 0.53.

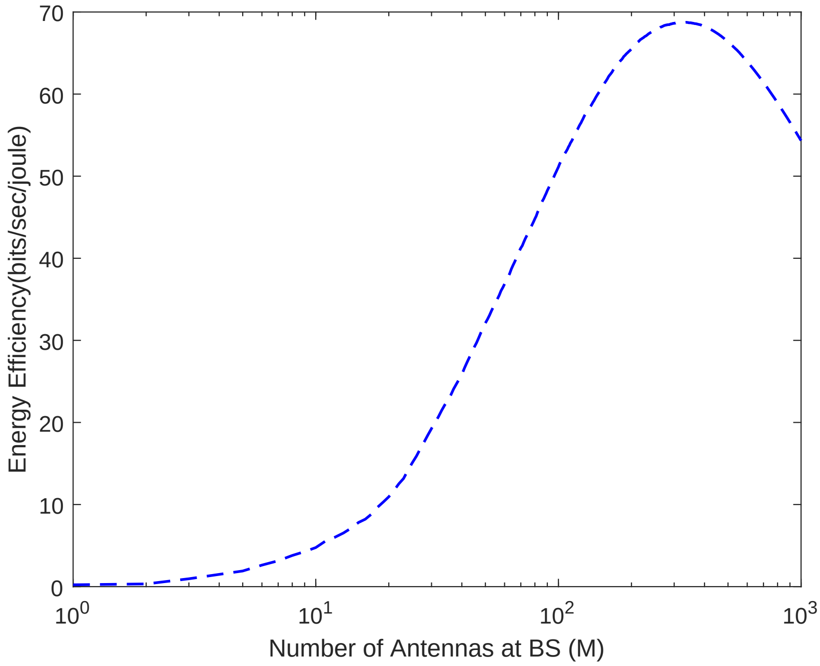

Figure 6.1: Energy efficiency curve.

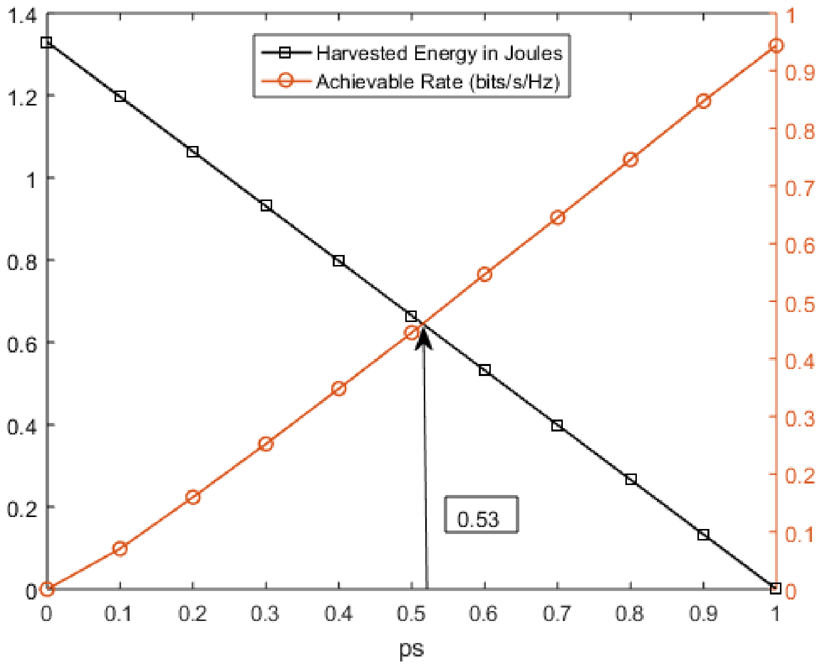

Figure 6.2: HE, Achievable rate VS P_s.

6.5 Summary

Here, we tried to find the quantity of massive, how much large it can be. It is true that increasing antenna at BS will increase the performance of the system. But, it will increase complexity, cost of deployment, circuit power consumption. So, there is a limitation of massive MIMO. It is observed through simulated result that, it is more efficient when there is 300-400 antenna at BS. We have also seen the use of fraction of power for harvesting energy and decoding information. It is more efficient to use almost half of the recieved power for harvesting energy and remaining for decoding information.

