Energy Analysis of Large Antenna and Spatial Modulated System in Different Fading Channels

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CERTIFICATE AND DECLARATION

I, Arzoo Khetarpal hereby declare that the work which is being presented in the dissertation entitled **"Energy Analysis of Large Antenna and Spatial Modulated System in Different Fading Channels"**, by me in partial fulfillment of the requirement for the award of degree of Master of Engineering in Electronics and Communication submitted in Electronics and Communication Engineering Department of Thapar University, Patiala is an authentic record of my own work carried out under the guidance of **Dr. Rajesh Khanna (Professor)**, Electronics and Communication Engineering Department. The matter presented in this dissertation has not been submitted in any other University/Institute for the award of degree.

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This is to certify that the above statement made by the student is correct to the best of my knowledge and belief.

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ABSTRACT

In the last ten years we have seen significant advances of multi-user MIMO (MU-MIMO) in wireless communication. MU-MIMO is now being introduced in several new generation wireless standards (example LTE-Advanced, 802.16 m). The number of users is increasing with more and more applications. At the same time high data rates and communication reliability are required. Therefore, MU-MIMO systems have to satisfy the three main requirements i) serving many autonomous users in same time-frequency resource ii) having high data rate and communication reliability iii) less energy consumption/radiation. These are seemingly contradictory requirements. Since the more users are served, the system will suffer from more interference and for achieving high data rate more transmit power is required. MU-MIMO with large number of antennas located at the base station (say tens or hundreds), the channel vectors are nearly orthogonal and hence multi-user interference can be significantly reduced. As a result many users can be served with high data rates. In particular the transmit power is reduced by the number of antennas present at the base station or by the square-root of the number of antennas located at the base station depending on the CSI and fading technique used.

In this thesis the energy efficiency analysis for uplink MU-MIMO using linear receivers in Rayleigh and Ricean fading channels with scaled and un-scaled transmit power is done. In analysis it is assumed that each user has single antenna for transmission and base station has large number of antennas (100 and 200) with imperfect CSI. We also consider transmit power, circuit power and loss factors for the analysis. In Rayleigh fading channel the tradeoff is observed between energy and spectral efficiency for MRC and ZF receivers considering transmit power, transmit and circuit power and transmit, circuit power and loss factors for scaled and un-scaled transmit power. It has been observed that considering circuit power and loss factors high energy efficiency is obtained with less number of antennas placed at the base station. In Ricean fading channel the tradeoff is also observed between energy and spectral efficiency using MRC receiver considering transmit and circuit power, transmit, circuit power and loss factors for un-scaled transmit power. High energy and spectral efficiency is obtained in Ricean fading channel. With scaled transmit power the spectral efficiency reduces in comparison to the un-scaled transmit power. The energy efficiency is also analyzed by variation of transmit power in dB using imperfect CSI in Rayleigh (MRC and ZF receivers) and Ricean (MRC receiver) fading channels. At low transmit power MRC receiver performance is better in comparison to ZF receiver and at high transmit power ZF receiver performance is better in comparison to MRC receiver.

Spatial Modulation technique is also analyzed using MRC receiver with imperfect CSI for single and multi users having multiple antennas for transmission and large number of antennas at base station, and radio frequency chain equal to the number of users in Rayleigh and Ricean fading channels. Energy efficiency and spectral efficiency is analyzed using spatial modulation and results are compared with single and multi users each having single antenna for transmission. The analysis is done for single user having 4 and 8 transmission antennas and 4 users each user having 4 and 8 transmission antennas and base station has 100 antennas and it has been concluded that single user having 4 and 8 antennas is preferred in comparison to single user having single antenna for transmission. High energy efficiency is obtained using spatial modulation in Ricean fading channel in comparison to user having single antenna for transmission. It has also been concluded that energy efficiency and spectral efficiency increases as users have large number of antennas for transmission and less number of radio frequency chains.

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ABBREVIATIONS

MIMO	Multiple Input-Multiple Output
MISO	Multiple Input-Single Output
CSI	Channel State Information
BS	Base Station
MU-MIMO	Multi-user Multiple Input-Multiple Output
ZF	Zero-Forcing
MRC	Maximum-Ratio-Combining
MMSE	Minimum Mean-Square Error
RF	Radio Frequency
MRT	Maximum Ratio Transmission
MLD	Maximum Likelihood Detection
LS	Least Square
SNR	Signal-to-Noise Ratio
SINR	Signal-to-Interference-Noise Ratio
SM	Spatial Modulation
LSAS	Large Scale Antenna System
BER	Bit Error Rate
EE-SE	Energy Efficiency Spectral Efficiency
MMSE-SIC	Minimum Mean Squared Error Successive Interference Cancellation
GSM	Generalized Spatial Modulation
RE	Resource Efficiency
MU-SM	Multi-user Spatial Modulation
STBC	Space Time Block Codes
V-Blast	Vertical-Bell Laboratories Layered Space-Time
RZF	Regularized Zero-Forcing
GMAPD	Generalized Approximate Message Passing Detector
QAM	Quadrature Amplitude Modulation
i.i.d.	Independent Identical Distributed
MF	Matched Filter
TDD	Time Division Duplexing

BF	Beam Forming
OFDMA	Orthogonal Frequency Division Multiple Access
PDF	Probability Density Function
ICI	Inter-Cell Interference
RVs	Random Variables
SU-MIMO	Single User Multiple Input-Multiple Output
DAC	Digital to Analog Converter
ADC	Analog to Digital Converter
LO	Local Oscillator
PA	Power Amplifier
LNA	Low Noise Amplifier
IFA	Intermediate Frequency Amplifier
IAS	Inter Antenna Synchronization

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CHAPTER 1

INTRODUCTION

1.1 Introduction

From the times of yore decades the personnel communication fields have been changed by wireless networking. Now, with the help of cellular networks many people connect to the internet media for exchanging the data. The volume of data to be transferred is increased because of applications used by the people such as video streaming etc and mobile terminals are used to handle this large amount of data. It is found that as the number of users in a cell increases the spectral efficiency also increases, but increased number of users increase the power consumption. Hence study of techniques to enhance the energy efficiency in order to improve the performance of wireless system is also required. Hence, in the coming years the demand for data transfer will increase as many people are using mobile phones and internet so there is a need to develop the future wireless networks for enhancing the capacity and energy efficiency. The information and communication technologies have caused the environment effects such as large amount of emission of carbon dioxide [1].

Researchers proposed a Multiple Input-Multiple Output (MIMO) systems having multiple antennas at receiver and transmitter for providing spectrally competent wireless systems, around 90s [1][2]. MIMO channel capacity increases with the minimum number of antennas at the receiver and transmitter if perfect Channel State Information (CSI) is known both at the receiver and transmitter end. Because of MIMO technology we can transmit multiple data streams at the same time and frequency interval. This mode of transmission is known as orthogonal transmission. Further, MIMO system improves the diversity and hence it leads to reliable communication [3].

The realization of MIMO system multiplexing gain can be done in rich scattering environment. The following are the cases when high multiplexing gains are not achievable with point to point MIMO i) when there is a strong correlation present at both transmitter and receiver side ii) when the line-of-sight component is present iii) when the received signal power is very weak in comparison to noise power. To overcome the disadvantages of point to point MIMO we switch to Multi-user MIMO (MU-MIMO) which provides high multiplexing gains and transmits data as a single user MIMO. Another advantage of MU-MIMO is that is does not require a rich scattering environment for achieving high multiplexing gains [4]. In case of MU-MIMO many users on the transmitter side communicate with the base station (BS) antennas in the same frequency and time interval. MU-MIMO spatial multiplexing gains are retained by users that are orthogonal to one another. Therefore, MU-MIMO is used for the upcoming cellular networks.

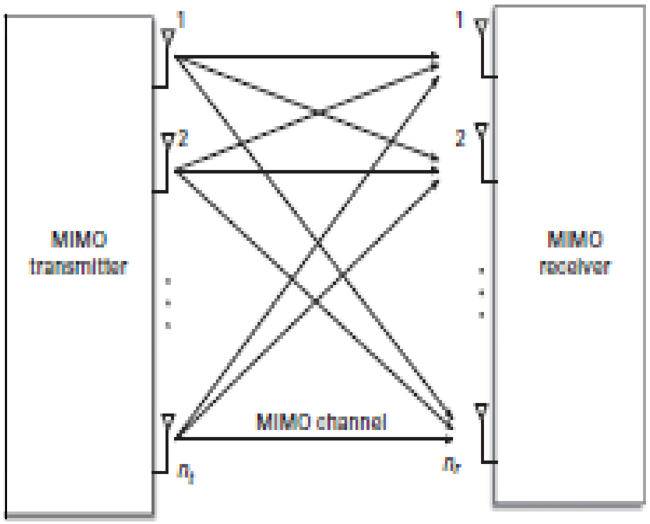


Figure 1.1 Point to point MIMO [43]

In point to point MIMO large number of antennas is placed at the transmitter and the receiver side to obtain high capacity but high bandwidth is not possible with point to point MIMO. In MU-MIMO downlink called as point-to-multipoint MIMO the communication is done from base station antennas to the users and users can have either single antenna or multiple antennas to achieve high capacity. MU-MIMO uplink is called as multipoint-to-point MIMO because the transmission of data is done from the user end having single or multiple antennas to the base station having large number of antennas as shown in Figure 1.2.

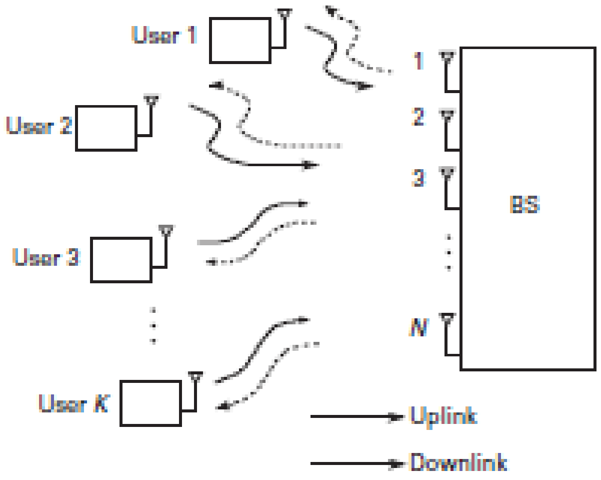


Figure 1.2 Multi-user MIMO system [43]

Recently, it has been observed that for achieving high data rates and energy efficiency we can employ large number of antennas at the base station (BS) [5]. Employing large number of antennas at the base station is called as Large Antenna System and also called as Massive MIMO system or Large MIMO system. In Large Antenna System many single antenna users communicate with the large number of antennas located at the base station. The number of antennas located at the base station is in terms of tens or hundreds and so and the users are less in comparison to the number of antennas at the base station. Large Antenna Systems are complex because of large number of antennas located at the base station. The signal transmitted by the user in the uplink is estimated at the receiver side of communication system. The various techniques used in the detection are linear receivers such as Zero-Forcing Receiver (ZF), Maximum-Ratio-Combining (MRC) and Minimum Mean-Square Error (MMSE) receivers are used [6]. The components that are equipped for transmission and reception in Large Antenna Systems such as radio frequency (RF) chains, power amplifiers are inexpensive. So, for the Large Antenna System introduction, there is a requirement of new design cellular networks. In [7] it has been shown by Marzetta that simple signal processing when number of antennas is large is nearly optimal. It has been found that by incorporating maximum-ratio-combining (MRC) on the uplink and maximum ratio transmission (MRT) on the downlink the effect of uncorrelated noise, small scale fading and inter-cell interference (ICI) is vanished when number of antennas at the base station (BS) goes to infinity. In [7] considering the multi cell scenario it has been quantified that by using a bandwidth of 20 MHz on the downlink transmission each user gets a throughput of 17 Mbits/s. Very Large Antenna Systems have a numerous advantages. Some of them are stated below:

a) **Data rate improvement and reliable communication:** All gains from conventional MIMO are inherited by MU-MIMO having large number of antennas at the base station. With P antennas at the base station and M users each having single-antenna then a diversity order of P and multiplexing gain of min (P,M) is achieved.

b) **Signal processing ease:** Channel Hardening problem occurs because of large number of antennas located at the base station. As an effect, consequences of fast fading and thermal noise are averaged out. As channel vectors are orthogonal with simple and linear signal processing the consequence of inter-user interference is eliminated.

c) **Power efficiency:** In uplink high array gain is achieved with coherent combining and the transmitted power of each user is also reduced. Energy is focused by base station into multiple directions in the downlink where number of terminals is located. 100 antennas array requires 1% of power as compared to single antenna system.

1.2 Background and Preliminary

This thesis work consist of uplink Multi User-Multiple Input-Multiple Output (MU-MIMO) system so we discuss next the MU-MIMO system and the linear receivers used in MU-MIMO

- **MU- MIMO System**

In MIMO technology spatial multiplexing gain and diversity gain provides increase in data tariff and reliable communication respectively. Multiple access techniques are used in conventional cellular networks that means each user is scheduled at different frequency and time interval. However, when number of antennas located at the BS increases more and more users can transmit data at same time and frequency interval and these systems are called as Multi-user MIMO systems.

- **Advantages of MU-MIMO**

The following are the advantages of MU-MIMO system

- Spatial multiplexing gain is achieved by MU-MIMO at BS and for this multiple antennas at the user terminal is not required. BS can support a large number of antennas but users cannot support large number of antennas because of physical size limitation and low cost requirement.
- Multi-User Multiple Input-Multiple Output (MU-MIMO) does not harvest all remuneration of single user MIMO systems but the limitations of single user MIMO are overcome by MU-MIMO. Scheduling schemes are used to overcome the limitation of ill channels in single user MIMO. Line-of-sight propagation is an issue in single user MIMO by which there is a reduction in performance and it is not an issue in case of MU-MIMO systems.

However, tradeoff always occurs between complexity and system performance. The benefit of MU-MIMO systems comes at a penalty.

- **Challenges**

Current wireless standards, such as IEEE 8O2.11n/11ac (WiFi) and 3GPP LTE-A, use MIMO techniques for increasing spectral efficiency. These wireless standards use a maximum of 6 to 8 antennas at both transmitter and receiver side. Using these wireless standards a maximum of 15 bps/Hz or less spectral efficiency is obtained. However for obtaining significant benefits a large number antennas at the BS should be employed. By using number (10s to 100s) of antennas at the BS a multi Giga bit-rate transmission is possible and spectral efficiency in the range of tens to hundreds can be obtained. For realizing these Large Antenna Systems following challenges need to be met.

- Multi-user interference exist so interference cancellation or reduction techniques for example dirty paper coding techniques for downlink [8], maximum likelihood multi-user detection for the uplink [9] and interference alignment [10] should be used.

- CSI: Received signals should be processed coherently by the base station for achieving high spatial multiplexing gain. For this accurate and time acquisition of CSI is required. This is a challenge for high mobility scenarios.
- Pilot contamination: System performance is reduced due to the effect known as pilot contamination. In cellular networks utilization of non-orthogonal pilot sequences is done in different cells because of a constraint of channel coherence interval. Therefore, the estimated signal obtained in one cell is contaminated by the pilot signals transmitted by the other users in another cell.

1.3 Linear Receivers

Linear Receivers are used to detect the signal at the BS transmitted by the M users. BS has perfect CSI. Maximum Likelihood detection (MLD) technique can be used for obtaining optimum performance. More precisely [5],

$$\hat{\mathbf{y}} = \arg\min \left\| \mathbf{z} - \sqrt{p_o}\mathbf{H}\mathbf{y} \right\|^2 . \qquad (1.1),$$

The above problem represented in (1.1) is the finite alphabet constraint Least Square (LS) problem. All possible values of vector transmitted vector **y** have to be found out by the BS. The disadvantage of using maximum likelihood detection is its complexity which increases exponentially as the number of user increases.

For reducing the problem of decoding complexity at BS we can use the linear receivers. However the detection reliability of linear receivers is less as compared to maximum likelihood (ML) detection technique. Tradeoff between complexity and system performance is always observed. As the number of users M increases linear detectors become optimal [5][11], therefore this thesis work will be focused only on linear detectors.

At the BS the received vector **z** is multiplied by the detection matrix **B** to separate the signal into M streams when linear detection schemes are applied. With linear detection schemes at BS received vector **z** is multiplied by the detection matrix **B** to separate the signal into M streams. Each stream is decoded autonomously. The complexity order of this scheme is $M|\chi|$ where χ is finite alphabet. Linear Receivers are discussed below.

1.3.1 Maximum-Ratio-Combining

By ignoring the consequences of multi-user interference when MRC technique is used, the BS desires to maximize the received SNR of each multiplexed stream.

- **Advantage of MRC:** The detection process is simple as to detect the transmitted signal the received signal **z** at the BS is multiplied with $\mathbf{h}_m$, the conjugate transpose of channel matrix **H** then each signal is detected separately. The another advantage of using MRC technique is that it can be implemented in distributed manner. The value of signal-to-noise-interference ratio (SINR) is equal to $p_o\|\mathbf{h}_m\|^4$ for small value of transmit power so the MRC performance for multi-user system is equivalent to the single user system.
- **Disadvantage of MRC:** MRC performs worst in interference-limited scenarios because it neglects the consequences of multi-user-interference.

1.3.2 Zero-Forcing Receiver

The ZF receiver is a linear receiver in which linear transformation on received vector **z** is done by using pseudo-inverse of channel matrix **H**. Let **Q** represents the M × P matrix which is pseudo inverse of **H**

$$\mathbf{Q} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H \tag{1.2}$$

as $\mathbf{QH} = \mathbf{I}_\mathbf{M}$, the transformation **Qz** cancels the interference completely from other users but the consequence of interference cancellation introduces noise. The another name for ZF receiver is interference-nulling receiver.

- **Advantage of ZF receiver:** The advantage of using this receiver is that it works good in interference-limited scenarios and signal processing at the BS is simple.
- **Disadvantage of ZF receiver:** With the pro of completely removing the multi-user interference the con added is the additional noise so ZF receiver does not perform well in noise-limited scenarios. Another con of ZF receiver is its

complexity as it is more complex to implement in comparison to MRC receiver because of the pseudo-inverse of channel matrix **H** required at the BS**.**

1.3.3 Minimum Mean-Square Error Receiver

The MMSE is a linear receiver whose transformation matrix minimizes the error between the received signal i.e. estimated $\mathbf{B}^H\mathbf{z}$ and transmitted signal **y**. Let **B** be a P × M linear detection matrix. More specifically,

$$\mathbf{B}_{MMSE} = \arg\min \mathrm{E}\left\{\left\|\mathbf{B}^H\mathbf{z}-\mathbf{y}\right\|^2\right\} \tag{1.3}$$

$$\mathbf{B}_{MMSE} = \arg\min \sum_{m=1}^{M} \mathrm{E}\left\{\left|\mathbf{b}_m^H\mathbf{z}-\mathbf{y}_m\right|^2\right\} \tag{1.4}$$

where, b_m is the mth column of the detection matrix **B**.

It is well known that the advantage of MMSE receiver is that it maximizes the received signal-to-interference-noise ratio (SINR). Therefore, among these linear receivers MRC, ZF and MMSE, MMSE is the best linear receiver.

1.4 Mathematical Preliminary for Very Large Antenna System

Very long random vectors results are reviewed by [13] which are used in the thesis. Let **a = [**a_1 a_2 a_3----- a_p]^T and **b** = [b_1 b_2 b_3 ---- b_p]^T be p × 1 independent identical distributed random vectors whose elements are random variables (RVs) with E{a_i} =E{b_i} = 0, E{$|a_i|^2$} = σ_a^2 and E{$|b_i|^2$} = σ_b^2 , i=1, 2, 3 --- p. Assume that both **a** and **b** are independent.

