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Performance Analysis of MIMO Relaying Communication Systems

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science In Electrical and Electronics Engineering

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January / 2015

UNIVERSITY OF BAHRAIN

College of Engineering **Department of Mechanical Engineering**



Optimum Planning and Scheduling of Repetitive Construction Projects Using Multi-Objective Cuckoo Search Algorithm

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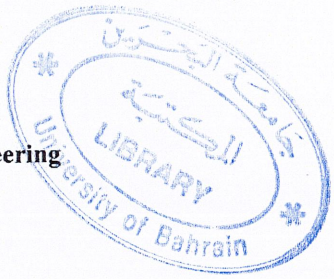
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College of Engineering

Department of Electrical and Electronics Engineering

Master of Science in Electrical and Electronics Engineering



The Student Raed Moosa Mesmar, student ID 19927908, has defended the thesis in partial fulfillment of the requirements for the degree of Master of Science with the title "Performance Analysis of MIMO Relaying Communication systems" on 15 Jan. 2015

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ABSTRACT

This thesis considers the performance of MIMO relay Amplify and forward (AF) systems. The capacity and performance investigations are carried out assuming a correlated fading channel. Two-hop and multi-hop system models are studied. A realistic outdoor spatial statistical clustered (OSSC) channel model is and applied in the simulations of MIMO relay systems. This model is concurrent with the special channel model (SCM) model that is adopted by 3GPP standardization body to be used for cellular communications applications. The path loss calculations for the OSSC model are based on the Urban Hata model. Also, a coverage analysis is presented for different configurations of MIMO relay AF systems with different number of antennas at source, relay and destinations. Uniform Linear Array (ULA) and Uniform Circular Array (UCA) antenna structures are implemented. The outage probabilities and ergodic capacities of systems are also compared when employing ULA and UCA. The resilience of the basic MIMO Relay AF system over the normal MIMO system has been demonstrated. Ways of improving relay gain via filter matrix design were also demonstrated. A comparison between three different relay filter design namely blind, singular value decomposition (SVD) and matched filter (MF) was discussed. This work is extended to design a relay multiuser MIMO system with linear precoding beamforming. Channel inversion (CI), Minimum Mean Square Error (MMSE) precoding, block-diagonalization (BD) and Tomlinson-Harashima (TH) are the three precoding techniques examined. Simulations were carried out to compare different MU-MIMO relay schemes performance under correlated channel by calculating both bit error rates and sum rate capacity

Dedication

Alone one can go fast, with a team one can go far. I dedicate this work to my parents who showed me the way to go and my family who endured going far.

Acknowledgements

I would like to seek the opportunity to thank all those who made this happen. Special thanks to Dr. Mohab Mangoud for sharing his mind and thoughts with me. A big thanks for the electrical Engineering Department Faculty for their teachings that I got in both Undergrad and grad courses. And a special thank to my colleague Hamad Al Dosary for fueling a decent competition throughout this course.

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Notation

Abbreviations and mathematical operators used in this thesis are listed below.

Abbreviations

3GPP	3th Generation Partnership Project
AF	Amplify and Forward
AoA	Angle of Arrival
AoD	Angle of Departure
AP	Access Point
AS	Angular Spread
BER	Bit Error Rate
BLAST	Bell-Labs Layered Space Time
BPSK	Binary Phase Shift Keying
BS	Base Station
CDF	Cumulative Density Function
CI	Channel Inversion
CSI	Channel State Information
DPC	Dirty Paper Coding
EVD	Eigen Value Decomposition
GSCM	Geometry-Based Stochastic Channel Model
LMMSE	Linear Minimum Mean Square Error
LOS	Line of Sight
LS	Least Squares
LST	Layered Space-Time
MF	Matched Filter
MIMO	Multiple-Input Multiple-Output

ML	Maximum Likelihood
MISO	Multiple-Input Single-Output
MMSE	Minimum Mean Square Error
MS	Mobile Station
MSE	Mean Square Error
MT	Mobile Terminal
NLOS	Non Line of Sight
OSSC	Outdoor Stochastic Spatial Clustered Channel Model
PAS	Power Azimuth Spectrum
PDF	Probability Density Function
PDP	Power Delay Profile
PIC	Parallel Interference Cancellation
QPSK	Qadrature Phase Shift Keying
RMMSE	Relaxed MMSE
SIC	Successive Interference Cancellation
SIMO	Single-Input Multiple-Output
SISO	Single-Input Single-Output
SLS	Scaled Least Squares
SSC	Stochastic Spatial Clustered
STA	Wireless station
STBC	Space-Time Block Codes
STC	Spatial-Temporal Clustered
STTC	Space-Time Trellis Code
SVD	Singular Value Decomposition
TD-FWGN	Time-Domain Filtered White Gaussian Noise
TGn	Task Group n
UCA	Uniform Circular Array
ULA	Uniform Linear Array
V-BLAST	Vertical-BLAST