Chapter 7

Spectral Efficiency and User Maximization

In this chapter, we will use various technique to maximize the spectral efficiency and user optimization.

7.1 Area Throughput

To keep up with the rapid increasing traffic growth, a key goal of the 5G technologies is to improve the area throughput by orders of magnitude hundred times, higher throughput are regularly mentioned as 5G design goals.

$$Throughput = BW * CD * SE \tag{7.1}$$

Here, bandwidth (Hz) is denoted as BW and cell density (cells/km^2) is denoted as CD and spectral efficiency (bits/sec/Hz per unit area) or (bits/sec/Hz per cell) is denoted as SE. The improvement in area throughput in previous network generation technology has increased by the cell densification and the allocation of more bandwidth. The spectral efficiency has not seen any major improvement in previous network generations. Hence, it might be a factor that can be greatly improved in the future and possibly become the primary way to achieve high area or data throughput in 5G networks.

7.2 Frequency Reuse Factor

Each cell has been allocated a frequency band. Each channel is equidistant from its co-channel and hence the co-channel interference is optimally distributed. F is called as the frequency reuse factor or pilot reuse factor that is given as:

$$F = i^2 + ij + j^2 \tag{7.2}$$

Here, i is the number of cells in horizontal direction and j is the number of cells i.e, 60° to the horizontal direction. For the value of i=(0,1,2...) and j= (0,1,2...), F can take the value (1,3,4,7...). We note that with a pilot reuse factor of f = 7, one can divide the cells into seven different disjoint group of different frequency range. As Interference is more likely to occur at the boundary of the cell than the center of the cell. So, we can divide each cell into two subcells: cell edge and cell center. The latter is known as fractional pilot reuse. Pilot reuse factor is increased to minimize the pilot contamination or co-channel interference, but it divides the available resource bandwidth.

7.3 Simulation Results and Discussion

We have analyzed average spectral efficiency versus the number of users with different precoding process i.e, maximum ratio precoding and zero forcing precoding process.

7.3.1 Spectral Efficiency vs the number of user in MR Precoding

In Figure 7.1, for MR precoding, full resource is availabe to the users when pilot reuse factor is 1 and it is more efficient for high user density, as in plotted graph, more than 70 users per cell is efficient. Increasing pilot reuse divide the available resource in between users and it is preferred for the low user density. Pilot reuse factor is increased in order to reduce the contamination or interference between users. F=3 is preferred for 20 to 70 users per cell, F= 4 is preferred for around 10 to 20 users per cell and F=7 is preferred for less than 10 users per cell.