By using law of large numbers the following results are obtained

$$\frac{1}{p}\mathbf{a}^H\mathbf{a}\xrightarrow{a.s.}\sigma_a^2 \text{, as } p\to\infty \tag{1.5}$$

$$\frac{1}{p}\mathbf{b}^H\mathbf{b}\xrightarrow{a.s.}\sigma_b^2 \text{, as } p\to\infty \tag{1.6}$$

$$\frac{1}{p}\mathbf{b}^H\mathbf{a}\xrightarrow{a.s.}0 \text{, as } p\to\infty \tag{1.7}$$

where, $\xrightarrow{a.s.}$ represents almost sure convergence.

By using Lindeberg-Levy Central limit theorem we get,

$$\frac{1}{\sqrt{p}}\mathbf{a}^H\mathbf{b}\xrightarrow{d}CN(0,\sigma_a^2\sigma_b^2)\text{, as } p\rightarrow\infty \tag{1.8}$$

where, $\xrightarrow{d}$ represents distribution in convergence.

1.5 Spectral Efficiency, Energy Efficiency and Spatial Modulation

These terms are briefly described below

Spectral Efficiency: In a communication system the information rate that is transmitted over a given bandwidth is called spectral efficiency. It is measured in bits/s/Hz. It is measure of how efficiently frequency limited spectrum can be utilized by physical and media access layer.

$$R=\sum_{i=1}^{M}R_m \tag{1.9}$$

where, R is known as spectral efficiency and R_m is the achievable rate of the m$^{\text{th}}$ user.

Energy Efficiency: Energy efficiency (η) is defined as the total sum rate or spectral efficiency divided by the total transmit power. It is measured in bits/J/Hz.

$$\eta=\frac{R}{P_t} \tag{1.10}$$

where, P_t is defined as the total power transmitted and R is spectral efficiency.

Spatial Modulation: Spatial Modulation is a new proposed technique for MIMO systems in which users have multiple antennas for transmission and number of radio frequency (RF) chain is one. So, with the reduced number of RF chains the power consumption decreases and the energy efficiency increases. Spatial Modulation is further extended to Generalized Spatial Modulation in which high spectral and energy efficiency is achieved by using RF chains between 1 and number of users.

1.6 Goal of Thesis

The main goal of the thesis is to study the energy and spectral efficiency tradeoff of vey large antenna system considering different conditions using linear receivers under different fading environment.

- Performance evaluation of the tradeoff between energy and spectral efficiency in MU-MIMO with un-scaled transmit power, circuit power and loss factors with imperfect CSI using linear receivers in different fading channels.
- Performance evaluation of the tradeoff between energy and spectral efficiency in MU-MIMO with scaled transmit power, circuit power and loss factors with imperfect CSI using linear receivers in different fading channels.
- Performance evaluation of the tradeoff between energy efficiency and transmit power in MU-MIMO with un-scaled and scaled transmit power with imperfect CSI using linear receivers in different fading channels.
- Performance evaluation of the tradeoff between energy and spectral efficiency using Spatial Modulation (SM) for single user Multiple Input-Multiple Output (SU-MIMO) and MU-MIMO with MRC receiver and imperfect CSI in different fading channels.

1.7 Organization of the Thesis

Chapter 1 gives the introduction of the Multi-user Very Large Antenna MIMO systems, Linear Receivers, energy efficiency, spectral efficiency, Spatial Modulation Goal of thesis and Organization of the Thesis.

Chapter 2 gives the overview of the Very Large Antenna Systems, Energy Efficiency of MIMO Systems and Spatial Modulation.

Chapter 3 gives system model for calculating the spectral efficiency of multi-user single antenna systems with imperfect CSI using linear MRC and ZF receivers in Rayleigh fading. The results are extended with MRC receiver in Ricean fading channel also. In this chapter a single cell scenario is considered in which M users are placed in the cell and P antennas are placed at the BS.

In chapter 4 the energy efficiency equations are derived for MU-MIMO system with imperfect CSI for MRC and ZF receivers in Rayleigh fading channel. The energy efficiency equations are also derived for MU-MIMO system with imperfect CSI for MRC receiver in Ricean fading channel. The simulation studies for energy and spectral efficiency, energy efficiency and transmit power are done for both fading channels for all the receivers when the transmit power of each user is un-scaled and when transmit power of each user is scaled. Energy and spectral efficiency simulation is done considering the transmit power, circuit power and loss factors.

In chapter 5 the energy efficiency analysis is done for Spatial Modulation (SM) technique for single user and multi-users each having 4 and 8 transmit antennas and results are compared with single user having single antenna for transmission and multi-users each having single antenna for transmission.

In chapter 6 the conclusion about the work done in thesis are drawn and future scope is discussed.

CHAPTER 2

LITERATURE SURVEY

In this chapter the work done by the various researchers in the field of Very Large Antenna Systems has been described. As enhancing the energy efficiency is the current research issue of the Very Large Antenna System so work done in the field of energy efficiency has been also described.

2.1 Very Large Antenna Systems

In **2006** Thomas L. Marzetta determined the number of single antenna users that were simultaneously served by fixed number of antennas present at the BS, for a given coherence interval and fixed forward and reverse SINR's while maximizing the lower bounded sum rate. Lower bound is applicable on all values of SINR. It has been concluded from the research that at a small value of coherence interval say 10 symbols, -10 dB reverse SINR, 0 dB forward SINR and number of antennas at the BS is 16 or more it is possible to estimate the forward channel by Time Division Duplexing (TDD) reciprocity and simultaneously data can be transmitted to large number of users. It is advantageous to increase the number of antennas at the BS as it removes noise and serves large number of users even when channel estimate is poor [14].

In **2010** T.L. Marzetta proposed a new scheme known as Massive MIMO system in which, BS has large number of antennas. With this new technique evoked, as number of antennas at BS increases without limit the effects of fast fading and uncorrelated noise vanishes and only problem is inter-user interference. This scheme provides high reliable inputs both in the forward and reverse link. As the antennas located at the BS are large in comparison to the users that are served it has been concluded that simple precoding techniques are used in forward link and processing in reverse link [11].

In **2011** Jakob Hoydis et. al. analyzed the uplink multi-cell environment with fixed number of antennas at the BS to study that to what extent transmit power of users can be made small and how the BS analysis the transmit pilot signals. In this paper, number of antennas required at the user terminal is derived to achieve ultimate performance and number of antennas needed by the MF is also derived to achieve ultimate performance. These results are also applicable to downlink system [15].

In **2012** Hoon Huh et. al. studied a novel MIMO-TDD network architecture whose achievable spectral efficiency is compared with Massive MIMO system and few antennas are required per user per cell. In this scheme the users are partitioned into bins and time-scheduling slots are allocated to the bins for MU-MIMO transmission. In this paper, system optimization is done for 1-D and 2-D cell layouts. Closed form expressions were developed for spectral efficiency. From the analysis it is concluded that different schemes perform well at different user locations [16].

In **2013** Hein Ngo et. al. derived the lower capacity bounds for the ZF, MRC and MMSE detection techniques. In this paper the tradeoff between energy and spectral efficiency is plotted considering transmit power both for single cell and multi cell Rayleigh fading environment considering the effect of small scale fading and neglecting the effect of large scale fading. It has been concluded that if perfect CSI is available with no reduction in performance, each user transmit power is dropped out by 1/M and if imperfect CSI is available the transmit power is dropped out by 1/ sqrt(M) with no reduction in performance where M is number of antennas at BS. It has been concluded that ZF performs better than MRC but at low value of SNR the performance of MRC is better in case of single cell scenario but the performance gets diminished in case of multi-cell scenario because of the effect of pilot contamination [6].

In **2013** Jakob Hoydis et. al. derived the approximate achievable rate with numerous linear detectors and precoders for multi-cellular non-cooperative TDD system when large number of antennas are located at BS and users in a single cell. The system model used here accounts for the path loss, pilot contamination, channel estimation and antenna correlation. In the previous work it has been studied that the simple precoders and detectors such as Matched Filter (MF)/Eigen beam-forming were used when number of antennas at BS approaches infinity and number of users were fixed. In this paper, for achieving the ultimate performance, derivation of how many antennas at the user terminal are required and how many more antennas are required with Beam Forming (BF) and Matched Filter (MF) respectively for achieving the same performance as of regularized ZF and MMSE detection respectively. At the end it has been concluded that with MMSE/RZF (Regularized Zero-Forcing) same performance is achieved as MF/BF with less number of antennas [17].

In **2013** Fredrik Rusek et. al. studied different detection techniques such as MMSE-SIC (Minimum Mean-Square Error-Successive Interference Cancellation) and Trellis Search for the uplink considering the case when number of antennas at BS is equal to number of users. A practical analysis with 128 antennas at BS and 6 single antenna users was done and the conclusion drawn was that the channels in reality are i.i.d. and there is degradation in performance in comparison to ideal channels. The severity of coupling depends on the array geometry. It is concluded in the paper that moderate coupling should be used in order to avoid power loss and antenna correlation [5].

In **2014** Lu Lu et. al. presented an overview on the research areas of Massive MIMO systems. In this paper the whole work done on Massive MIMO is described briefly and the research areas where further work can be done is also represented. The practical applications of Massive MIMO are also discussed in this paper [18].

In **2014** Qi Zhang et. al. derived the expression for approximate achievable rates for uplink large antenna system in Ricean fading environment for MRC and ZF receiver considering both perfect and imperfect CSI. The power scaling law for Ricean fading channel is also derived. The power of each user is scaled down by the number of antennas at BS both for perfect and imperfect CSI case and this is optimum only for non zero line of sight component. However, if Rayleigh fading is experienced by the channel than the transmit power of user is dropped down by 1/ sqrt(M) where M is number of antennas at BS. In this paper, the fast fading matrix consist of two components first is deterministic component and another is non line of sight i.e. Rayleigh component. It has been concluded that with increase in value of Ricean component K constant spectral efficiency value is approached with increase in number of antennas at the BS both for MRC and ZF receiver [19].

In **2014** Erik G. Larsson et. al. have highlighted the potential of using Massive MIMO systems for beyond the 4G technology. In this paper, the advantages of using Massive MIMO systems such as increased energy and spectral efficiency, robustness and reliability are explained. In this technology low cost hardware is used both at the BS and transmitter. All the research areas in this technology are discussed in this paper which has made this technology a goldmine of research for industry [20].

In **2014** Jocelyn Aulin et. al. presented results of spectral efficiency gains with physical realizable channels for downlink MIMO systems. The assumption here done was that average received power is always less than average radiated power. The results of spectral efficiency were presented for normalized channel models and comparison was done with traditional channel models. Power normalization was not done for M × 2 channels and their spectral efficiency is estimated as $\log_2(M)$ [21].

In **2015** Ang Yang et. al. have studied the effect of large scale fading on uplink massive MIMO systems. In this the transmission of data from multi-users having single antenna is done to the BS having large number of antennas. The novel expressions for the ergodic achievable rates are derived for both perfect and imperfect CSI considering the effect of large scale fading. It is concluded that large scale fading plays an important role in the analysis and simulated results are comparable to the derived expressions [22].

2.2 Energy Efficiency of MIMO Systems

In **2004** Shuguang CuI et. al. considered the nodes that operate on batteries in sensor networks in order to minimize the energy efficiency. The total energy utilization consists of transmission energy and circuit energy utilization. In this paper, first MIMO systems based on Alamouti diversity schemes were considered which have high circuitry and good spectral efficiency and it is further extended to individual single antenna systems nodes. In transmission from distance greater than threshold if both transmission and/or reception is done jointly high energy saving is possible. It is further concluded that for short range distances the SISO may be preferable than MIMO if modulation scheme and data rate is fixed and if cooperation of nodes is taken into account MIMO may be preferable than SISO systems [23].

In **2012** Hu Ying et. al. adjusted the number of antennas at BS and uplink transmit power of users to maximize the energy efficiency of very large MU-MIMO systems. The total power utilization comprises of transmit and circuit power. Low complexity iterative algorithms were derived and simulation results show that performance of anticipated algorithm is close to the optimum. It is also concluded that for increasing the energy efficiency the distance between users and BS plays an important role and energy efficiency increases as distance decreases [24].

In **2013** Daehan Ha et. al. considered the case when transmission of data is done from the BS having large number of antennas to the users having single antenna in multi-cell environment. In this paper, new power utilization model was proposed that considers the transmit power of the power amplifier, circuit power consumed by the analog devices and residually loss factors at the BS. As new energy efficiency formulation was done it has been concluded that as number of antennas at BS increases the energy efficiency becomes quasi-concave function. From the derivation that maximizes the energy efficiency the number of antennas at the BS was calculated [25].

In **2013** Hong Yang et. al. quantified Large Antenna System spectral and energy efficiency in both sub urban and dense urban multi-cellular scenarios using a new energy efficiency model which comprises of lower capacity bound and power model accounting for RF generation, per antenna internal power utilization and Large Scale Antenna System (LSAS) critical computing and each antenna internal power utilization and other electronics such as analog to digital converters and digital to analog converters. It was concluded that each antenna consuming 128 mW power above the power required for LSAS computing and RF generation, it can serve fifteen users with a total energy efficiency of 1000 times greater than of LTE BS [26].

In **2013** Hui Li et. al. for improving the energy efficiency they performed transmit antenna selection of large-scale MIMO systems. They derived approximated distribution of mutual information in antenna selection system. For accessing the energy efficiency a closed-form expression is used. The performance of energy efficiency is evaluated in two different ways i) the circuit power dominates the transmit power ii) ignore the circuit power if transmit power is high. The results by indicate that for maximizing the energy efficiency the required number of antennas is less than available number of antennas [27].

In **2014** Zhenyu Zhou et. al. proposed an iterative offline power allocation and antenna selection algorithm with hybrid energy supply for large scale numerous antenna system to maximize the energy efficiency subjected to the constraints of users quality of service (QoS). For solving the non-convex energy efficiency optimization problem by exploiting the property of non-linear fractional programming an offline iterative algorithm was proposed. The analysis and verification was done on the relationship between selected antenna number, energy efficiency, (Energy efficiency-Spectral efficiency) EE-SE tradeoff and battery capacity by computer simulation [28].

In **2014** Jie Tang et. al. proposed a resource efficiency (RE) paradigm for EE-SE tradeoff for Orthogonal Frequency Division Multiple Access (OFDMA) cellular networks in which different bandwidths are considered. In this paper, the properties of (Resource Efficiency) RE are analyzed and proved that it is capable of optimizing EE-SE tradeoff considering the overall power consumption and different bandwidths. A generalized RE optimization problem was formulated and a scheme optimum power adaptation based on gradient is used to solve it. To reduce the complexity suboptimum algorithm based on power allocation scheme was proposed [29].

2.3 Spatial Modulation

In **2013** Konstantinous Ntontin et. al. presented the comparison of performance and energy efficiency between single RF MIMO perception of SM and single antenna transmission employing MRC technique at the receiver end. Three different fading techniques were used that were Rayleigh, Weibull and Nakagami. The results shown that the nature of the fading technique has bigger impact on energy efficiency gain and signal-to-noise ratio (SNR). The high severity of the fading is that more accurately SM technique is applicable with large number of antennas at transmitter end in comparison to the smaller number of antennas at transmitter end [30].

In **2013** Anthanasios Stavridis et. al. compared the energy efficiency gains between the Spatial Modulation technique, Multiple Input-Single Output (MISO), Multiple Input-Multiple Output (MIMO) and Space-Time-Block- Codes (STBC) under different types of BSs. The analysis was done using Monte Carlo Simulations and limits of Shannon Capacity. The results concluded was that for every type of base station there is a transmission point where energy efficiency is maximized. It was further concluded that same performance is obtained with SM in comparison to MIMO with the advantage of reduced power consumption [31].

In **2013** Tanumay Datta et. al. proposed a new technique known as Generalized Spatial Modulation (GSM). This technique has an advantage that required number of RF chains is less than that used in V-Blast multiplexing technique. In this paper it is shown that by optimum selection of combination of RF chains and transmit antennas, the achievable rate/BER is far better than spatial multiplexing. The analysis is done for 16 transmit antennas and 4-QAM modulation technique and results shows that there is 9.375% increase in achievable rate and 18.15% saving in the number of RF chains. For the detection of GSM signals an algorithm based on Gibbs Sampling was proposed. The performance results of proposed algorithm are better than spatial multiplexing with (Maximum Likelihood Detection) MLD for the same number of RF chains and spectral efficiency [32].

In **2014** Shengehu Wang et. al. designed an uplink transceiver for a multi-user Massive Spatial Modulation over frequency-selective fading channels, where each BS is equipped with large number of antennas but only one transmit RF chain. A low complexity Generalized Approximate Message Passing Detector (GAMPD) is constructed which is used for hardware implementation and its un-coded (Bit error rate) BER and Mean Square Error is analyzed. The comparison of the proposed technique is done with linear detectors and the conclusion drawn was that proposed algorithm has lower complexity. Simulated result of GMAPD approaches to the performance of ML detector and outperforms MMSE appreciably [33].

In **2014**Mako De Renzo et. al. presented a comprehensive state-of-art survey on Spatial Modulation technique. As in today wireless networks, high spectral and energy efficiency are required and Spatial Modulation techniques require only one RF chain so Spatial Modulation is most prominent technique that can be used in future wireless networks. The conclusion was made giving the advantages of Spatial Modulation, the areas where Spatial Modulation application is beneficial and research areas where this technique has not being applied [34].

In **2014** Sandeep Narayanan et. al. studied that multi-user SM is applicable for uplink MIMO systems and is not applicable for linear downlink precoders such as ZF/MMSE. A new precoder for MU-SM single cell system was proposed for mitigating the MU interference. This new precoder has the advantage that it completely eliminates the multi-user interference and allows the users to use ML optimum detection and the performance achieved is same as that of interference-free point to point SM [35].

CHAPTER 3

SYSTEM MODEL

In this chapter the spectral efficiency equations for MU-MIMO system are derived in different fading channels. The spectral efficiency equations derived in [6,19] when receiver has to estimate the transmitted signal from the pilot signals i.e. imperfect CSI are used. The analysis has been done for the different linear detectors. The analysis is done for the multi-users uplink single-cell scenario when the BS has large number of antennas located on it and each user has a single antenna for transmission. The system model for spectral efficiency used for analysis here is same as discussed in [6][19]. The spectral efficiency equation derived in [6] and [19] are used for deriving the energy efficiency equations for Rayleigh and Ricean fading channels.

3.1 Types of Fading Channels

Channel models are used for analyzing the system performance. Due to multipath propagation in wireless communication it is difficult to locate exact channel properties in each environment. There are two types of fading channels for which the spectral efficiency equations are derived using different types of linear detectors. These fading channels are discussed below

3.1.1 Rayleigh Fading Channel

The model assumption is that the signals reflected back and scatter from different paths are i.i.d. complex Gaussian random variables. The element of channel matrix is written in complex form as [36]

$$h_{ij} = c + jd \tag{3.1}$$

The joint probability density function (PDF) for Rayleigh fading channel is written as

$$f_{(c,d)}(c,d)=\frac{1}{2\pi\sigma^2}\exp\left(\frac{-(c^2+d^2)}{2\sigma^2}\right) \tag{3.2}$$

In polar form h_{ij} can be expressed as

$$h_{ij}=r\exp(j\theta) \tag{3.3}$$

where,

$$r=\sqrt{c^2+d^2} \tag{3.4}$$

and

$$\theta=arc\tan\left(\frac{d}{c}\right) \tag{3.5}$$

The joint PDF from polar form in the form of r, can be written as

$$f_{R,\theta}(r,\theta)=\left(\frac{r}{2\pi\sigma^2}\right)\exp\left(-\frac{r}{2\sigma^2}\right) \tag{3.6}$$

3.1.2 Ricean Fading Channel

Ricean fading is the fading in which signal comes from different paths and line-of-sight component is strong than signals coming from other paths. The two parameters used in Ricean fading are K, Ω where K is defined as ratio of powers between the line-of sight-path and scattered paths and Ω is defined as the total power from the line-of-sight path and the scattered paths and is given as $\Omega=v^2+\sigma^2$ and is known as the scaling factor. The PDF for the Ricean fading channel is given as

$$f(x)=\frac{2(K+1)x}{\Omega}\exp\left(-K-\frac{(K+1)x^2}{\Omega}\right)I_O\left(2\sqrt{\frac{K(K+1)}{\Omega}}x\right) \tag{3.7}$$

where, $I_O(.)$ is the zero order Bessel function

The amplitude of the received signal **z** is Rice distributed with parameters $v^2=\frac{K}{K+1}\Omega$ and $\sigma^2=\frac{\Omega}{2(1+K)}$.