WLAN	Wireless Local Area Network
ZF	Zero Forcing
ZMCSCG	Zero-Mean Circular Symmetric Complex Gaussian

Mathematical Operators

$[\cdot]^H$	Hermitian transpose operation
$[\cdot]^*$	Complex conjugate operation
$[\cdot]^T$	Matrix/vector transpose
$\|\cdot\|_F^2$	Frobenuis matrix norm
$\mathrm{Tr}\{\cdot\}$	Trace of a matrix
$I_o[\cdot]$	Zero order Bessel function of the first kind
$\odot$	Hadamard multiplication
$\otimes$	Kronecker product
$\det(\cdot)$	Determinant Operation

Chapter 1

Introduction

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Chapter 1

Introduction

In this chapter, background work for this thesis will be briefly discussed. This will include previous work on the topic, the research problem and the proposed course of work. The contributions of this work will be listed along with the outline.

1.1 Background

The need for more bandwidth and faster networks drives the developments of today's mobile communications. Following the introduction and implementation of multiple input multiple output in the 4G mobile networks, MIMO Relay networks has been introduced. Its promising application is in extending the cell coverage for 5G networks. The performance of MIMO relay systems is investigated in correlated fading channel. A realistic outdoor spatial statistical clustered (OSSC) channel model is proposed in this work. This channel model implementation forms one of several research contributions. This model is concurrent with the special channel model (SCM) that is adopted by 3GPP standardization body to be used for cellular communications applications. Since relaying and MIMO are two techniques were adopted in the latest cellular communications standards and most likely they will be used in 5G evolutions, it is essential to study how they cooperatively work. Relaying and MIMO both can improve transmission in the wireless

channel, but they accomplish this using different means. MIMO takes advantage of the signal scattering in the channel to provide higher data rates and better cell coverage. This happens even without increasing average transmit power or frequency bandwidth this leads to linearly increase the channel capacity, spectral efficiency and link reliability.

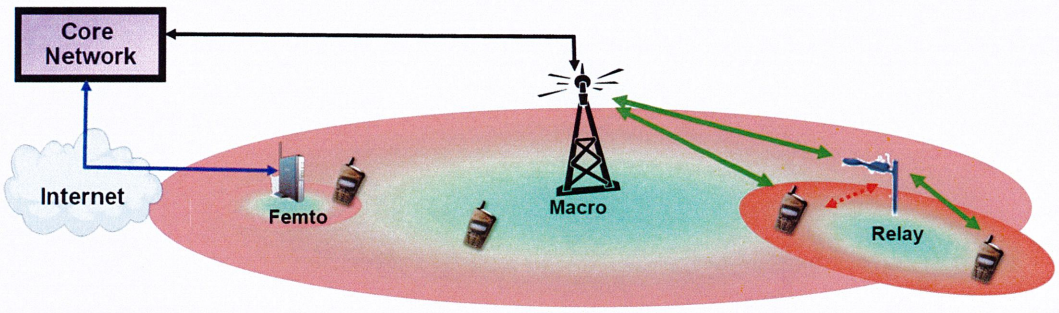


Figure 1.1, MIMO Relay AF systems in 5G networks

Two-hop relaying improves transmission by lowering the path loss, which increases the SNR. It is important to recognize that high scattering in a wireless channel also means high path loss. So correct analysis of the combination of the techniques in a given cellular system geometry requires an accurate system and a channel model that ties together the scattering effect and the path loss as functions of distance. Lots of recently specified wireless communications standards are set to support MIMO Relay technologies for example WIFI (IEEE 802.11n, ac, ad) and Cellular communications (3GPP's LTE 4G, Advanced LTE-4G and IEEE 802.16). A special type of relay systems is the cooperative relaying where users share and coordinate their resources to enhance transmission quality and optimize power allocation. Recently, it has been shown that MIMO cooperative relaying gives additional degrees of freedom to improve the capacity of the overall cooperative system.