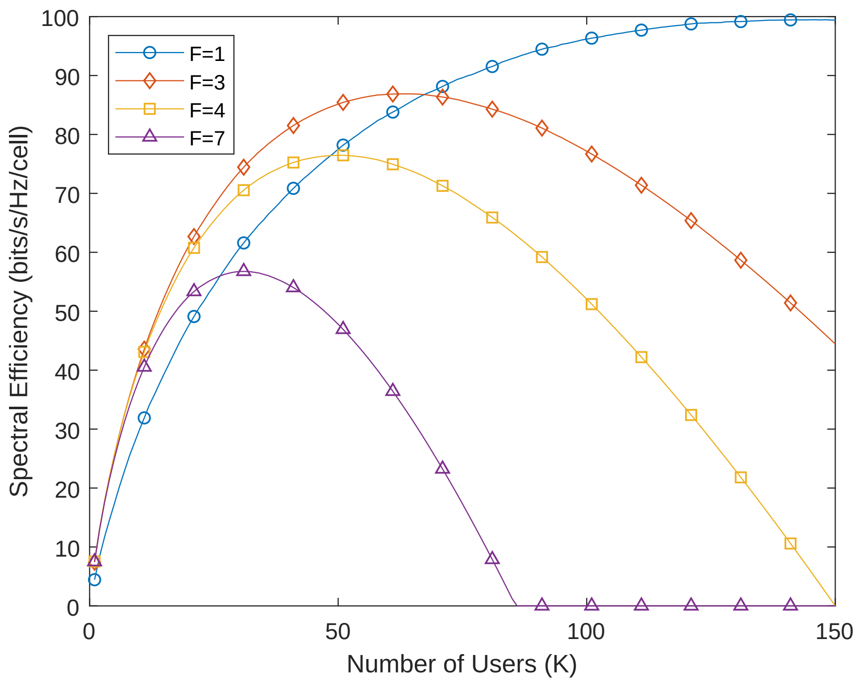

Figure 7.1: Average spectral efficiency versus the number of users, with maximum ratio precoding and different pilot reuse factors at SNR=10dB.

7.3.2 Spectral Efficiency vs the number of user in ZF Precoding

In Figure 7.2, for ZF precoding, F=1 is preferred when there is more than 90 users per cell, F=3 is preferred for 20 to 90 users per cell, F=4 is preferred for 10 to 20 users per cell and F=7 is preferred for less than 10 users per cell. Results show that ZF gives better SE performance than MR precoding and MR precoding gives the better estimation with respect to perfect CSI.

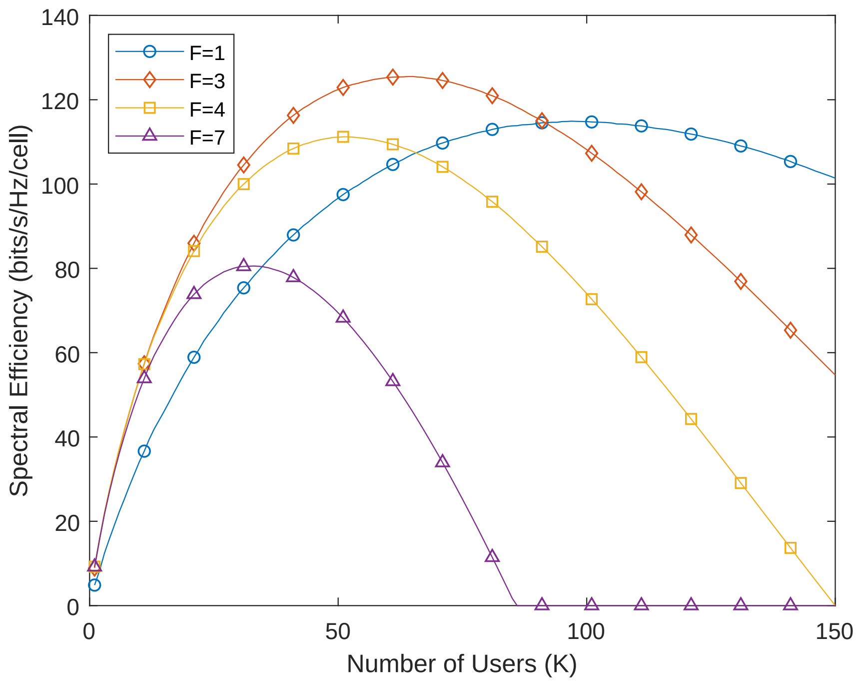

Figure 7.2: Average spectral efficiency versus the number of users, with zero forcing processing and different pilot reuse factors at SNR=10dB.

7.3.3 Spectral Efficiency and User Maximization

In Fig. 7.3, The number of users is optimized for the different number of BS antenna to yield the highest spectral efficiency, and the corresponding number of users is also shown. In 4G network communication system, spectral efficiency is in the range of 2-4 bit/s/Hz/cell. The Massive MIMO network as considered in simulated result in Fig.7.3, achieves 53 bit/s/Hz/cell using M=100 antennas, which is a 20 times improvement over 4G network, With M=400 antennas the Massive MIMO system achieves around 112 bit/s/Hz/cell, which is an incredible 40 times improvement over previous generation network. Thus, spectral efficiency and number of user is maximized in 5G communication. For 100 and 400 antenna at BS, 32 and 43 user is optimum respectively, for most spectral efficiency.