3.2 Uplink MU-MIMO Systems

Let us consider communication between the ‘M’ single antenna users and base station equipped with ‘P’ antennas. The coherent detection of the signals transmitted by the M users is done by the BS by using received vector ‘**z**’ with the knowledge of CSI.

The estimation of CSI is done using uplink pilot signals. The assumption is done here that for T symbol interval the channel remains constant. There are two phases in each coherence interval. In the initial phase, for the uplink training only a part τ from coherence interval is used to estimate the channel of users. In later phase, all the M users simultaneously transmit the data to the BS.

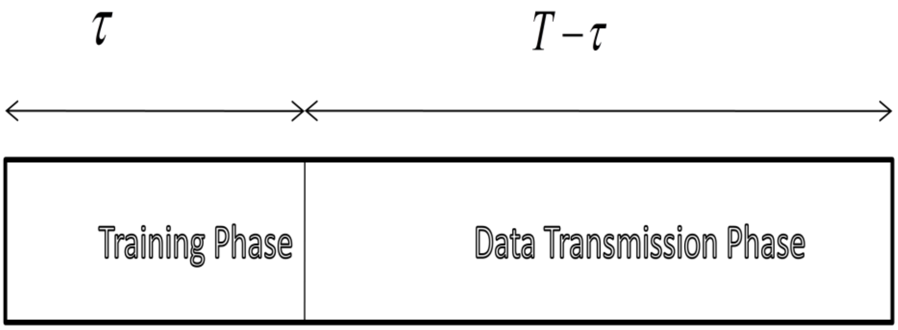


Figure 3.1 Uplink Training protocol

3.3 System Model for Rayleigh Fading Channel

Consider an uplink MU-MIMO system model with P antennas placed at BS and M single antenna users where users transmit data in uplink to BS on same time-frequency channel as shown in Figure 3.2. The vector received $\boldsymbol{z} \in C^{PX1}$ at BS is written as [6]

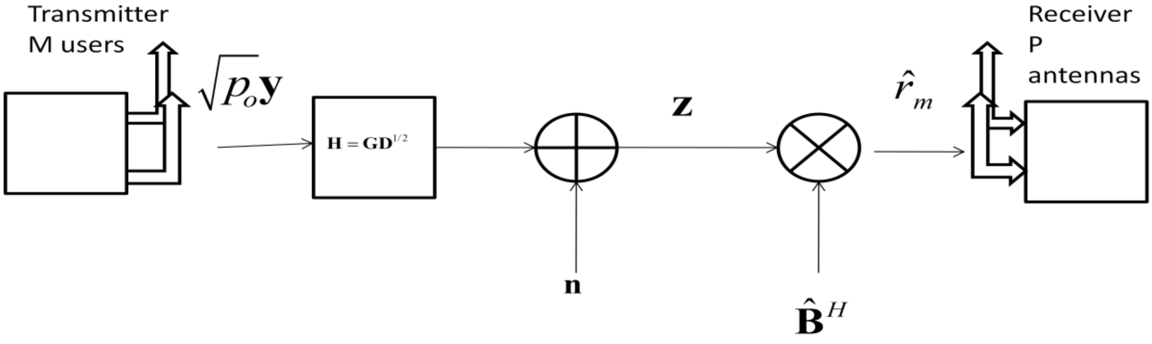


Figure 3.2 Uplink system model

$$\mathbf{z} = \sqrt{p_o}\mathbf{H}\mathbf{y} + \mathbf{n}, \qquad (3.8)$$

where, **H** denotes the P × M channel matrix between users and BS. $\sqrt{p_o}\mathbf{y}$ is M × 1 vector containing signals transmitted from all users and each user transmit p_o average power. **n** is a P × 1 vector containing additive white Gaussian noise whose variance is equal to 1. The h_{pm} channel coefficient stuck between mth user and pth BS antenna comprises of fast fading, log normal shadowing and geometric attenuation [7] is written below as

$$h_{pm} = g_{pm}\sqrt{\beta_m}\ , \tag{3.9}$$

where, $g_{pm}$is fast fading element from mth user to pth antenna of BS and β_m is large fading component containing attenuation and shadow fading. Hence channel matrix **H** is written as

$$\mathbf{H}=\mathbf{G}\mathbf{D}^{1/2}, \tag{3.10}$$

where, **G** is fast fading P × M matrix from users to BS and **D** is M × M diagonal matrix containing attenuation.

The following MRC and ZF linear detector equations respectively are given below

$$\mathbf{B} = \begin{Bmatrix} \mathbf{H} \\ \mathbf{H}(\mathbf{H}^H\mathbf{H})^{-1} \end{Bmatrix} \text{ for MRC and ZF .} \tag{3.11}$$

- **Achievable Rate for Imperfect CSI**

In this case channel matrix **H** is estimated at BS. This is estimated by using the uplink pilot signals τ. For the uplink training a part from the coherence interval is used. Together with the coherence interval used for uplink training, τ symbols orthogonal pilot sequence is assigned to each user. The length of pilot sequences should be greater than or equal to number of users i.e. $\tau \geq M$. The pilot sequences that are used by the M users are represented in the form of the τ × M matrix $\sqrt{p_t}\boldsymbol{\varphi}$, which satisfies $\boldsymbol{\varphi}^H\boldsymbol{\varphi} = \mathbf{I}_M$, where $p_t = \tau$ p_o.

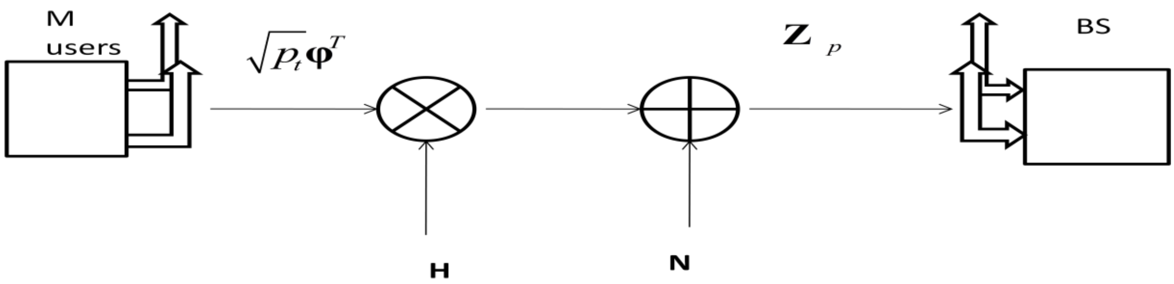


Figure 3.2 System model when pilot matrix is received at BS

The $\mathbf{Z}_p$ P × τ pilot matrix received at BS is given as [9] and is shown in Figure 3.2

$$\mathbf{Z}_p = \sqrt{p_t}\mathbf{H}_w\boldsymbol{\varphi}^T + \mathbf{N} \tag{3.12}$$

where $(.)^T$ denotes the transpose, $(.)^H$ denotes the Hermitian transpose and $\mathbf{N}$ is additive white Gaussian noise P × τ matrix with mean = 0 and variance = 1.

The minimum mean–square error estimate of $\hat{\mathbf{H}}_w$ from $\mathbf{Z}_p$ is

$$\hat{\mathbf{H}}_w = \frac{1}{\sqrt{p_t}}\mathbf{Z}_p\boldsymbol{\varphi}^*\tilde{\mathbf{D}} \tag{3.13}$$

where $(.)^*$ is the complex conjugate and $\tilde{\mathbf{D}} = \left(\frac{1}{p_t}\mathbf{D}^{-1} + \mathbf{I}_M\right)^{-1}$. From equation (3.13) we get

$$\hat{\mathbf{H}}_w = \left(\mathbf{H}_w + \frac{1}{\sqrt{p_t}}\mathbf{W}\right)\tilde{\mathbf{D}} \tag{3.14}$$

where, $\mathbf{H}_w = \mathbf{G}_w\mathbf{D}^{1/2}$ and $\mathbf{W} = \mathbf{N}\boldsymbol{\varphi}^*$. The entries of $\mathbf{W}$ as $\boldsymbol{\varphi}^H\boldsymbol{\varphi} = \mathbf{I}_M$ are i.i.d. Gaussian random variables with mean = 0 and variance =1.

The received vector $\hat{\mathbf{r}}$ at BS is written as

$$\hat{\mathbf{r}} = \sqrt{p_o}\hat{\mathbf{B}}^H\left(\hat{\mathbf{H}}\mathbf{y} - \boldsymbol{\Xi}\mathbf{y}\right) + \hat{\mathbf{B}}^H\mathbf{n} \tag{3.15}$$

The received vector transmitted by mth user after applying the linear detection is given by

$$\hat{r}_m = \underbrace{\sqrt{p_o}\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_m\mathbf{y}_m}_{signal} + \underbrace{\sqrt{p_o}\sum_{\substack{i=1\\ i\neq m}}^{M}\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_i\mathbf{y}_i - \sqrt{p_o}\sum_{i=1}^{M}\hat{\mathbf{b}}_m^H\boldsymbol{\xi}_i\mathbf{y}_i + \hat{\mathbf{b}}_m^H\mathbf{n}}_{Noise+Interference} \tag{3.16}$$

where, $\hat{b}_m, \hat{h}_i, \xi_i$ are the i^{th} columns of $\hat{\mathbf{B}}, \hat{\mathbf{H}}, \boldsymbol{\Xi}$ respectively.

The energy of desired signal and energy of interference and noise is given by

$$E\left[\left|\sqrt{p_o}\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_m\mathbf{y}_m\right|^2\right] = \left|\sqrt{p_o}\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_m\right|^2 E\left|\mathbf{y}_m\right|^2 = \left|\sqrt{p_o}\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_m\right|^2$$

$$E\left[\left|\sqrt{p_o}\sum_{\substack{i=1\\i\neq m}}^{M}\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_i\mathbf{y}_i-\sqrt{p_o}\sum_{i=1}^{M}\hat{\mathbf{b}}_m^H\boldsymbol{\xi}_i\mathbf{y}_i+\hat{\mathbf{b}}_m^H\mathbf{n}\right|^2\right]=p_o\left|\sum_{\substack{i=1\\i\neq m}}^{M}\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_i\right|^2 E\left|\mathbf{y}_i\right|^2+p_o\left|\sum_{i=1}^{M}\hat{\mathbf{b}}_m^H\boldsymbol{\xi}_i\right|^2 E\left|\mathbf{y}_i\right|^2+\left\|\hat{\mathbf{b}}_m^H\right\|^2 E\left|\mathbf{n}\right|^2$$

$$=p_o\left|\sum_{\substack{i=1\\i\neq m}}^{M}\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_i\right|^2+p_o\left|\sum_{i=1}^{M}\hat{\mathbf{b}}_m^H\boldsymbol{\xi}_i\right|^2+\left\|\hat{\mathbf{b}}_m^H\right\|^2 \qquad (3.17)$$

The variance of estimation error vector elements is given by [13]

$$E\left\{\left|[\boldsymbol{\Xi}]_{mi}-E[\boldsymbol{\Xi}]_{mi}\right|^2\right\}=\frac{\beta_i}{\left(1+p_t\beta_i\right)\left(K_i+1\right)} \qquad (3.18)$$

The uplink rate of mth user is defined by

$$R_m=E\left(\log_2(1+SNR)\right) \qquad (3.19)$$

where, SNR is defined as the ratio of signal power to noise power. Since K_i is Ricean component and for Rayleigh fading channel it is considered to be $-\infty$ dB so R_m is rewritten using (3.19)

The uplink rate achieved from the mth user for transmission to the BS is given by

$$R_{IP,m}=E\left\{\log_2\left(1+\frac{p_o\left|\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_m\right|^2}{p_o\sum\limits_{i=1,i\neq m}^{M}\left|\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_i\right|^2+p_o\left\|\hat{\mathbf{b}}_m\right\|^2\sum\limits_{i=1}^{M}\frac{\beta_i}{\tau p_o\beta_i+1}+\left\|\hat{\mathbf{b}}_m\right\|^2}\right)\right\} \qquad (3.20)$$

If transmit power of each user is cut down, power reduction is suffered by both pilot signals and data. The power of each user is cut down by the square root of number of antennas placed at the BS. By putting the value of $p_o=\frac{Eu}{\sqrt{P}}$ and P→∞ the uplink rate by using the MMSE estimation is given by [19]

$$R_{IP,m}=\log_2\left(1+\tau Eu^2\beta_m^2\right) \qquad (3.21)$$

- **Maximum-Ratio-Combining:** On substituting $\hat{\mathbf{b}}_m = \hat{\mathbf{h}}_m$ for MRC the (3.20) is written as

$$R^{mrc}_{IP,m} = E\left\{ \log_2 \left(1 + \frac{p_o \left\| \hat{\mathbf{h}}_m \right\|^4}{p_o \sum\limits_{i=1, i\neq m}^{M} \left| \hat{\mathbf{h}}_m^H \hat{\mathbf{h}}_i \right|^2 + p_o \left\| \hat{\mathbf{h}}_m \right\|^2 \sum\limits_{i=1}^{M} \frac{\beta_i}{\tau p_o \beta_i + 1} + \left\| \hat{\mathbf{h}}_m \right\|^2} \right) \right\} \tag{3.22}$$

The lower bounded uplink rate for the case of imperfect CSI and Rayleigh fading channel for P ≥ 2 obtained from mth user is given by [19]

$$\tilde{R}^{mrc}_{IP,m} = \log_2 \left(1 + \frac{\tau p_o (P-1) \beta_m^2}{(\tau p_o \beta_m + 1) \sum\limits_{i=1, i\neq m}^{M} \beta_i + (\tau + 1)\beta_m + \frac{1}{p_o}} \right) \tag{3.23}$$

On putting $p_o = \frac{Eu}{\sqrt{P}}$ in (3.23) and P→∞ the above equation reduces to (3.21).

- **Zero-Forcing Receiver**: On putting $\hat{\mathbf{b}}_m^H \hat{\mathbf{h}}_i = \delta_{mi}$ in (3.20) the uplink rate achieved for mth user is given by [19]

$$R^{zf}_{IP,m} = E\left\{ \log_2 \left(1 + \frac{p_o}{\left(\sum\limits_{i=1}^{M} \frac{p_o \beta_i}{\tau p_o \beta_i + 1} \right) \left[\left(\hat{\mathbf{H}}^H \hat{\mathbf{H}} \right)^{-1} \right]_{mm}} \right) \right\} \tag{3.24}$$

The lower bounded uplink rate for the case of imperfect CSI and Rayleigh fading channel for P ≥ M+1 obtained from mth user is given by [19]

$$\tilde{R}^{zf}_{IP,m} = \log_2 \left(1 + \frac{\tau p_o^2 \left(P - M \right) \beta_m^2}{\left(\tau p_o \beta_m + 1 \right) \sum\limits_{i=1}^{M} \frac{p_o \beta_i}{\tau p_o \beta_i + 1} + \tau p_o \beta_m + 1} \right) \tag{3.25}$$

Similarly, on putting $p_o = \frac{Eu}{\sqrt{P}}$ in (3.25) and P→∞ the above equation reduces to (3.21).

3.4 System Model for Ricean Fading Channel

In this section the uplink achievable rate for mth user is discussed for imperfect CSI case considering Maximum-Ratio-Combining Receiver. The initial equations are same as (3.8), (3.9) and (3.10). The $\mathbf{G}$ channel P × M matrix contains two components one line-of-sight i.e. Ricean component and other is non line-of-sight i.e. Rayleigh component. The **G** which is P × M fast fading channel matrix is written as [36]

$$\mathbf{G}=\bar{\mathbf{G}}[\boldsymbol{\theta}(\boldsymbol{\theta}+\mathbf{I_M})^{-1}]^{1/2}+\mathbf{G}_w[(\boldsymbol{\theta}+\mathbf{I_M})^{-1}]^{1/2} \tag{3.26}$$

where, $\boldsymbol{\theta}$ is M×M diagonal matrix with $[\boldsymbol{\theta}]_{mm}=K_m$ where K_m is the Ricean component whose power is measured in dB and $\mathbf{I}_M$ is the M × M identity matrix. The entries of $\mathbf{G_w}$ are Gaussian random variables whose mean is zero and variance is ½ and $\bar{\mathbf{G}}$ is the deterministic component. The line-of-sight component K_m is already known and evaluation of deterministic component $\bar{\mathbf{G}}$ is to be done. The channel matrix **H** is estimated as [19]

$$\hat{\mathbf{H}} = \bar{\mathbf{H}}[\boldsymbol{\theta}(\boldsymbol{\theta}+\mathbf{I}_M)^{-1}]^{1/2} + \hat{\mathbf{H}}_w[(\boldsymbol{\theta}+\mathbf{I_M})^{-1}]^{1/2} \tag{3.27}$$

where, $\bar{\mathbf{H}}$ and $\hat{\mathbf{H}}_w$ are the deterministic and the predictable random components of **H** respectively**.** The deterministic component of **H** can be expressed as $\bar{\mathbf{H}}=\mathbf{G}\mathbf{D}^{1/2}$ and $\mathbf{H}_w=\mathbf{G}_w\mathbf{D}^{1/2}$. In this, the channel is estimated using uplink pilot signals as done in [19] and τ is the number of pilot symbols. Orthogonal pilot sequences are transmitted by M users of τ symbols that are stacked into τ × M matrix $\sqrt{p_t}\boldsymbol{\varphi}$, which satisfies $\boldsymbol{\varphi}^H\boldsymbol{\varphi}=\mathbf{I}_M$, where $p_t=\tau\, p_o$.

- **Imperfect CSI Uplink Rate**

In this section the uplink rate for Ricean fading channel with imperfect CSI MRC receiver is discussed. The equations (3.12)-(3.19) are same as described in section 3.3 imperfect CSI case Rayleigh fading channel. The uplink rate achieved by the mth user is given as

$$C_{IP}=\frac{T-\tau}{T}\sum_{i=1}^{M}R_{IP,m} \tag{3.28}$$

- **Maximum-Ratio-Combining:** The uplink rate achieved by mth user using MRC receiver is given as

$$R_{IP,m} = E\left\{\log_2\left(1+\frac{po\left|\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_m\right|^2}{p_o\sum_{\substack{i=1\\i\neq m}}^{M}\left|\hat{\mathbf{b}}_m\hat{\mathbf{h}}_i\right|^2+p_o\sum_{i=1}^{M}\left|\hat{\mathbf{b}}_m^H\boldsymbol{\xi}_i\right|^2+\left\|\hat{\mathbf{b}}_m\right\|^2}\right)\right\} \tag{3.29}$$

On substituting $\hat{\mathbf{b}}_m = \hat{\mathbf{h}}_m$ for MRC the (40) is written as

$$R_{IP,m} = E\left\{\log_2\left(1+\frac{p_o\left\|\hat{\mathbf{h}}_m\right\|^4}{p_o\sum_{i=1,i\neq m}^{M}\left|\hat{\mathbf{h}}_m\mathbf{h}_i\right|^2+p_o\sum_{i=1}^{N}\left|\hat{\mathbf{h}}_m\boldsymbol{\Xi}_i\right|^2+\left\|\hat{\mathbf{h}}_m\right\|^2}\right)\right\} \tag{3.30}$$

On substituting the value of $\boldsymbol{\Xi}_i$ from (3.18) the (3.30) is rewritten as

$$R_{IP,m} = E\left\{\log_2\left(1+\frac{po\left|\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_m\right|^2}{p_o\sum_{\substack{i=1\\i\neq m}}^{M}\left|\hat{\mathbf{b}}_m^H\hat{\mathbf{h}}_i\right|^2+p_o\sum_{i=1}^{M}\left\|\hat{\mathbf{b}}_m\right\|^2\frac{p_o\beta_i}{(1+p_t\beta_i)(K_i+1)}+\left\|\hat{\mathbf{b}}_m\right\|^2}\right)\right\} \tag{3.31}$$

The uplink rate achieved for imperfect CSI using MRC receiver in Ricean fading channel is given as [19]

$$\tilde{R}_{IP,m}^{MRC} = \log_2\left(1+\frac{p_0\beta_m\left[P^2K_m^2+\left(2PK_m+2P^2K_m\right)\eta_m+\left(P+P^2\right)\eta_m^2\right]}{p_o\left(K_m+1\right)\sum_{\substack{i=1\\i\neq m}}^{M}\beta_i\Delta+Pp_0\beta_m\frac{K_m+\eta_m}{1+\beta_m pt}+P\left(K_m+1\right)\left(K_m+\eta_m\right)}\right) \tag{3.32}$$

where, η_m is given as $\eta_m = \frac{p_t\beta_m}{(1+p_t\beta_m)}$ and $p_t = \tau p_o$ and Δ is defined by (3.33)

$$\Delta = \left[\left(K_m+1\right)\left(K_i+1\right)\Phi^2+P\eta_m\left(K_i+1\right)+PK_m\right]\Big/\left(K_i+1\right) \tag{3.33}$$

and Φ is defined as (3.34)

$$\Phi \triangleq \frac{Sin\left(\frac{P\pi}{2}\left[Sin(\Omega_m)-Sin(\Omega_i)\right]\right)}{Sin\left(\frac{\pi}{2}\left[Sin(\Omega_m)-Sin(\Omega_i)\right]\right)} \tag{3.34}$$

In case of imperfect CSI when each user transmit power is cut, half of the power is cut down by the pilot signals and half while transmission from the users so the transmit power $p_o = \frac{Eu}{P}$, P→∞ and on putting Ricean K_m factor value =0 the (3.32) reduces to

$$\tilde{R}_{IP,m}^{mrc} = \log_2\left(1+\frac{p_o\beta_m P^2}{p_o\sum_{i=1,i\neq m}^{M}\beta_i\Phi^2+P}\right) \tag{3.35}$$

3.4 Spectral Efficiency Analysis

The spectral efficiency of single cell for the imperfect CSI is given as

$$R_{IP}^{B} = \frac{T-\tau}{T}\sum_{m=1}^{M}\tilde{R}_{IP,m}^{B} \tag{3.36}$$

where, **B** is linear detector matrix, T is coherence time interval, τ is length of pilot sequences and $\tilde{R}_{IP,m}^{B}$ is the achieved rate by m$^{\text{th}}$ user.

The spectral efficiency for Maximum Ratio Combining (MRC) receiver per-cell in Rayleigh fading channel is given by

$$\tilde{R}_{IP,m}^{mrc} = \frac{T-\tau}{T}M\log_2\left(1+\frac{\tau p_o(P-1)\beta_m^2}{(\tau p_o\beta_m+1)\sum_{i=1,i\neq m}^{M}\beta_i+(\tau+1)\beta_m+\frac{1}{p_o}}\right) \tag{3.37}$$

The spectral efficiency for Zero Forcing (ZF) receiver per-cell in Rayleigh fading channel is given by

$$\tilde{R}^{zf}_{IP,m} = \frac{T-\tau}{T} M \log_2 \left(1 + \frac{\tau p_o^2 \left(P - M \right) \beta_m^2}{\left(\tau p_o \beta_m + 1 \right) \sum_{i=1}^{M} \frac{p_o \beta_i}{\tau p_o \beta_i + 1} + \tau p_o \beta_m + 1} \right) \tag{3.38}$$

The spectral efficiency for Maximum Ratio Combining (MRC) receiver per-cell in Ricean fading channel is given by

$$\tilde{R}^{MRC}_{IP,m} = \frac{T-\tau}{T} M \log_2 \left(1 + \frac{p_0 \beta_m \left[P^2 K_m^2 + \left(2PK_m + 2P^2 K_m \right) \eta_m + \left(P + P^2 \right) \eta_m^2 \right]}{p_o \left(K_m + 1 \right) \sum_{\substack{i=1 \\ i \neq m}}^{M} \beta_i \Delta + P p_0 \beta_m \frac{K_m + \eta_m}{1 + \beta_m pt} + P \left(K_m + 1 \right) \left(K_m + \eta_m \right)} \right) \tag{3.39}$$

CHAPTER 4

ENERGY EFFICIENY ANALYSIS OF LARGE ANTENNA SYSTEMS

4.1 Introduction

Energy efficiency is a prominent research issue in massive MIMO wireless communication systems. In this chapter, the energy efficiency of large multi-user uplink antenna system using maximum-ratio-combining (MRC) receiver and zero-forcing (ZF) receiver has been analyzed. Each user has single antenna for transmission and BS has large number of antennas (say tens or hundreds). The analysis is done assuming imperfect channel state information (CSI). In this analysis the effect of large scale fading is ignored. For Rayleigh fading environment analysis is done for both MRC and ZF receiver and for Ricean fading only MRC receiver is considered. In the analysis the effect of transmit power consumption of all devices used in the channel and loss factors of DC-DC power supply, antenna feeder, Main power supply and active coolant system is also considered. The results are derived for scaled down and un-scaled transmitted power. The transmitted power of each user is scaled down by number of antennas at BS for Ricean fading channel and by the square root of number of antennas at the BS for Rayleigh fading channel.

4.2 Energy Efficiency versus Spectral Efficiency Tradeoff

Energy efficiency is defined as the relative amount of the capacity to the total power consumed.

$$\eta = \frac{\sum_{i=1}^{M} R_i}{p_o} \tag{4.1}$$

There is a need to increase the spectral efficiency but with an increase in spectral efficiency the power consumption increases and therefore the energy efficiency decreases. Therefore, there occurs a tradeoff between energy and spectral efficiency. There is a point where with increase in the spectral efficiency the energy efficiency decreases thus, there occurs a tradeoff. If the number of antennas at the BS is fixed the transmit power of the user, number of users and other factors can be adjusted to obtain high energy efficiency.

4.2.1 Energy Efficiency considering Transmit Power of User with imperfect CSI

The spectral efficiency for the imperfect CSI is given by (3.36) where **B** is the decoding matrix for MRC and ZF receiver. The energy efficiency considering the transmit power for imperfect CSI is given as

$$\eta_{IP}^{B} = \frac{\sum_{i=1}^{M} R_{IP}^{B}}{p_o} \tag{4.2}$$

where, η_{IP}^{B} is the energy efficiency with imperfect CSI, R_{IP}^{B} is the uplink achieved rate by the mth user and p_o is transmitted power. The effect of large-scale fading incorporated in R_{IP}^{B} is ignored because this causes the equations of energy efficiency of intractable form. The value of energy efficiency changes with change in the value of SNR.

4.2.1.1 Rayleigh Fading Channel

For the case of the perfect CSI, it is clear from [13] that with increase in the transmit power p_o the energy efficiency decreases. But this is not the case for the imperfect CSI. The spectral efficiency for MRC receiver with imperfect CSI is given by (3.37) and the energy efficiency (EE_{MRC}^{Ray}) for MRC receiver with imperfect CSI neglecting the effect of large scale fading is given by

$$EE_{MRC}^{Ray} = \frac{\frac{T-\tau}{T} M \log_2\left(1+\frac{\tau\left(P-1\right)p_o^2}{\tau\left(M-1\right)p_o^2+\left(M+\tau\right)p_o+1}\right)}{p_o} \tag{4.3}$$

where, M is number of users present in the single cell, P are the number of antennas located at the BS and τ is the number of pilot sequences.

The spectral efficiency for ZF with imperfect CSI is given by (3.38) and the energy efficiency (EE_{ZF}^{Ray}) for ZF receiver with imperfect CSI neglecting the effect of large scale fading is given by

$$EE_{ZF}^{Ray} = \frac{\frac{T-\tau}{T} M \log_2\left(1+\frac{\tau p_o{}^2(P-M)}{(M+\tau)p_o+1}\right)}{p_o} \tag{4.4}$$

4.2.1.2 Ricean Fading Channel

The spectral efficiency for MRC imperfect CSI, Ricean fading channel is given by (3.39) and the total energy efficiency (EE_{MRC}) with the imperfect CSI neglecting the effect of large scale fading is given by following equation. K_m is the line-of-sight component i.e. Ricean component whose value is expressed in dB for the mth user, η_m, p_t and Δ are given by (3.33).

$$EE_{MRC} = \frac{\frac{T-\tau}{T} M \left[\log_2\left(1+\frac{p_o(P^2K_m^2+2P^2K_m)\eta_m+(P+P^2)\eta_m}{p_o(K_m+1)(M-1)\Delta^2+Pp_o(\frac{K_m+\eta_m}{1+p_t})+P(K_m+1)(K_m+\eta_m)}\right)\right]}{p_o}$$

4.2.2 Total Energy Efficiency considering Transmit Power of User and Circuit Power of complete system with imperfect CSI

The circuit power of the system can be calculated using the block diagrams shown in Figures 4.1 and 4.2. Figure 4.1 shows the transmitter block diagram in which data transmitted by the user passes through Digital to Analog Converter (DAC) which is used to convert the digital signal to analog signal and then the signal passes through filter which is used to suppress the noise then further the signal is multiplied with the signal transmitted by Local Oscillator (LO) in the mixer. The output of the mixer is then passed by the filter to further suppress the noise added by the LO and then before transmitting the signal to the channel it is passed by the power amplifier (PA) which is used to amplify the power. The transmitter circuit power consumed by one user is given as

$$P_{TRANSMITTER} = (P_{DAC}+P_{MIXR}+P_{FILRT}) + P_{SYN} \tag{4.5}$$

The transmitter circuit power consumed by M users is given by

$$P_{TRANSMITTER} = M\ (P_{DAC}+P_{MIXR}+P_{FILRT}) + P_{SYN} \tag{4.6}$$

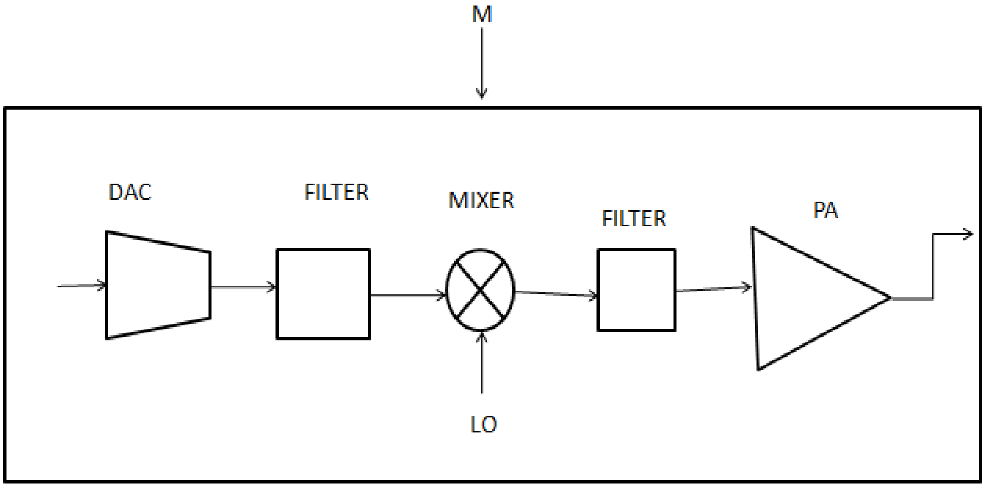


Figure 4.1 Transmitter circuit block

Figure 4.2 shows the receiver circuit power consumption model where the signal from the channel is first passed by filter to suppress the noise then it is passed by Low Noise Amplifier (LNA) which is used to amplify the very weak signals and then the signal is passed by the filter and then signal is multiplied by LO signal in the mixer. The signal from the mixer is passed by the filter to remove the unwanted signal and further it is passed by Intermediate Frequency Amplifier (IFA) to change the frequency levels in the circuit and then signal from IFA is passed to Analog to Digital Converter (ADC) to convert the analog signal to digital signal.

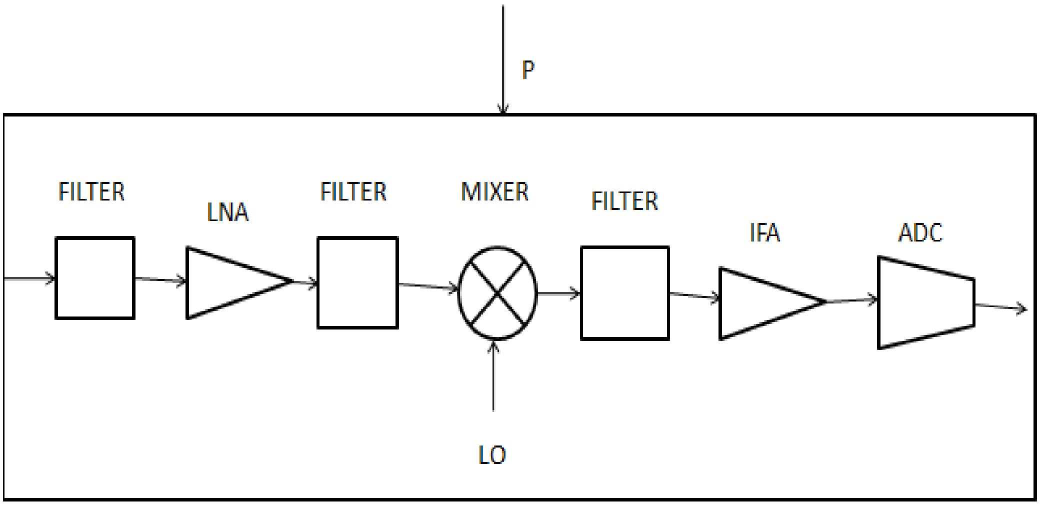


Figure 4.2 Receiver circuit block

The receiver circuit power used by one antenna at BS is given as

$$P_{RECEIVER} = P_{SYN} + (P_{LNA}+P_{MIXR}+P_{IFA}+P_{FILRR}+P_{ADC}) \qquad (4.7)$$

The receiver circuit power used by P antenna at BS is given as

$$P_{RECEIVER} = P_{SYN} + P\,(P_{LNA}+P_{MIXR}+P_{IFA}+P_{FILRR}+P_{ADC}) \qquad (4.8)$$

Total power consists of transmitted power and circuit power. Circuit power is defined as [24].

$$P_{CIRCUIT}= P_{TRANSMITTER}+ P_{RECEIVER} \qquad (4.9)$$

$$P_{CIRCUIT} = M\,(P_{DAC}+P_{MIXR}+P_{FILRT}) + 2P_{SYN} + P\,(P_{LNA}+P_{MIXR}+P_{IFA}+P_{FILRR}+P_{ADC}), \qquad (4.10)$$

where, M is number of antennas located at transmitter and P is number of antennas located at the BS. P_{DAC} is the power utilization value of Digital to Analog Converter (DAC), P_{MIXR} is the power utilization value of mixer, P_{FILTR} is the power utilization value of filters that are active at the transmitter end and P_{FILRR} is the power utilization value of filters that are active at the receiver end. P_{LNA} and P_{IFA} are the power utilization values of low noise amplifier and intermediate frequency amplifier. P_{ADC},P_{SYN} are power utilization values of analog to digital converters, frequency synthesizer respectively. By incorporating large scale fading the equations becomes intractable to plot so, we are neglected the effect of large scale fading.

4.2.2.1 Rayleigh Fading Channel

The per cell total energy efficiency (EE_{MRC}^{Ray}) of MRC receiver with imperfect CSI considering the transmit power and total circuit power of components used at transmitter and receiver side and neglecting the effect of large scale fading is given by

$$EE_{MRC}^{Ray} = \frac{\frac{T-\tau}{T} M \log_2\left(1+\frac{\tau\left(P-1\right)p_o^2}{\tau\left(M-1\right)p_o^2+\left(M+\tau\right)p_o+1}\right)}{\frac{p_o}{\kappa}+P_{CIRCUIT}} \tag{4.11}$$

where, κ is efficiency of power amplifier.

The per cell total energy efficiency (EE_{ZF}^{Ray}) with imperfect CSI for ZF receiver considering the transmit power and total circuit power of the components used at transmitter and receiver side and neglecting the effect of large scale fading is given by

$$EE_{ZF}^{Ray} = \frac{\frac{T-\tau}{T} M \log_2\left(1+\frac{\tau {p_o}^2(P-M)}{(M+\tau)p_o+1}\right)}{\frac{p_o}{\kappa}+P_{CIRCUIT}} \tag{4.12}$$

4.2.2.2 Ricean Fading Channel

In this both line-of-sight component and Rayleigh distributed component are considered. The per cell total energy efficiency (EE_{MRC}) of MRC receiver with imperfect CSI considering the transmit power and total circuit power of components used at the transmitter and receiver side and neglecting the effect of large scale fading is given by

$$EE_{MRC} = \frac{\frac{T-\tau}{T} M \left[\log_2\left(1+\frac{p_o(P^2K_m^2+2P^2K_m)\eta_m+(P+P^2)\eta_m}{p_o(K_m+1)(M-1)\Delta^2+Pp_o(\frac{K_m+\eta_m}{1+p_t})+P(K_m+1)(K_m+\eta_m)}\right)\right]}{\frac{p_o}{\kappa}+P_{CIRCUIT}}$$

4.2.3 Total Energy Efficiency considering Transmit Power of User, Circuit Power of complete system and Loss Factors with imperfect CSI

In this case the total energy efficiency (EE_{MRC}) analysis is done considering the transmit power, circuit power and loss factors such as antenna feeder loss, main supply loss, active coolant loss and DC-power supply loss. These loss factors have a great impact on the energy efficiency analysis.

4.2.3.1 Rayleigh Fading Channel

The per cell total energy efficiency (EE_{MRC}^{Ray}) analysis of MRC receiver neglecting the effect of large scale fading is given as

$$EE_{MRC}^{Ray} = \frac{\frac{T-\tau}{T} M \log_2\left(1+\frac{\tau\left(P-1\right)p_o^2}{\tau\left(M-1\right)p_o^2+\left(M+\tau\right)p_o+1}\right)}{\frac{\frac{p_o}{\kappa(1-\Omega_{feeder})}+P_{CIRCUIT}}{(1-\Omega_{dc})(1-\Omega_{ms})(1-\Omega_{cool})}} \tag{4.13}$$

where, $\Omega_{feeder}, \Omega_{dc}, \Omega_{ms}, \Omega_{cool}$ are the loss factor of antenna feeder, DC-DC power supply, main power supply and active coolant system respectively.