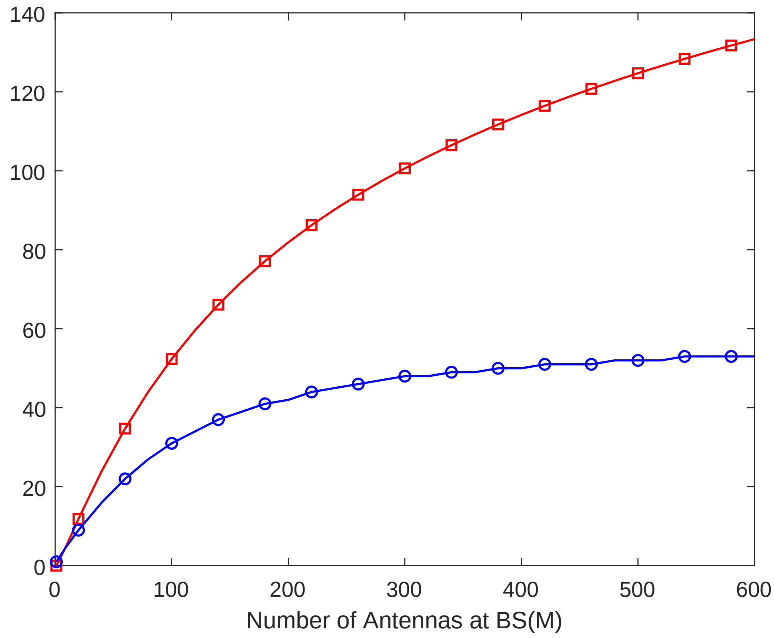

Figure 7.3: Average spectral efficiency versus the number of BS antennas, with ZF processing at pilot reuse factor f = 3, and an SNR of 10 dB, and the corresponding number of users to achieve the highest spectral efficiency.

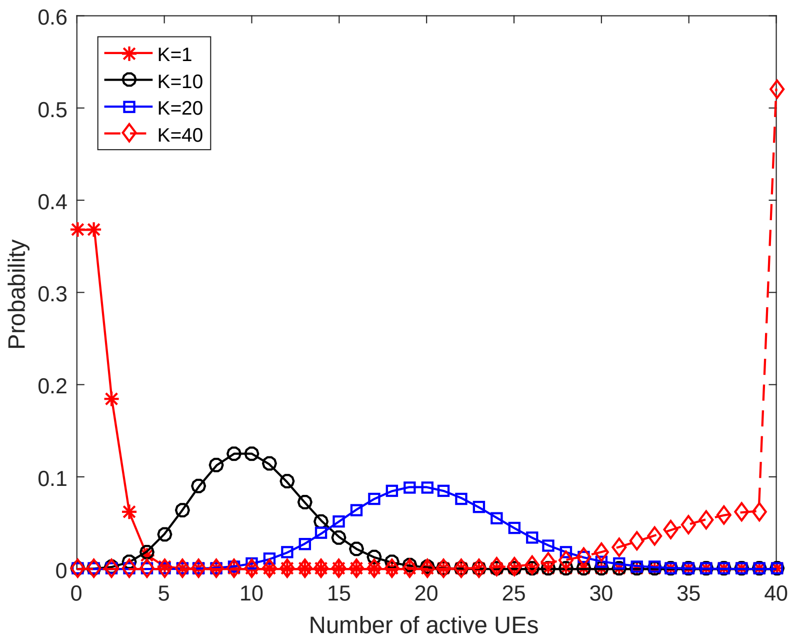

Figure 7.4: Distribution of the number of active UEs in a cell, modeled as min(K_{active}, τ_p) where K_{active} Probability(K) and $\tau_p = 40$.

7.3.4 Distribution of Active Users

The number of active UEs in an arbitrary coherence block can be treated as a random variable and Poisson distributions are commonly used to model such traffic variations. As shown in Fig. 7.4, When the traffic load is high, τ_p(Number of samples allocated for pilots per coherence block) can be selected based on what is needed to reach the maximum sum SE point. When the traffic load is low, τ_p can be selected based on the distribution to balance between having a low probability of pilot shortage with $K_{active} > \tau_p$ and keeping the pilot overhead low. Note that the probability of $K_{active} > \tau_p$ is substantial for K = 40, which leads to the large probability of having 40 active users in that case.