The per cell total energy efficiency (EE_{ZF}^{Ray}) analysis of ZF receiver neglecting the effect of large scale fading is given as

$$EE_{ZF}^{Ray} = \frac{\frac{T-\tau}{T} M \log_2\left(1+\frac{\tau p_o{}^2(P-M)}{(M+\tau)p_o+1}\right)}{\frac{\frac{p_o}{\kappa(1-\Omega_{feeder})}+P_{CIRCUIT}}{(1-\Omega_{dc})(1-\Omega_{ms})(1-\Omega_{cool})}} \tag{4.14}$$

4.2.3.2 Ricean Fading Channel

The total energy efficiency (EE_{MRC}) analysis of single cell MRC receiver with imperfect CSI neglecting the effect of large scale fading is given as

$$EE_{MRC}=\frac{\frac{T-\tau}{T}M\left[\log_2\left(1+\frac{p_o(P^2K_m^2+2P^2K_m)\eta_m+(P+P^2)\eta_m}{p_o(K_m+1)(M-1)\Delta^2+Pp_o(\frac{K_m+\eta_m}{1+p_t})+P(K_m+1)(K_m+\eta_m)}\right)\right]}{\frac{\frac{p_o}{\kappa(1-\Omega_{feeder})}+P_{CIRCUIT}}{(1-\Omega_{dc})(1-\Omega_{ms})(1-\Omega_{cool})}}$$

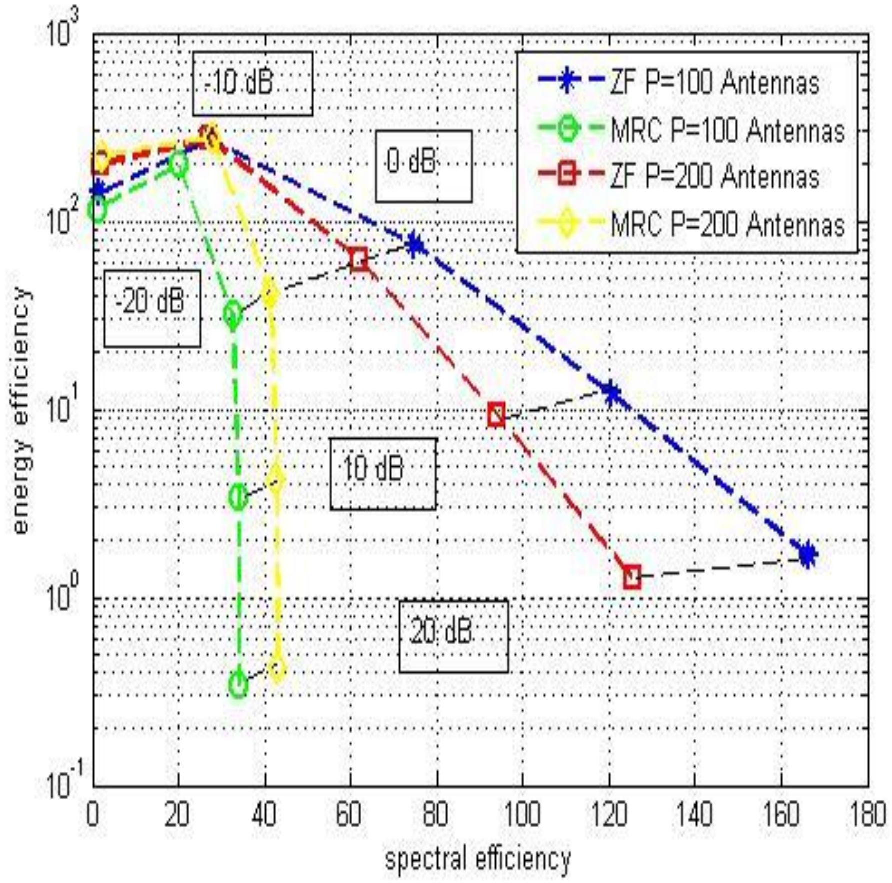
4.3 Results

For the simulation of total energy and spectral efficiency, energy efficiency and transmit power, a single cell scenario is considered, in which M single antenna users are placed at transmitter side and P antennas are placed at BS on receiver side. The spectral efficiency is calculated from the equations (3.37)-(3.39) described in chapter 3. The analysis is done for Rayleigh and Ricean fading channel. The transmit power p_o is varied from -20 to 20 dB. The analysis is done for M= 10 number of users and P=100 and 200 antennas placed at the BS with imperfect CSI and Rayleigh (MRC and ZF receivers) Ricean fading channels (MRC receiver). The results are shown when the transmit power is un-scaled and when transmit power of each user is cut down by number of antennas placed at BS in Ricean fading channel and by the square root of number of antennas placed at BS in Rayleigh fading channel. The Ricean factors K_m and K_i both equal to 10 dB are considered for Ricean fading and for Rayleigh fading K_m and K_i is considered to be zero i.e. $-\infty$ dB.

The values of feeder loss Ω_{feeder}, main power supply loss Ω_{ms}, DC-DC power loss Ω_{dc}, active coolant loss Ω_{cool}, P_{DAC} power utilization value of Digital to Analog converter, P_{ADC} power utilization value of Analog to Digital converter, P_{FILTR} power utilization value of filters active at transmitter end, P_{FILRR} power utilization value of filters active at receiver end, P_{IFA} power utilization value of Intermediate Frequency Amplifier, P_{LNA} power utilization value of Low Noise Amplifier are given in Table 4.1

Table 4.1 System Parameters

P_{MIXR}	30.3 mW	κ	38%
$P_{FILRT} = P_{FILRR}$	2.5 mW	Ω_{feeder}	0.5
$P_{LNA}=P_{IFA}$	20 mW	Ω_{dc}	0.6
P_{SYN}	50 mW	Ω_{ms}	0.7
$P_{ADC}=P_{DAC}$	1 mW	Ω_{cool}	0.8



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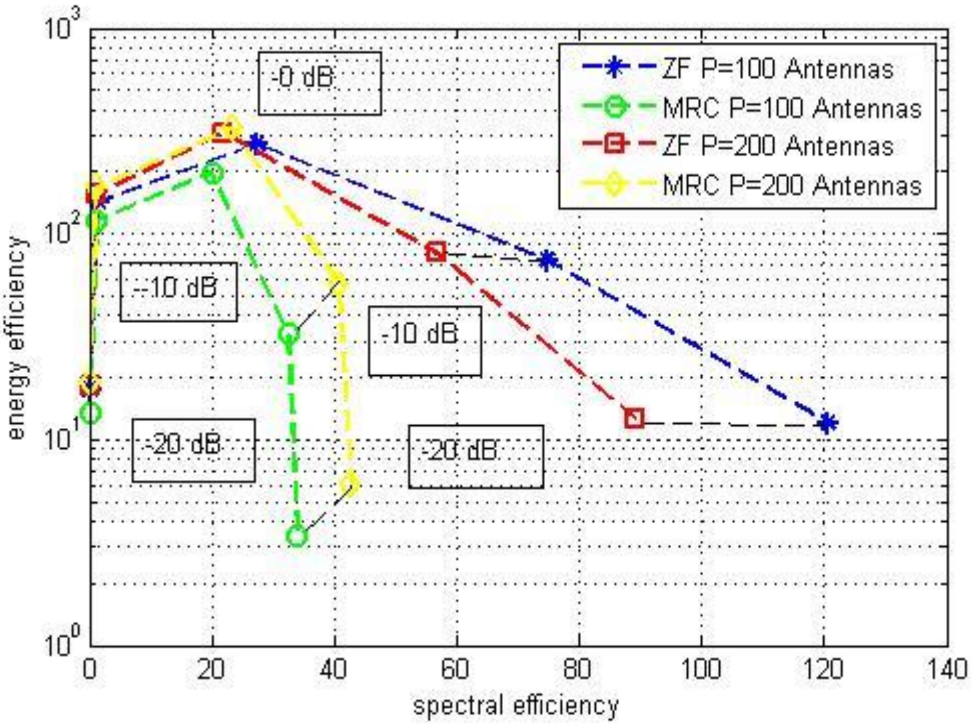

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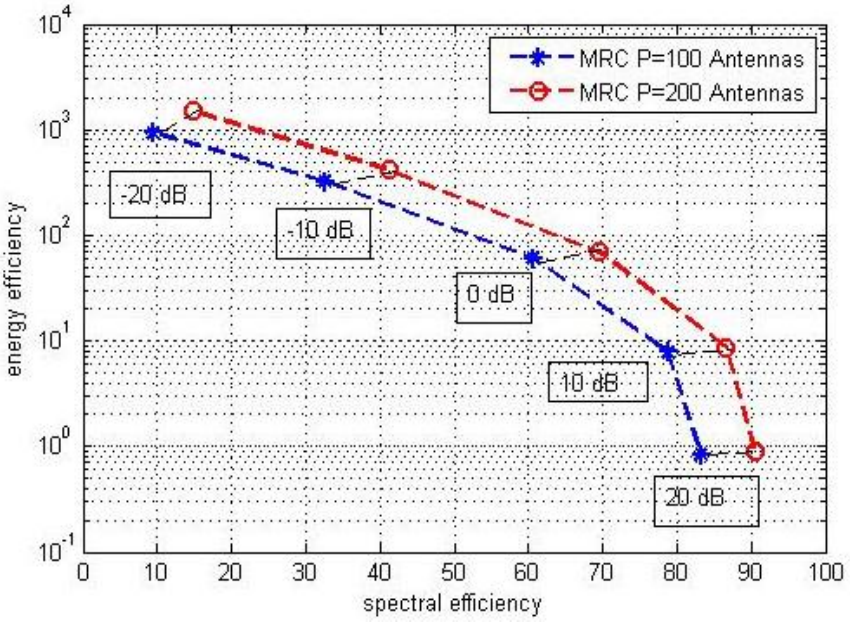
Figure 4.3 Energy Efficiency vs Spectral Efficiency for Rayleigh fading channel (a) un-scaled p_o=-20 to 20 dB and (b) scaled power p_o=Eu/sqrt (P) with transmitted power for M=10 users and P=100 and 200 antennas. Eu is varied from -20dB to 20 dB

Figure 4.3 (a) and(b) shows the graph between energy and spectral efficiency with MRC and ZF receivers Rayleigh fading channels with un-scaled transmit power and when tranmit power of each user is cut down by square root of number of antennas P placed at BS. It has been observed that ZF performance is better than MRC and tradeoff is observed between energy and spectral efficiency for both cases. In case of MRC when number of antennas at BS are doubled the energy and spectral efficiency increses but for the ZF receiver as tranmit power is incresed after 0 dB with increase in the number of antennas at BS the energy efficiency decreases. Spectral efficiency reduces alittle bit when the transmit power of each user is cut down by square root of number of antennas present at BS.

Figure 4.4 (a) and (b) shows the graph between energy and spectral efficiency of MRC receiver in Ricean fading fading for un-scaled transmit power and when tranmit power of each user is cut down by number of antennas present at BS. It has been observed that when number of antennas at BS increases both the spectral efficiency and energy efficiency increseases. Spectral efficieny reduces when the tranmit power of each user is cut down by the number of antennas present at BS.



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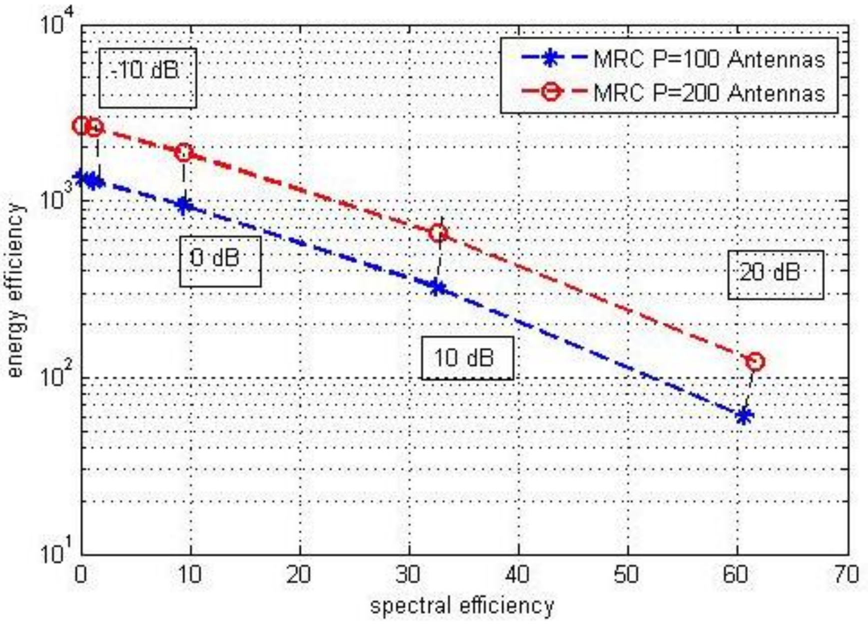

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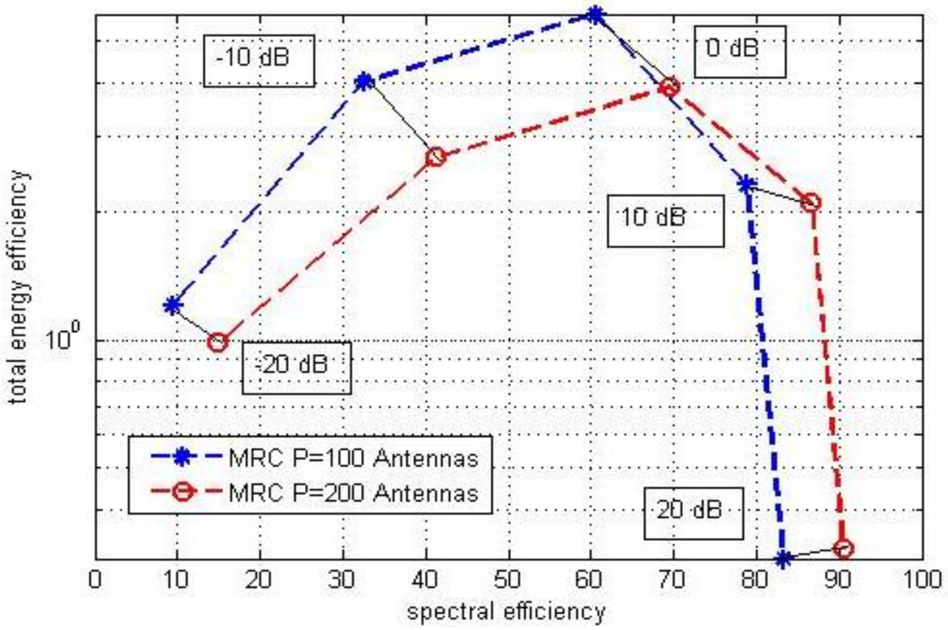
Figure 4.4 Energy Efficiency vs Spectral Efficiency for Ricean fading channel (a) un-scaled p_o=-20 to 20 dB and (b) scaled power p_o=Eu/P with transmitted power for M=10 users and P=100 and 200 antennas. Eu is varied from -20dB to 20 Db



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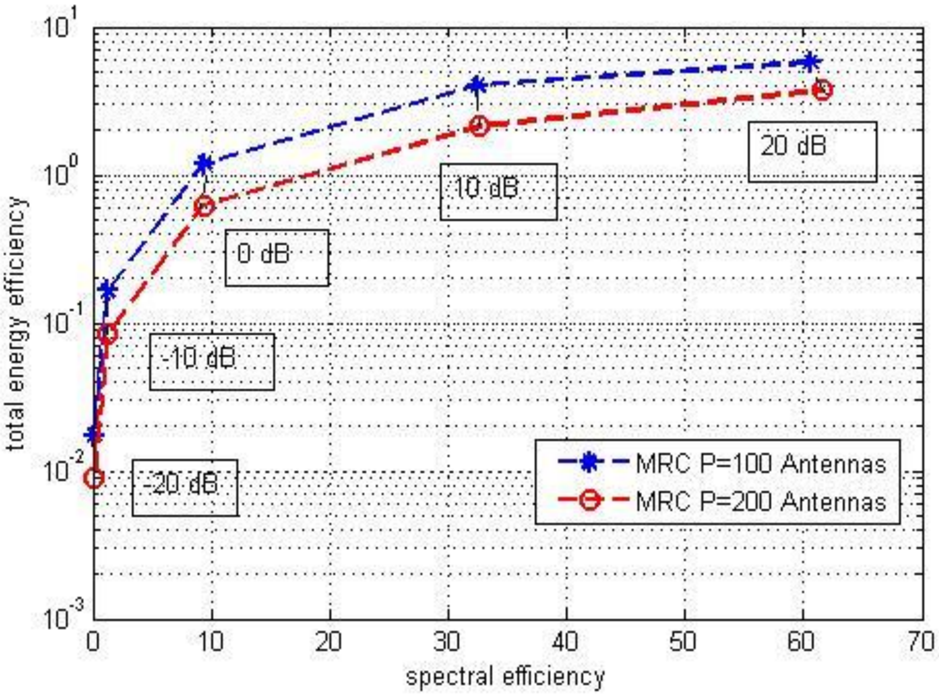

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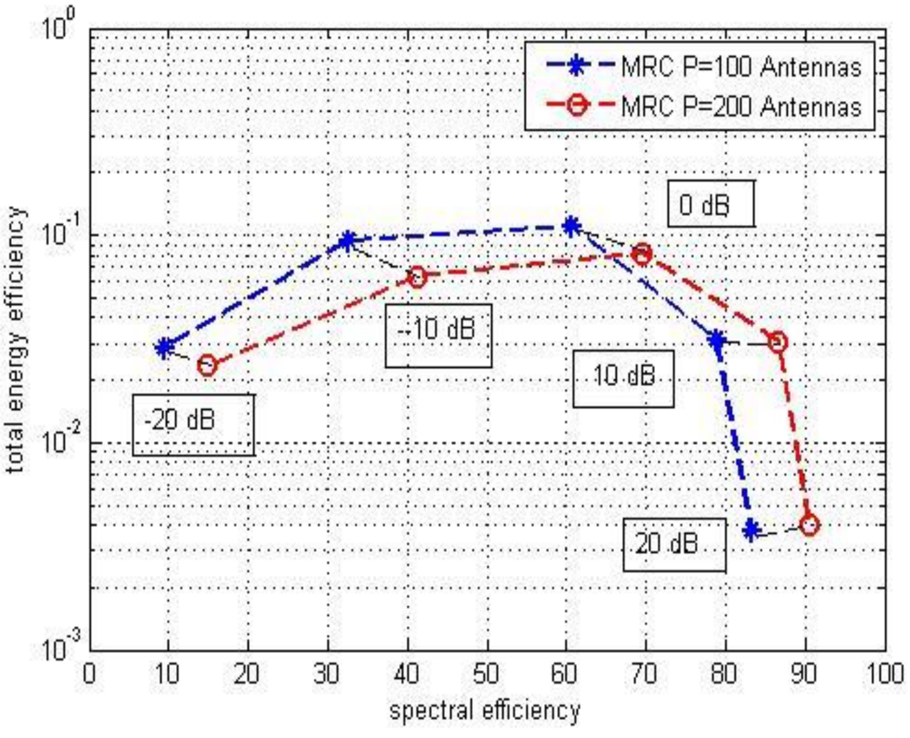
Figure 4.5 Energy Efficiency vs Spectral Efficiency for Ricean fading channel (a) un-scaled p_o=-20 to 20 dB and (b) scaled power p_o=Eu/P with circuit power and transmitted power for M=10 users and P=100 and 200 antennas. Eu is varied from -20dB to 20 dB.

Figure 4.5 (a) and (b) shows the graph between energy and spectral efficiency for un-scaled and scaled transmit power considering transmit and circuit power for Ricean fading channel. It has been concluded that when power is un-scaled the tradeoff is seen between the energy and spectral efficiency i.e. with increase in spectral efficiency energy efficiency first increases and then decreases but for scaled transmit power no tradeoff is observed the energy efficiency increases with increase in spectral efficiency.