7.4 Summary

Spectral efficiency is maximized around 40 times in massive MIMO 5G communication system as compared to the previous 4th generation network technology. Pilot reuse factor is increased in order to reduce the contamination or interference between users. High pilot reuse is better for less user as the resource is divided and low pilot reuse is better for high user as full resource is available for the user. Active user is random variable distributed as poison distributions. For different value of K, it is seen that the probability of having K active user is maximum when pilot sequence length is greater than K.

Chapter 8

BER Performance of Massive MIMO

In this chapter, we will analyse the bit error rate (BER) performance of massive MIMO.

8.1 BER Performance

Massive MIMO is the assymptotically noise and interference free communication. Bit error rate is almost zero as the number of antenna is too large at base station and mobile station. Massive MIMO is the asymptotically noise and interference free communication. BER is almost negligible as the number of antenna is too large at the base station and the mobile station. The BER in multi antenna system is given as [16]:

$$BER \approx \binom{2M-1}{M}\left(\frac{1}{SNR}\right)^{M} \tag{8.1}$$

Here M is the number of antenna at base station. For low SNR, BER is almost negligible. Thus, massive MIMO is a errorless and noise free communication system.

8.2 Simulated Results and Discussion

We have analyzed the bit error rate performance of Massive MIMO before that we have simulated the results for basic MIMO system with two, four, six and eight antennas. The observed result from simulation for basic MIMO and Massive MIMO system are shown in Table 8.1. For $M = 2$, BER is 10^{-10} at 49dB SNR. For $M = 4$, BER is 10^{-10} at 26dB SNR. For $M = 6$, BER is 10^{-10} at 18dB SNR. For $M = 8$, BER is 10^{-10} at 14dB SNR. For $M = 340$, BER is 10^{-70} at 5dB SNR. We can see the vast difference in result of Massive MIMO system. It requires very less SNR and BER is almost negligible.

8.2.1 BER of Basic MIMO system

As the plotted result in Figure 8.1, and Table I, It is shown that by increasing number of antenna at BS leads to decrement in BER drastically.