Figure 4.6 (a) and (b) shows graph between energy and spectral efficiency when transmit, circuit power and loss factors are considered for Ricean fading channel for un-scaled and scaled transmit power with 100 and 200 antennas located at the BS. It is conclued that tradeoff is observed for un-scaled transmit power i.e. with increase in spectral efficiency, energy efficiency first increases and then decreases and for scaled transmit power there is no tradeoff observed energy efficiency increases with increase in spectral efficiency. The spectral efficiency reduces when transmit power of each user is cut down by number of antennas presesnt at BS in comparison to the un-scaled tranmit power and energy efficiency increases when transmit power is scaled in comparison to un-scaled transmit power.



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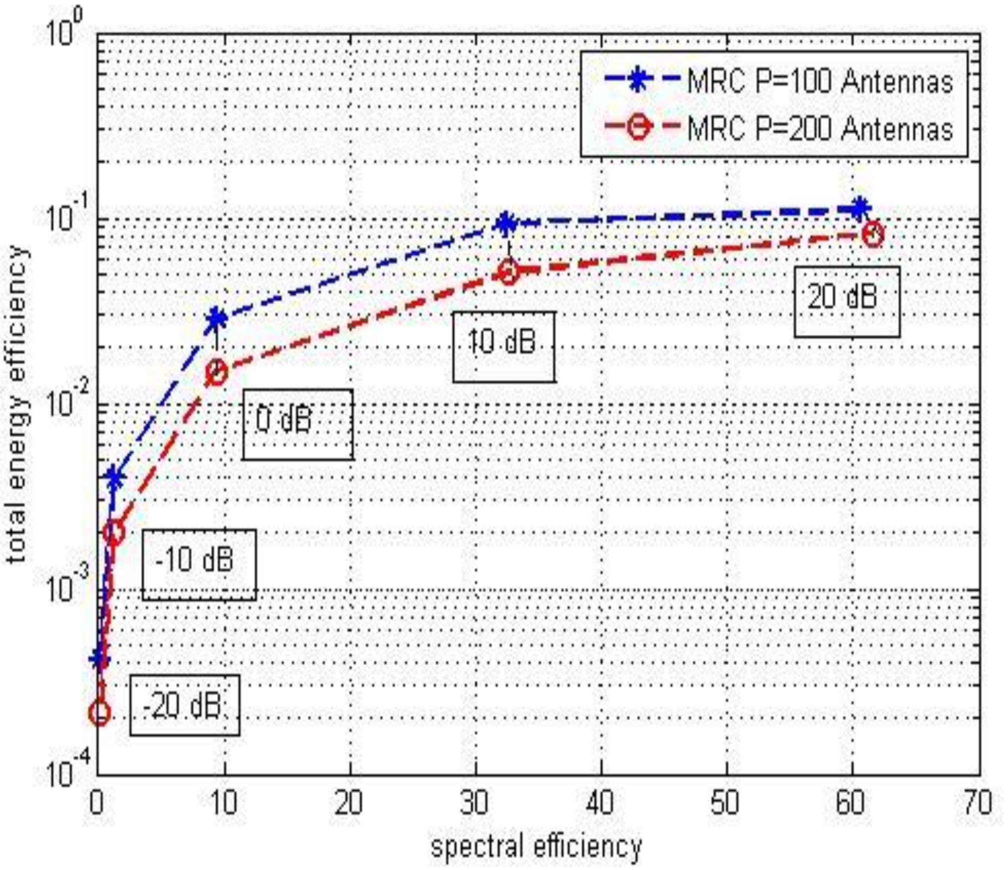

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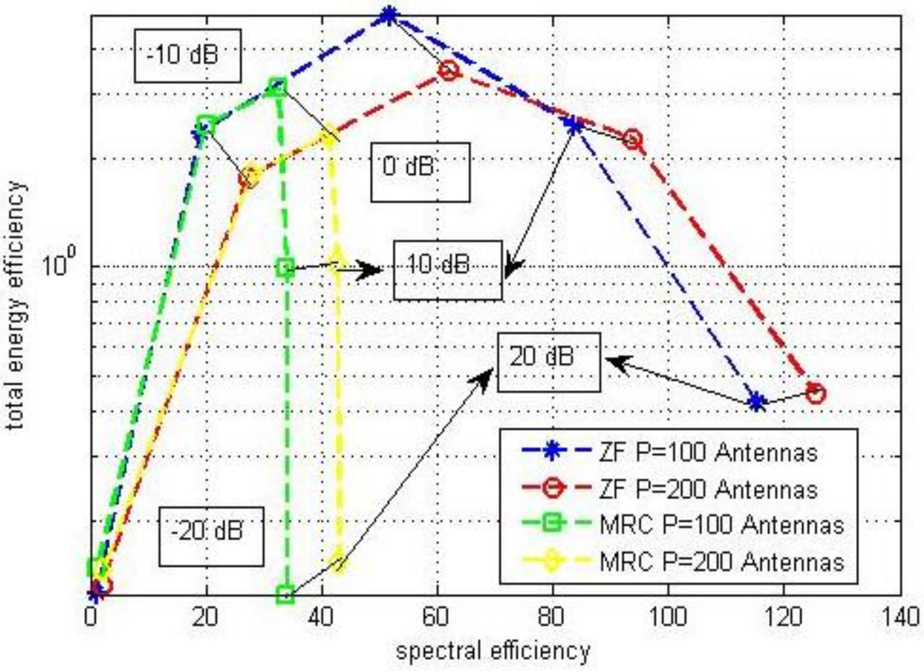
Figure 4.6 Energy Efficiency vs Spectral Efficiency for Ricean fading channel (a) un-scaled p_o=-20 to 20 dB (b) scaled power p_o=Eu/P with circuit power, transmitted power and loss factors for M=10 users and P=100 and 200 antennas. Eu is varied from -20dB to 20 dB.

Figure 4.7 (a) and (b) shows the graph between energy efficiency and spectral effciency for un-scaled and when power of each user is scaled down by number of antennas present at BS with transmit power and circuit power considered for Rayleigh fading channel when 100 and 200 antennas are located at the BS for MRC and ZF receiver. It has been conclued that for un-scaled and scaled transmit power the tradeoff is seen i.e. with increase in spectral efficiency the energy efficiency first increases and then decreases. ZF receiver performs better than MRC receiver. It has been observed that with when number of antennas at the BS gets doubled the spectral efficiency increases but with large number of antennas present at BS circuit power consumption increases and energy efficiency decreases.



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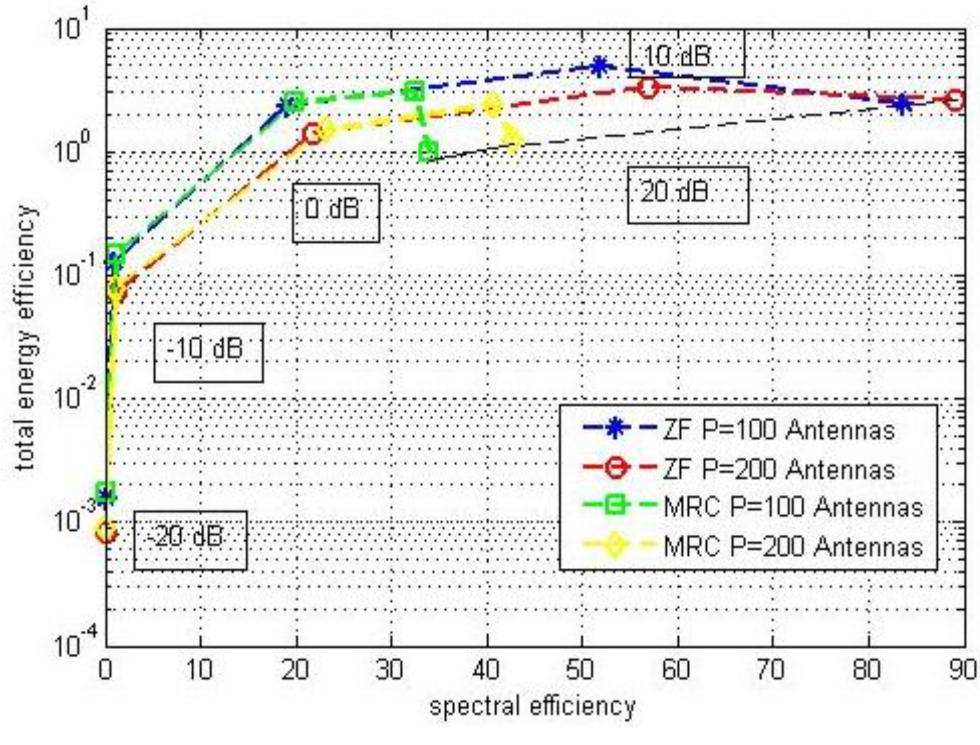

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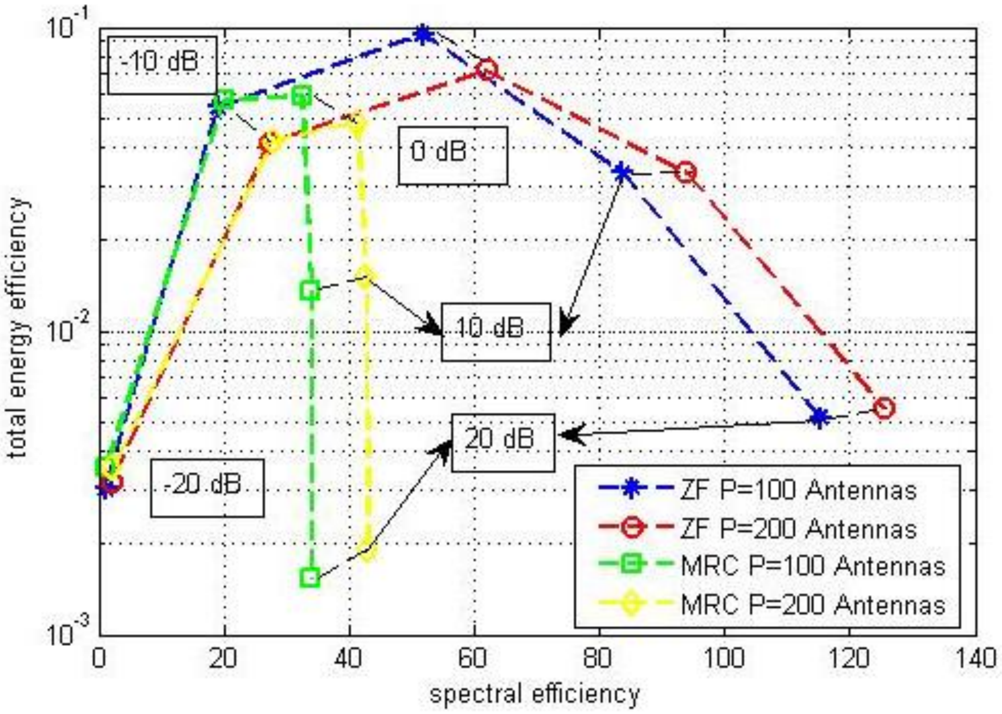
Figure 4.7 Energy Efficiency vs Spectral Efficiency for Rayleigh fading channel (a) un-scaled p_o=-20 to 20 dB (b) scaled power p_o=Eu/sqrt(P) with circuit power, transmitted power for M=10 users and P=100 and 200 antennas. Eu is varied from -20dB to 20 dB.



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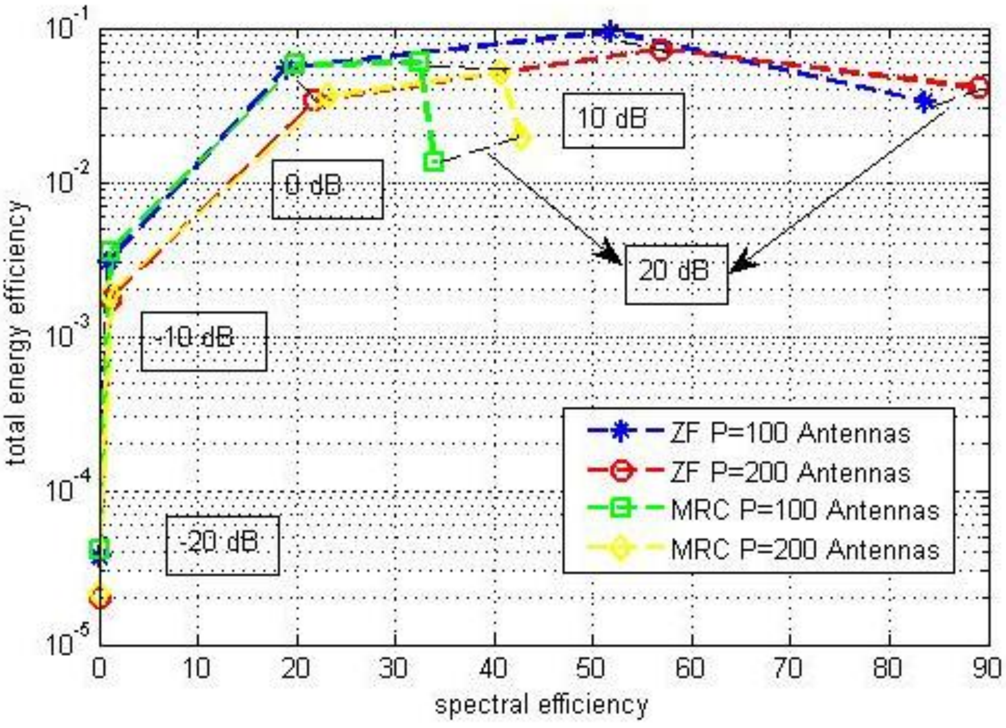

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Figure 4.8 Energy Efficiency vs Spectral Efficiency for Rayleigh fading channel (a) un-scaled p_o=-20 to 20 dB (b) scaled power p_o=Eu/sqrt(P) with circuit power, transmitted power and loss factors for M=10 users and P=100 and 200 antennas. Eu is varied from -20dB to 20 dB

Figure 4.8 (a) and (b) shows the graph between energy effciciency and spectral effciency for un-scaled and scaled transmit power with transmit, circuit power and loss factors considered for Rayleigh fading channel when 100 and 200 antennas located at the BS. It has been conclued that for un-scaled and scaled transmit power the tradeoff is

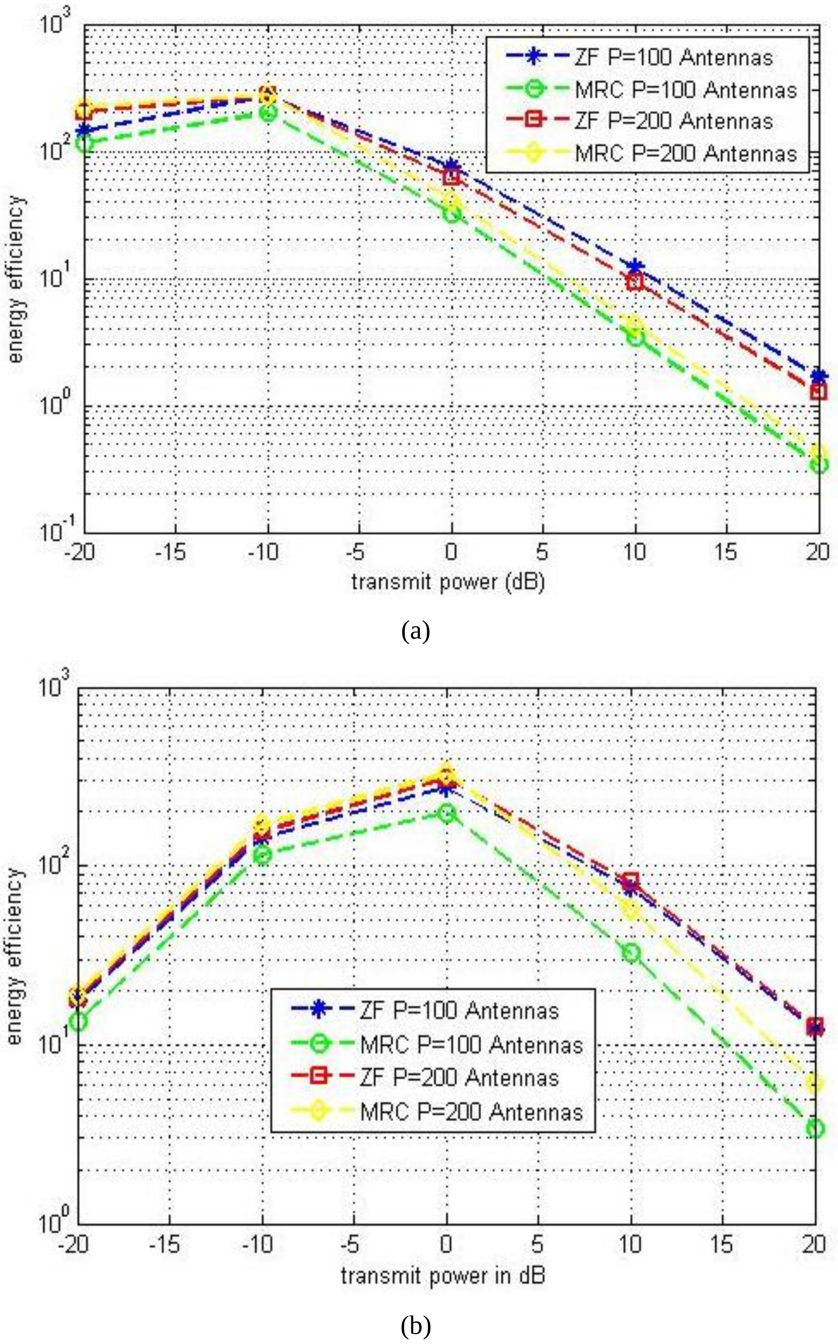

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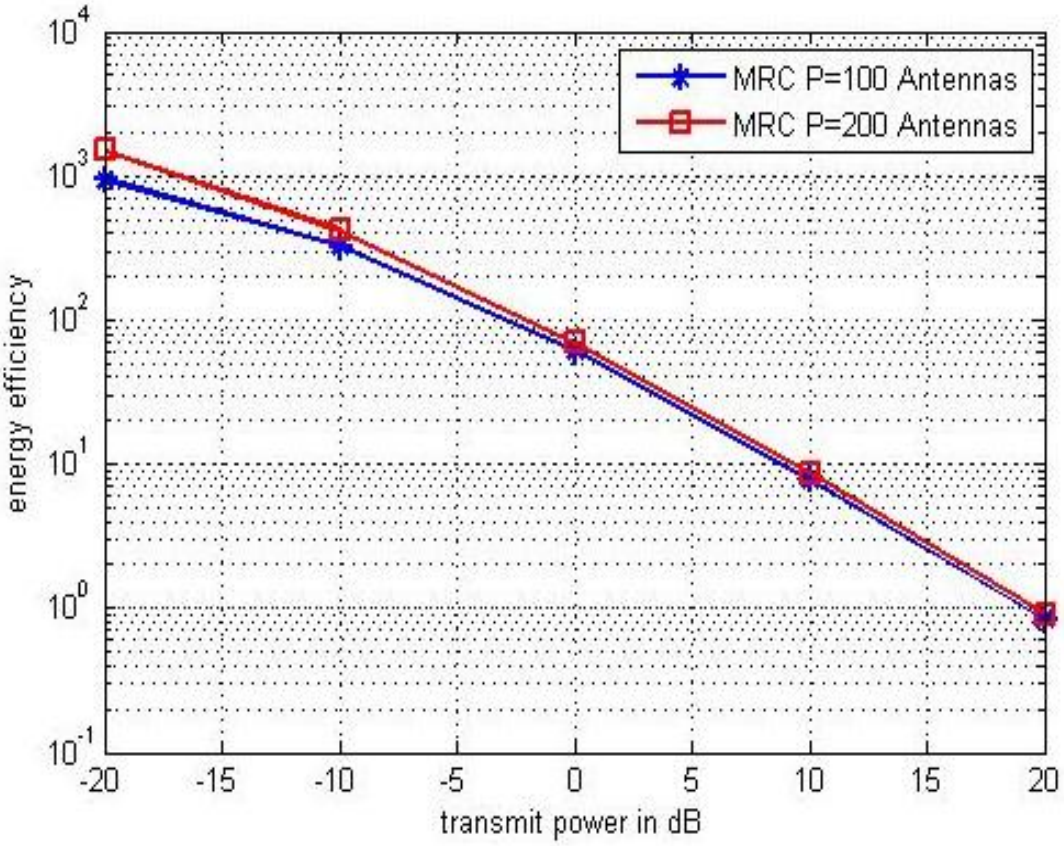
Figure 4.9 Energy Efficiency vs Transmit Power (dB) for Rayleigh fading channel (a) un-scaled p_o=-20 to 20 dB (b) scaled power p_o=Eu/sqrt(P) for M=10 users and P=100 and 200 antennas. Eu is varied from -20dB to 20 dB observed i.e. with increase in spectral efficiency the energy efficiency first increases and then decreses. ZF receiver performance is better in comparision to MRC receiver. As number of antennas at BS increases due to circuit power and loss factors energy efficiency decreases.

Figure 4.9 (a) and (b) shows the graph between energy efficiency and transmit power in dB for un-scaled and scaled transmit power with imperfect CSI using MRC and ZF receivers in Rayleigh fading channel for 10 users and 100 and 200 antennas at the BS. It has been concluded from the graph that tradeoff is observed between energy efficiency and transmit power that is with increse in transmit power, energy efficiency first increases and then decreases. The performance of MRC receiver is better at low values of transmit power in comparison to ZF receiver but at high value of transmit power the performance of ZF receiver is better in comparison to MRC receiver. High energy efficiency is obtained for scaled transmit power in comparison to un-scaled transmit power.



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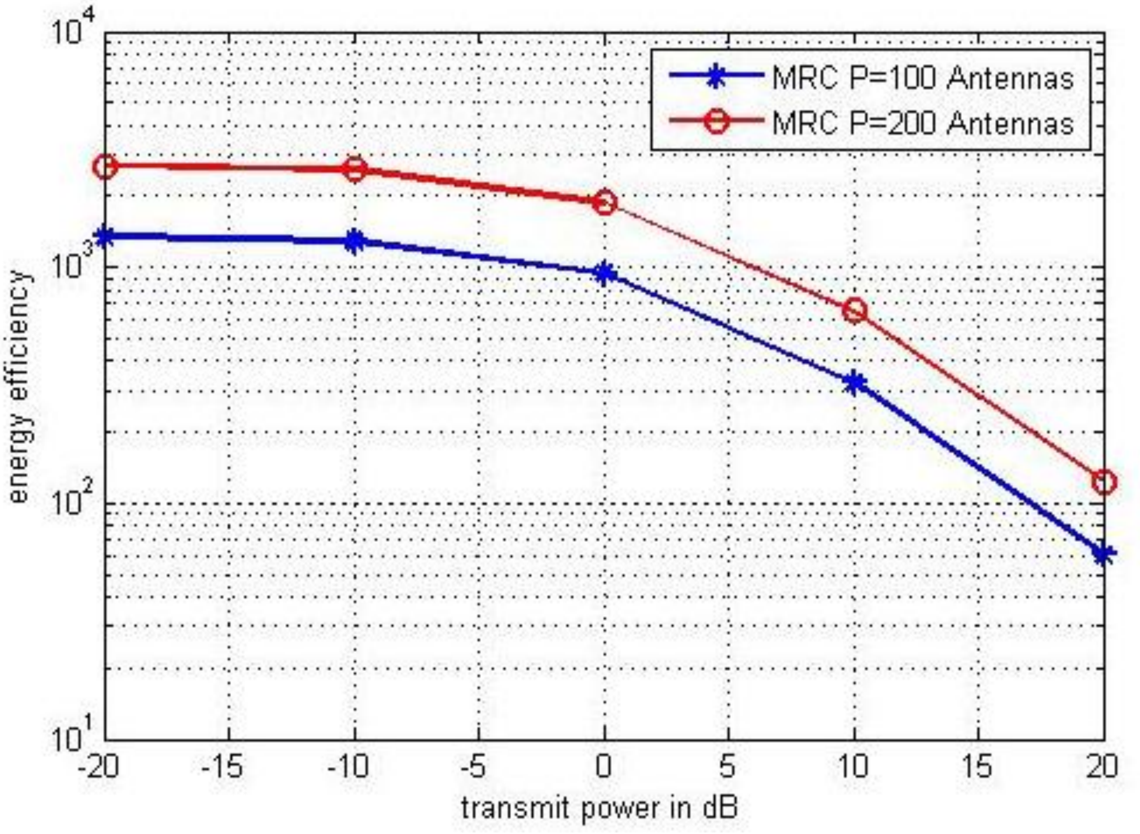

(b)

Figure 4.10 Energy Efficiency vs Transmit Power (dB) for Ricean fading channel (a) un-scaled p_o=-20 to 20 dB (b) scaled power p_o=Eu/P for M=10 users and P=100 and 200 antennas. Eu is varied from -20dB to 20 dB.

Figure 4.10 (a) and (b) shows the graph between energy efficiency and transmit power in dB for un-scaled and scaled transmit power with imperfect CSI using MRC receiver in Ricean fading channel for M=10 users and P= 100 and 200 antennas at the BS. It has been concluded from the graphs that energy efficiency decreases with increase in the transmit power. High energy efficiency is obtained when transmit power of each user is scaled down by the number of antennas P present at the BS in comparison to the un-scaled transmit power.

CHAPTER 5

SPATIAL MODULATION

In this chapter the Spatial Modulation (SM) technique is discussed and is applied to single user and multi-user systems when users have multiple antennas for transmission to plot the graph between Energy-Efficiency and Spectral-Efficiency and the results are compared with single user and multi-users single antenna system having large number of antennas at the BS.

5.1 Overview of Spatial Modulation

MIMO wireless communication research has concluded that for energy and spectral efficient future wireless networks only multiple antennas at transmitter and receiver is needed [38][39]. To achieve high data tariff the Vertical-Bell Laboratories Layered Space Time (V-Blast) algorithm can be used and for steadfast data transfer Space Time Block Coding (STBC) can be used. However, multiple antennas at both transmitter and receiver require large number of RF chains and they are expensive but to overcome the problem of large number of RF chains a technique called SM is urbanized. An RF chain contains power amplifiers that consume 50-60% of total power [40].

SM is a technique that uses single RF chain and in which information bits are conveyed by spatial constellation diagram and signal constellation diagram [41],[42]. In SM multiple antennas are present at transmitter but at a time only one antenna is chosen for transmission. The number of transmit antenna present depends on the number of information bits to be conveyed. The bits that are conveyed are divided into two parts. Half of the bits are encoded through signal constellation diagram and other half is used for single antenna selection i.e. done by spatial constellation diagram. Only one antenna is active at a time and the remaining antennas are silent. Due to the data bits conveyed through spatial constellation diagram instead of signal constellation diagram, the spectral efficiency can be obtained with the single antenna and thereafter logarithmically increases with number of transmit antennas. Due to this pro of SM it is used in the uplink for mobile terminals. SM is cheap technology because of only one RF chain due to which both size and hardware is reduced [42]. The advantage of SM is that inter channel interference is reduced at the receiver end and Inter Antenna Synchronization (IAS) at the transmitter end. The number of transmit antennas depend on the 'm' information bits conveyed where $m=\log_2(n_t)$ where n_t is number of transmit antennas. On the active antenna i.e. used for transmission M array modulation symbol is sent and remaining antennas are idle. Here, in this chapter Rayleigh and Ricean fading channels are considered for SM analysis and the simulation results are compared with the multi-user system and single user system employing single antennas at the transmitter end. Macro BS is considered and for the calculation of energy efficiency the total power consumption is used.

Table 5.1 Data bits to SM signal mapping for n_t=4 and m=2 $\mathbb{A}_m$=M-ary modulation

Antenna sel. Bits m=2	SM Tx signal vector, x	Antenna1	Antenna2	Antenna3	Antenna4
00	$[x,0,0,0]^T$	$x\in\mathbb{A}_m$	OFF	OFF	OFF
01	$[0,x,0,0]^T$	OFF	$x\in\mathbb{A}_m$	OFF	OFF
10	$[0,0,x,0]^T$	OFF	OFF	$x\in\mathbb{A}_m$	OFF
11	$[0,0,0,x]^T$	OFF	OFF	OFF	$x\in\mathbb{A}_m$

Signal detection of SM is used to detect the index of signal transmitted vector **x** and the symbol sent on it. The transmitted vector will have M-ary symbol in one coordinate and zero in other coordinates.

5.2 Spectral Efficiency Analysis

The system model of SM is same as discussed in chapter 3 for multi-user Large Antenna Systems for Imperfect CSI.

The spectral efficiency of single user employing SM technique and multiple antennas L at transmitter and P antennas present at BS for MRC receiver is given by

$$\tilde{R}^{SM}_{IP,m} = \frac{T-\tau}{T} L \log_2\left(1+\frac{p_o\beta_m\left[P^2K_m^2+\left(2PK_m+2P^2K_m\right)\eta_m+\left(P+P^2\right)\eta_m^2\right]}{Pp_o\beta_m\frac{K_m+\eta_m}{1+\beta_m p_t}+P\left(K_m+1\right)\left(K_m+\eta_m\right)}\right) \tag{5.1}$$

For multiple users employing SM the spectral efficiency is given by (5.1) where, L is the total number of antennas that all users have. The K_m is called Ricean component, T is the coherence time interval and τ is the length of the pilot signals. p_o is the transmit power, $p_t = \tau p_o$ where, τ is the length of the pilot sequences transmitted by the users to the BS.

5.3 Energy Efficiency Analysis

The macro BS is considered for calculating the energy efficiency of both multi-user multiple antenna system and multi-user single antenna system. The total power supplied to the user is given by

$$P_{\sup ply} = \tau a p_d + \tau a p_o \tag{5.2}$$

where, τa is the number of RF chains, p_d is power consumed per RF chain when antenna is active and p_o is the transmit power of each user. The power per user employing SM is given by [31]:

$$P^{SM}_{\sup ply} = \frac{P^{MU}_{\sup ply}}{\tau a} \tag{5.3}$$

where, $P^{SM}_{\sup ply}$ is the power supplied during SM and $P^{MU}_{\sup ply}$ is the power supplied to multi-user single antenna system.

The energy efficiency ignoring the effect of large scale fading for single user SM for Imperfect CSI is given by:

$$EE^{SM} = \frac{\frac{T-\tau}{T} L \log_2 \left(1 + \frac{p_o \left[P^2 K_m^2 + \left(2PK_m + 2P^2 K_m \right) \eta_m + \left(P + P^2 \right) \eta_m^2 \right]}{p_o \left(K_m + 1 \right) + P p_o \frac{K_m + \eta_m}{1 + pt} + P \left(K_m + 1 \right) \left(K_m + \eta_m \right)} \right)}{P_{\sup ply}} \qquad (5.4)$$

where, L is number of antennas user has, P is number of antennas located at BS, p_o is power supplied to the user and $P_{\sup ply}$ is the total power consumption.

The energy efficiency of a multi-user single antenna system for Imperfect CSI employing MRC receiver is given by:

$$EE_{IP,m} = \frac{\frac{T-\tau}{T} M \left[\log_2 \left(1 + \frac{p_o (P^2 K_m^2 + 2P^2 K_m) \eta_m + (P + P^2) \eta_m}{p_o (K_m + 1)(M-1)\Delta^2 + P p_o (\frac{K_m + \eta_m}{1 + pt}) + P(K_m + 1)(K_m + \eta_m)} \right) \right]}{P_{\sup ply}}$$

where, M are the number of users and K_m is the Ricean component.

The energy efficiency of multi-user multiple antennas system is given by the above equation where M is the total number of antennas present at the transmitter end.

5.4 Results

A single cell scenario is considered for analysis in which number of users M is placed on transmitter side and number of antennas P =100 at BS is placed on the receiver side. The transmission of the data in the cell is done in the uplink direction i.e. from the users to the BS. The analysis is done for imperfect CSI and MRC receiver is used for the detection of the transmitted signal at the receiver. The energy efficiency and spectral efficiency tradeoff is plotted both for i) single user single antenna and single user multiple antenna ii) multiple users each having single antenna and multiple users each having multiple antennas. In first case the RF chain required is one and in second case the RF chain required is equal to the number of users. Single user each having multiple antennas and multiple users each having multiple antennas is a case of SM. For SM the results are plotted for both fading channels when each user transmits two bits and three bits respectively. When two and three bits are transmitted the number of transmit antennas each user have is four and eight respectively as number of antennas $n_t=2^m$. The value of K_m is considered as 10 dB for Ricean fading channel and $-\infty$ dB i.e. 0 for Rayleigh fading channel. The value of the transmitted power p_o is considered to be 20 dB. The value of p_d is considered to be 118.7 Watts.

In Figure 5.1 and 5.2 the tradeoff between energy and spectral efficiency are shown between single user having one transmit antenna, four transmit antennas and eight transmit antennas and P=100 antennas using imperfect channel state information (CSI) for maximum-ratio-combining (MRC) receiver in Rayleigh and Ricean fading channels respectively.

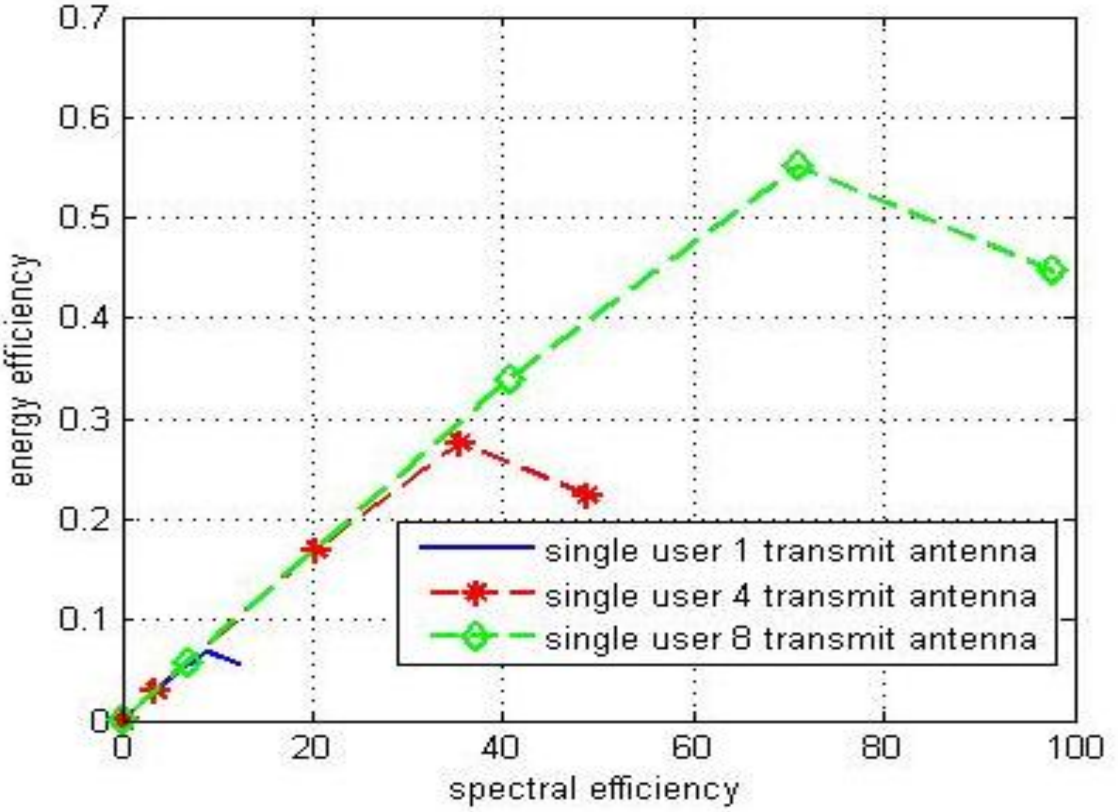

Figure 5.1 Energy efficiency vs spectral efficiency tradeoff between single user having single transmit antenna, four transmit antennas and eight transmit antennas for Rayleigh fading channel

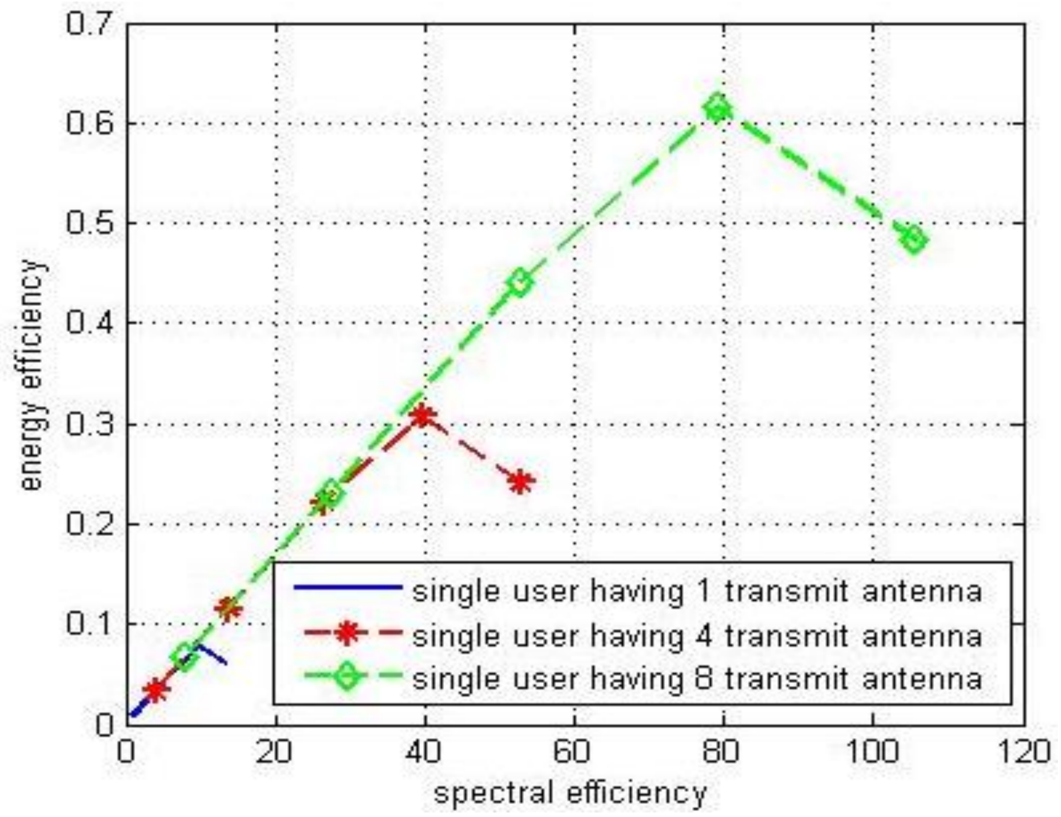

Figure 5.2 Energy efficiency vs spectral efficiency tradeoff between single user having single transmit antenna, four transmit antennas and eight transmit antennas for Ricean fading channel

It is concluded that with increase in the spectral efficiency energy efficiency first increases and then decreases. The RF chain used is one. Only one antenna is active at a time and rest all are idle. The highest energy and spectral efficiency is obtained with 8 transmit antennas, T is called coherence time interval whose value is 196. High energy and spectral efficiency is obtained for Ricean fading channel in comparison to Rayleigh fading channel The graph between energy and spectral efficiency is plotted for 20 dB transmit power.