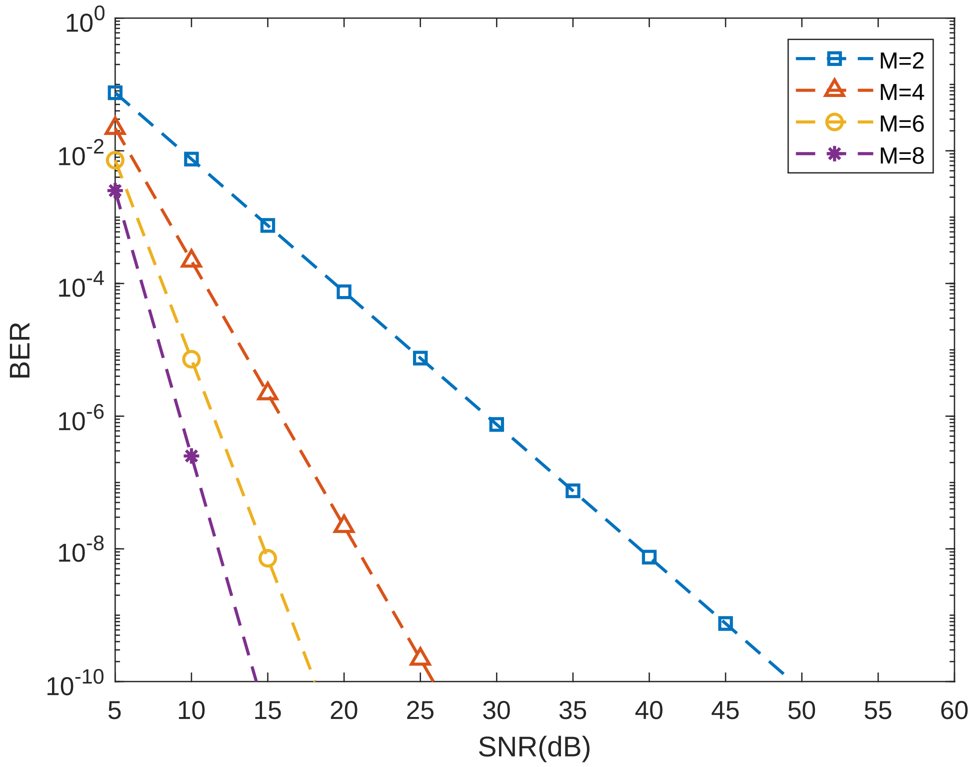

Figure 8.1: BER versus SNR(dB) for different smaller values of BS antenna M.

8.2.2 BER of Massive MIMO System

Hence for large antenna system model as in massive MIMO, BER is negligible and it is in the order of 10^{-70} for 5dB SNR at M=340 as shown in Figure 8.2. Hence, we can say that the massive MIMO is error free communication system due to large number of antenna at base station and more number of user served simultaneously.

Table 8.1: SNR and BER for different value of M.

M(No. of antenna)	SNR(dB)	BER(approx.)
2	49	10^{-10}
4	26	10^{-10}
6	18	10^{-10}
8	14	10^{-10}
340	5	10^{-70}

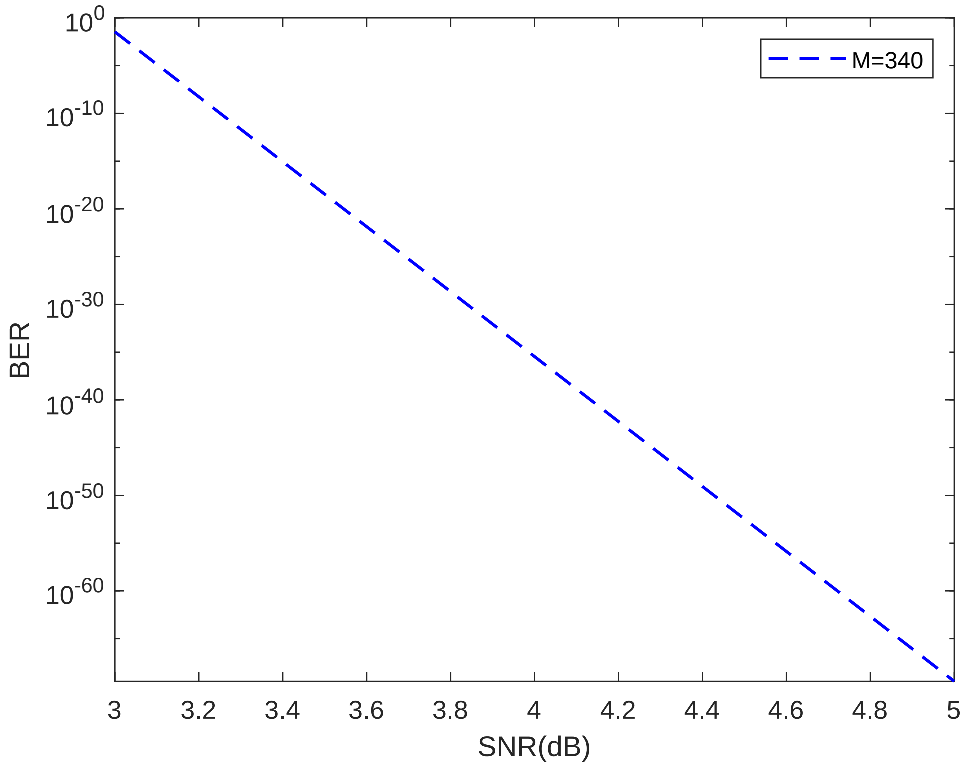

Figure 8.2: BER versus SNR(dB) at M=340.