In Figure 5.3 and 5.4 the tradeoff between energy and spectral efficiency is shown for M=4 users each having single transmit antenna, four transmit antennas and eight transmit antennas and P=100 using imperfect CSI for MRC receiver in Rayleigh and Ricean fading channels respectively. High spectral efficiency and energy efficiency is obtained when each user has eight transmit antennas and Ricean fading environment.

High energy and spectral efficiency is obtained in Ricean fading channel in comparison to Rayleigh fading channel.

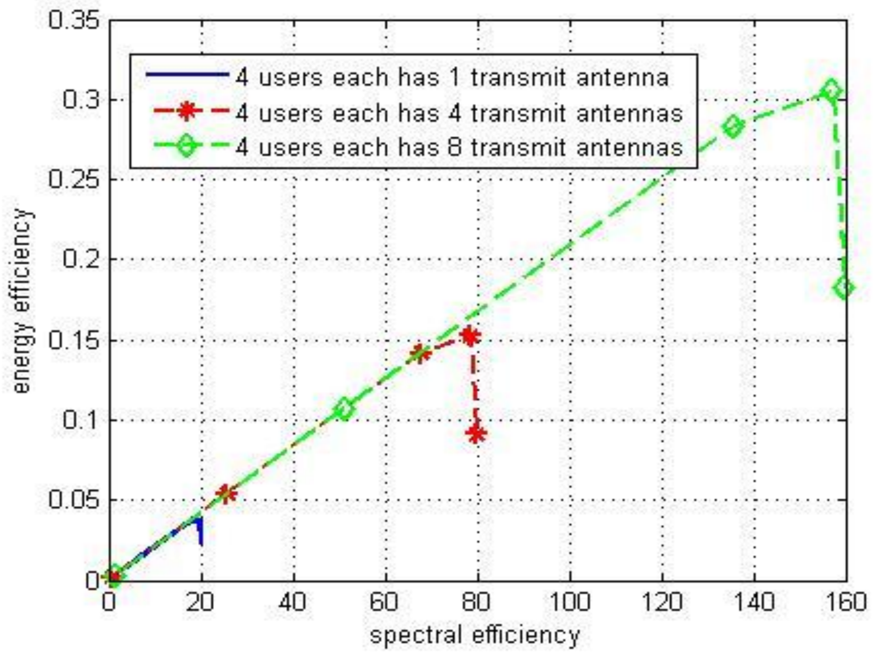

Figure 5.3 Energy efficiency vs spectral efficiency tradeoff between four users each having single transmit antenna, four transmit antennas and eight transmit antennas for Rayleigh fading channel and RF chain=4

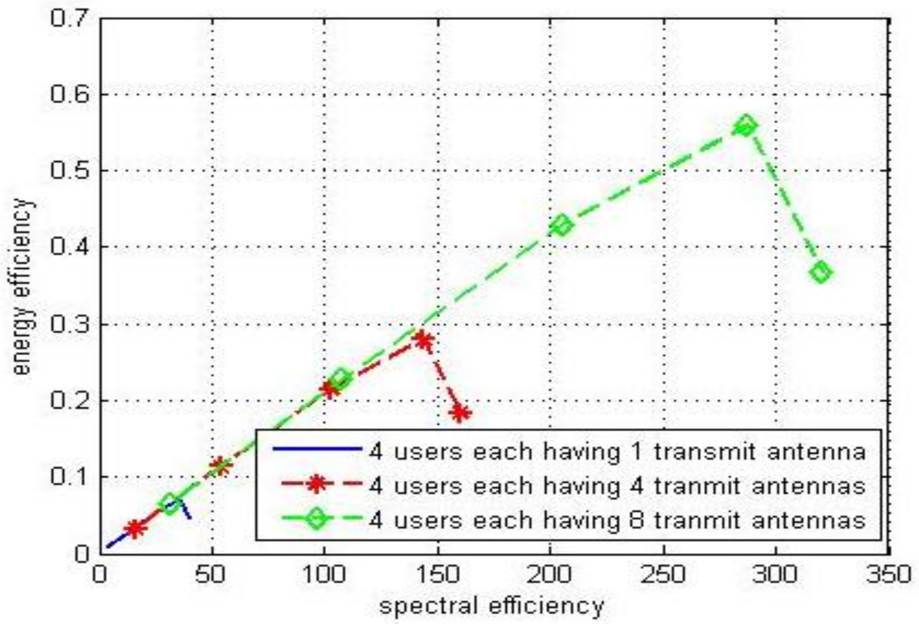

Figure 5.4 Energy efficiency vs spectral efficiency tradeoff between four users each having single transmit antenna, four transmit antennas and eight transmit antennas for Ricean fading channel and RF chain=4

In this chapter, spectral and energy efficiency comparison is done between i) single user single antenna system/MRC and single user multiple antenna system/MRC ii) multi-user single antenna system/MRC and SM/MRC when 2 and 4 bits are transmitted for Rayleigh and Ricean fading channel. The main conclusion based on energy and spectral efficiency is

i) SM/MRC Rayleigh and Ricean fading are preferred in comparison to multi-user single antenna system when number of antennas at the BS is large say 100

ii) Single user multiple antenna system/MRC for both Rayleigh and Ricean fading channel is preferred in comparison to single user single antenna system/MRC

iii) High energy and spectral efficiency are obtained with SM/MRC Ricean fading channel environment.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

Very large number of antennas located at BS is used for increasing the spectral efficiency and energy efficiency. The analysis of energy and spectral efficiency is done for imperfect CSI using MRC and ZF linear receivers in Rayleigh and MRC receiver in Ricean fading channels. The analysis is done by considering the transmit power, circuit power and loss factors ignoring the effect of large scale fading for 10 users and 100 and 200 antennas at the BS. The analysis of energy efficiency and transmit power in dB considering the transmit power in Rayleigh and Ricean fading channels is also done. The analysis of energy and spectral efficiency is also done for single user having single antenna for transmission, single user having multiple antennas for transmission (SM), multi-user each having single antenna for transmission and multi-user each having multiple antennas for transmission (SM). The tradeoff is observed between energy and spectral efficiency for both fading channels and using MRC and ZF receivers. The tradeoff is observed between energy and spectral efficiency using MRC and ZF receiver in Rayleigh fading channel when the transmit power is un-scaled and scaled down by square root of number of antennas present at the BS for all cases when circuit power and transmit power are considered, transmit power is considered and circuit, transmit and loss factors are considered. There is no tradeoff observed for Ricean fading channel when the transmit power is un-scaled and scaled down by number of antennas present at BS when only transmit power is taken into consideration, scaled power when circuit, transmit power and loss factors are considered and scaled power when transmit and circuit power is considered. The tradeoff is obtained for the MRC Ricean fading channel between energy and spectral efficiency for un-scaled transmit power when transmit, circuit power and loss factors are considered and when transmit power and circuit power is considered. It is also observed that high energy and spectral efficiency is obtained for Ricean fading channel and due to circuit power consumption and loss factors the energy efficiency decreases when number of antennas at BS increases.

The tradeoff is also observed between energy efficiency and transmit power using imperfect CSI MRC and ZF receivers in Rayleigh fading channel for scaled and un-scaled transmit power. It is observed that MRC performance is better at low values of transmit power and at high values of transmit power ZF performance is better in comparison to MRC receiver. It has been observed that using MRC receiver in Ricean fading channel the energy efficiency decreases with increase in transmit power for un-scaled and scaled transmit power. High energy efficiency is observed with scaled transmit power.

The tradeoff between energy and spectral efficiency is also observed for un-scaled transmit power when single user and multiple users have multiple antennas for transmission with imperfect CSI using MRC receiver in Rayleigh and Ricean fading channels. The total power consumption is considered for the analysis. The comparison between a) single user having single antenna for transmission and single user having 4 and 8 antennas for transmission b) multi-user each having single antenna for transmission and multi-user each having 4 and 8 antennas for transmission is done between energy and spectral efficiency curve for Rayleigh and Ricean fading channel using MRC receiver. The results observed is that

i) SM/MRC Rayleigh and Ricean fading are preferred in comparison to multi-user single antenna system when number of antennas at the BS is large say 100

ii) Single user multiple antenna system/MRC for both Rayleigh and Ricean fading channel is preferred in comparison to single user single antenna system/MRC

iii) High energy and spectral efficiency are obtained with SM/MRC in Ricean fading channel environment.

6.2 Future Scope

i) In the thesis energy efficiency analysis is done for single cell, imperfect CSI using MRC receiver in Ricean fading channel and MRC and ZF receivers in Rayleigh fading channel this can be extended to ZF and MMSE receivers with imperfect CSI in Ricean fading channel. Energy efficiency analysis can be using MMSE receiver in Rayleigh fading channels.

ii) Energy efficiency analysis can be done for multi-cell scenario using linear and non linear receivers and different fading channels

iii) Energy efficiency analysis can be done for single cell, imperfect CSI using linear receivers in Nakagami fading channel.

REFERENCES

[1] I. E. Telatar, “Capacity of Multi-Antenna Gaussian Channels,” *European Transactions on Telecommunications*, vol. 10, no. 6, pp. 585-595, November-December 1999.

[2] G. Foschini, and M. Gans, “On limits of Wireless Communications in a Fading Environment When Using Multiple Antennas,” *Wireless Personal Communications,* vol. 6, no. 3, pp. 311-335, March 1998.

[3] L. Zheng, and D. Tse, “Diversity and Multiplexing: A Fundamental Tradeoff in Multiple-Antenna Channels,” *IEEE Transactions on Information Theory,* vol. 49, no. 5, pp. 1073-1096, March 1998.

[4] D. Gesbert, M. Kountouris, R. W. Heath Jr., C. B. Chae, and T. Salzer, “Shifting the MIMO Paradigm,” *IEEE Signal Processing Magazine,* vol. 24, no. 5, pp.36-46, September 2007.

[5] F. Rusek, D. Persson, B. K. Lau, E. Larsson, T. Marzetta, O. Edfors, and F. Tufvesson, “Scaling up MIMO: Opportunities and Challenges with Very Large Arrays,” *IEEE Signal Processing Magazine,* vol. 30, no. 1, pp. 40-60, January 2013.

[6] Hien Quoc Ngo, Erik G. Larsson, and Thomas L. Marzetta, “Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems,” *IEEE Transactions on Communications,* vol. 61, no.4, pp. 1436-1449, April 2013.

[7] J. Jalden, and B. Ottersten, “On the Complexity of Sphere Decoding in Digital Communication,” *IEEE Transaction on Signal Processing,* vol. 53, no. 4, pp. 1474-1484, April 2005.

[8] N. Jindal, and A. Goldsmith, “Dirty-Paper Coding vs. TDMA for MIMO broadcast channels,” *IEEE Transactions on Information Theory,* vol. 51, no. 5, pp. 1783-1794, May 2005.

[9] S. Verdu, “Multiuser Detection,” *Cambridge, UK: Cambridge University Press,* 1998.

[10] C. Suh, M. Ho, and D. N. C. Tse, “Downlink Interference Alignment,” *IEEE Transactions on Communications,* vol. 59, no. 9, pp. 2616-2626, September 2011.

[11] T. L. Marzetta, “Non-Cooperative Cellular Wireless Systems with Unlimited Number of Base Station Antennas,” *IEEE Transaction on Wireless Communication,* vol. 9, no. 11, pp. 3590-3600, November 2010.

[12] D. N. C. Tse, and P. Viswanath, “Fundamentals of Wireless Communications,” *Cambridge, UK: Cambridge University Press,* 2005.

[13] H. Cramer, “Random Variables and Probability Distributions,” *Cambridge, UK: Cambridge University Press,* 1970.

[14] T. L. Marzetta, “How Much Training is Required for Multi-User MIMO?,” *IEEE Proceedings in 40th Asilomar Conference on Signal Systems and Computers, Pacific, Grove, CA, USA,* pp. 359-363, October 2006.

[15] Jakob Hoydis, Stephan ten Brick, and Merouane Debbah, “Massive MIMO: How Many Antennas Do We Need,” *IEEE 49th Annual Allerton Conference Allerton House, UIUC, Illinois, USA,* pp. 545-550, September 2011.

[16] Hoon Huh, G. Caire, H. C. Papadopoulos, and S. A. Ramprashad, “Achieving Massive MIMO Spectral Efficiency with a Not-So-Large Number of Antennas,” *IEEE Transactions on Wireless Communications,* vol. 11, no.9, pp. 3226-3239, September 2012.

[17] Jakob Hoydis, Stephan ten Brick, and Merouane Debbah, “Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas Do We Need?,” *IEEE Journal of Selected Areas of Communications,* vol. 31, no. 2, pp. 160-171, February 2013.

[18] Lu Lu, Geoffrey Ye Li, A. Le Swinderhurst, Alexei Ashikhmin, and Rui Zhang, “An Overview of Massive MIMO: Benefits and Challenges,” *IEEE Journal of Selected Topics in Signal Processing,* vol. 8, no. 5, pp. 742-758, October 2014.

[19] Qi Zhang, Zhaohua Lu, Shi Jin, Kai-Kit Wong, Hongbo Zhu, and Michail Matthaiou, “Power Scaling of Massive MIMO with Arbitrary-Rank Channel Means and Imperfect CSI,” *IEEE Journal of Selected Topics in Signal Processing,* vol. 8, no. 5, pp. 962-988, October 2014.

[20] Erik G. Larsson, F. Tufvesson, O. Edfors, and T. L. Marzetta, “Massive MIMO for Next Generation Wireless Systems,” *IEEE Communication Magazine,* vol. 52, no. 2, pp. 186-195, February 2014.

[21] Jocelyn Aulin, and Mattias Gustafsson, “Assessing Realistic Gains of Massive MIMO,” *IEEE 8th European Conference on Antenna and Propagation,* pp. 3060-3064, April 2014.

[22] Ang Yang, Zunwen He, Chengwen Xing, Zesong Fei, and Jingming Kuang, “The Role of Large Scale Fading in Uplink Massive MIMO Systems,” *IEEE Transactions on Vehicular Technology,* Accepted for Publication, 2015.

[23] Shuguang Cui, Andrea J. Goldsmith, and Ahmad Bahai, “Energy Efficiency of MIMO and Cooperative MIMO Techniques in Sensor Networks,” *IEEE Journal on Selected Areas in Communications,* vol. 22, no. 6, pp. 1089-1098, August 2004.

[24] Hu Ying, Daofeng Xu, Baofeng Ji, Yongming Huang, and Yang Luxi, “Energy Efficiency of Very Large Multi-User MIMO Systems,” *IEEE International Conference on Wireless Communications and Signal Processing*, pp. 1-5, October 2012.

[25] Daehan Ha, Keokook Lee, and Joonhyuk Kang, “Energy Efficiency Analysis with Circuit Power Consumption in Massive MIMO Systems,” *IEEE 24th International Symposium on Personal, Indoor and Mobile Radio Communications: Fundamental and PHY Track,* pp. 938-942, September 2013.

[26] Hong Yang, and T. L. Marzetta, “Total Energy Efficiency of Cellular Large Scale Antenna System Multiple Access Mobile Networks,” *IEEE Conference on Green Communications,* pp. 27-32, October 2013.

[27] Hui Li, Lingyang Song, Dalin Zhu, and Ming Lei, “Energy Efficiency of Large Scale MIMO Systems With Transmit Antenna Selection,” *IEEE Signal Processing for Communications Symposium,* pp. 4641-4645, June 2013.

[28] Zhenyu Zhou, Sheng Zhou, Jie Gong, and Zhisheng Niu, “Energy Efficienct Antenna Selection and Power Allocation for Large Scale Multiple Antenna Systems with Hybrid Energy Supply,” *IEEE Globecom Symposium on Selected Areas in Communications,* pp. 2574-2579, December 2014.

[29] Jie Tang, Daniel K. C. So, Emad Alsusa, and Khairi Ashour Hamdi, “Resource Efficiency: A New Paradigm on Energy Efficiency and Spectral Efficiency Tradeoff,” *IEEE Transactions on Wireless Communications,* vol. 13, no. 8, pp. 4656-4669, August 2014.

[30] Konstantinous Ntontin, Marcos Di Rhenzo, Ana Perez-Neira, and Christos Verikoukis, “Towards the Performance and Energy Efficiency Comparison of Spatial Modulation with Conventional Single-Antenna Transmission Over Generalized Fading Channels,” *IEEE 17th International Workshop on Computer Aided Modeling and Design of Communications Links and Networks,* pp. 120-124, September 2012.

[31] Athanasios Stavridis, Sinan Sinanovic, Marco Di Rhenzo, and Harald Haas, “Energy Evaluation of Spatial Modulation at a Multi-Antenna Base Station,” *IEEE Conference,* September 2013.

[32] Tanumay Datta, and A. Chokalingam, “On Generalized Spatial Modulation,” *IEEE Wireless Communications and Networking Conference,* pp. 2716-2721, April 2013.

[33] Shengehu Wang, Yonzhou Li, Ming Zhao, and Jing Wang, “Energy Efficient and Low Complexity Uplink Transceiver for Massive Spatial Modulation MIMO,” *IEEE Transactions on Vehicular Technology,* November 2014.

[34] Marco Di Rhenzo, Harald Haas, Ali Ghayreb, Shinya Sugiura, and Lajos Hanzo, “Spatial Modulation for Generalized MIMO: Challenges, Opportunities and Implementation,” *IEEE Proceedings,* vol. 102, no.1, pp. 56-103, January 2014.

[35] Sandeep Narayanam, Marium Jalal Choudhary, Athanasios Stavridis, Marco Di Rhenzo, Fabio Graziosi, and Harald Haas, “Multi-User Spatial Modulation MIMO,” *IEEE Wireless Networking Communications and Networking Conference,* pp. 671-676, April 2014.

[36] S. Jin, X. Gao, and X. You, “On the Ergodic Capacity of Rank-1 Ricean Fading MIMO Channels,” *IEEE Transactions on Information Theory,* vol. 53, no. 2, pp. 502-517, February 2007.

[37] Namshik Kim, Yunsung Lee, and Hyuncheol Park, “Performance Analysis of MIMO System with Linear MMSE Receiver,” *IEEE Transactions on Wireless Communications,* vol. 7, no. 11, pp. 4474-4478, November 2008.

[38] G. J. Foschini, and M. J. Gans, “On Limits of Wireless Communications in a Fading Environment When Using Multiple Antennas,” *IEEE Wireless Personal Communications,* vol. 6, no. 6, pp. 311-335, May 1998.

[39] D. Tse, and P. Viswanath, Fundamentals of Wireless Communications.

[40] L. Correia, D. Zeller, O. Blume, D. Ferling, A. Kangas, I. Godor, G. Auer, and L. Van Der Perre, “Challenges and Enabling Technologies for Energy Aware Mobile Radio Networks,” *IEEE Communications Magazine,* vol. 48, no. 11, pp. 66-72, November 2010.

[41] J. Jeganath, A. Ghrayeb, and L. Szczecinski, “Spatial Modulation: Optimum Detection and Performance Analysis,” *IEEE Communications Letter,* vol. 12, pp. 545-547, August 2008.

[42] M. Di Rhenzo, H. Haas, and P. M. Grant, “Spatial Modulation for Multiple Antenna Wireless Systems: A Survey,” *IEEE Communications Magazine,* vol. 49, no. 12, pp. 182-191, December 2011.

[43] A. Chockalingam, and B. Sunder Rajan, “Large MIMO Systems,” *Cambridge University Press*, 2014.

LIST OF PUBLICATIONS

[1] Arzoo Khetarpal, and Rajesh Khanna, “Energy Efficiency of Large Antenna System Using Linear Receivers in Fading Channels,” communicated in *International Journal of Electronics*.