8.3 Summary

We have analyzed the BER performance of Massive MIMO system. It is observed that large antenna communication system is free from noise, interference, and bit error rate is negligible. Hence, Massive MIMO is noiseless system.

Chapter 9

Conclusion & Future Work

In this chapter, we will discuss about the summary of work done & future direction of this project.

9.1 Project Summary

Harvested energy and the achievable rate has been derived for the massive MIMO enabled SWIPT systems over Rician fading channel under the channel reciprocity error. In this project, we have analysed the impact of the channel reciprocity error caused by the RF mismatches, on the performance of linear precoding schemes such as MRT in TDD massive MIMO systems with imperfect channel estimation. Harvested energy is increasing with increment of antenna at base station. Achievable rate was increasing with increase in number of antenna at base station and getting constant after the increment of certain number of antenna at base station side. MATLAB simulations were done and results have validated the accuracy of the derived expressions. The number of antenna at base station can't be increased too high because circuitry power consumption and deployment cost will increase and it will make the communication system less energy efficient. Simulated result also prove that the spectral efficiency is getting constant after the massive MIMO regime. Thus, massive MIMO regime was the most energy efficient. It is better to use almost half of the recieved power to harvest energy and other half to decode information.

Also, the spectral efficiency and user capacity are maximized for energy efficient multi cell Massive MIMO system. The channel state information is better estimated by maximum ratio and minimum mean square error algorithm but zero forcing algorithm gives better performance. TDD mode was preferred over FDD mode as the pilot length sequence in TDD mode doesn't depends on the number of base station antenna. TDD operation was fully scalable with respect to the number of BS antennas, while FDD operation can only handle more antennas by also increasing the pilot overhead. The channel estimation was simplified when operating in TDD mode, since the pilot sequences only need to be of length K irrespective of the number of BS antennas M. The pilot reuse factor was an important design parameter in Massive MIMO networks and the best choice depends on the user load. High pilot reuse was better for less user as the resource was divided and low pilot reuse was better for high user as full resource was available for the user. Pilot reuse 1 was better for high user density and pilot reuse 3 and 4 were better for low user density. In high pilot reuse, interfence and pilot contamination have been reduced. In Massive MIMO, spectral efficiency was around 50 times improvement over 4G network. For billions of device inter-networked in new technolgy like IOTs, it will provide a better addressing technique. Active user was random variable distributed as poison distributions. For different value of K it was seen that the probability of having K active user was maximum. For 40 users terminal there is large probability of having 40 active users. Massive MIMO technology was key to not only improve the SE, but can also be the driving force towards achieving orders of magnitude higher area throughput in 5G technologies. Also large antenna system model in communication system is almost noise and interference free. Therefore, Bit error rate was negligible. Hence, Massive MIMO is the most efficient system for 5th generation communication system.

The performance of Massive MIMO system was evaluated. The average harvested energy and achievable rate of massive MIMO under rician fading channel were analyzed considering the channel reciprocity error. The performance was found to be inferior compared to the performance by assuming that the channel is reciprocal. The term massive was quantified through energy efficiency curve. Various linear precoding scheme was used to estimate the channel state information and maximize the spectral efficiency. The technique of frequency reuse to minimize pilot contamination was analyzed. Frequency reuse factor was increased when user density was less and vice versa for user's resource optimization. It is observed that the spectral efficiency of massive MIMO was 40 times more than the previous 4G network technology. Simulated result shows that massive MIMO provides an error and interference free communication system. For small value of SNR, bit error rate was also negligible.

9.2 Future Work

The following will be the future direction of this project:

- Spectral Efficiency: To scale up the spectral efficiency by 100 times or more.
- An antenna selection method: By proper antenna selection, we can reduce the number of antennas used by the user. The optimal number of selected antennas will be investigated.

Publication

[1] A. Thakur, R. C. Mishra, “Performance Analysis of Energy-Efficient Multi-Cell Massive MIMO System” (Manuscript submitted in “THE 10th INTERNATIONAL CONFERENCE ON COMPUTING, COMMUNICATION AND NETWORKING TECHNOLOGIES (ICCCNT))” at IIT Kanpur.

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