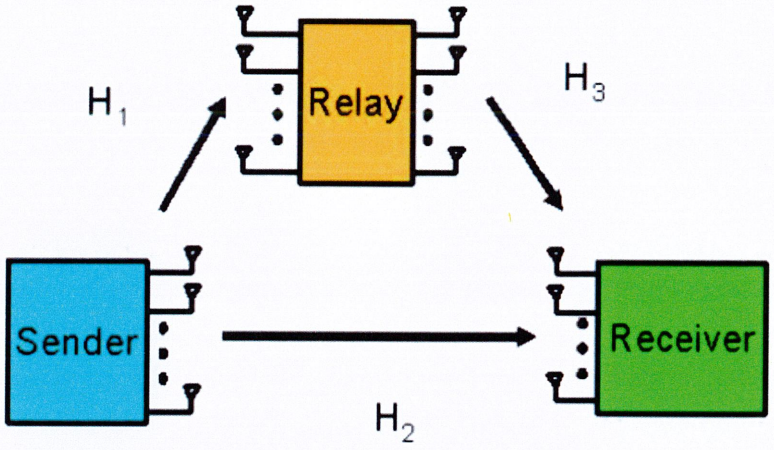


Figure 1.2, Basic MIMO relay system

1.2 Overview of Research

Applying MIMO to wireless relaying systems has attracted high interest recently (Goldsmith 2002). For example it is used in the latest cellular systems standard (LTE-Advanced - 4G) where it supports more advanced relays, which first decode the transmissions and then forward only those destined for the mobile units that each relay is serving. This scheme reduces interference and lets more users link with the relay and assist in improving the performance of infrastructure-based networks by increasing their coverage. LTE-Advanced also allows a relay to communicate with the base station and with devices using the same spectrum and protocols as the base station itself. This has the advantage of letting regular LTE handsets connect to the relay as if it were a traditional tower. The relay avoids interfering with the base station by scheduling its transmissions during certain times when the base station is silent.

Two hop single relay scenarios are previously investigated (Shi 2005) with relay either above rooftop or at ground level using both

measurements and simulations. Techniques such as cross- polarized antenna or optimal power allocation are utilized when the relay is in the LOS propagation environment. Also, it is shown that if the destination is far enough away from the source to make their central area NLOS to both of them, it is better to place the relay in the region close to the LOS component between the source and destination. Therefore a study about the relay coverage and the effect of the array configuration is always required and it differs according to the type of environment. Previous studies proposed different relaying schemes that achieve full diversity according to optimizing the number of antennas; their relative performance merits are determined by noise amplification at the relays and the exact configuration of the distributed array. Antenna heights of MS, RS and BS are also key parameters that will affect the system performance. Therefore a major objective of this thesis is to extend previous work in further investigating to the location of the relay, the coverage extent, LOS existence between the relay and the source or the destination and the scattering clusters and fading in the channel influence on the capacity and data rates at the receiver.

The channel modeling is one of the most significant challenges in designing wireless communications system because of the time-varying nature of the channel. In real propagation environments, fading correlation should be considered and this depends on numerous factors. The antenna configuration, Doppler spread, the distance between the transmitter and receiver to name a few. The list extends to include the distribution of scattering objects that are present in the path between the transmitter and receiver. One of the wave propagation scenarios the Line-of-sight (LOS) case where the MIMO system exhibits a reduced performance since the LOS component overwhelms the multipath

components in the received signal and this results that the system is incapable of acquiring high spatial multiplexing gain, which seriously affects the performance of the system. This is a low-rank line-of-sight communication environment in the outdoor open space, where there are less scattering objects and the channel matrix is in a low-rank state. The widely used Rayleigh channel model overestimates the performance of the channel compared with realistic models. Therefore, simulation of relay MIMO systems and investigating its performance requires utilizing an accurate channel model, which is another aim in this thesis.

The realistic fading correlation MIMO channel model was previously presented in (Mangoud 2008). The results were utilized for indoor WLAN system. In this model, the groups of scatterers are modeled as multi-clusters located around the antenna arrays. The spatial fading correlation can be determined from the physical parameters of the model, which include antenna spacing, antenna arrangement, angular spread (AS), Power Azimuth Spectrum (PAS), and the central angle of incidence of the waves. Three different PAS were assumed with uniform, truncated Gaussian and truncated Laplacian. This model is realized for both uniform linear array (ULA) and uniform circular array (UCA) antennas. The spatial correlation properties of a MIMO system is modeled as the Kronecker product of the spatial correlation matrices defined independently at the transmitter and at the receiver.

In this thesis, the channel model needs to be modified to be compatible with 3GPP-SCM model. Accurate path loss model, different array types AoA and AoD statistics were included. In addition, antennas spacing between antenna arrays, direction angles at the transmitting and receiving ends, the correlation analysis and multi clusters scattering were

included as well in the model.

Another objective of this thesis is to look to the design of the Relay station. The way the signal is forwarded and encoded at the relay station can be classified into two categories: amplify-and- forward (AF) and decode-and-forward (DF). In AF the relays simply amplify and forward the received signal. In the DF case, the relays demodulate and decode the signal prior to re-encoding and retransmission. In this paper, we will focus through the thesis to the amplify-and-forward case. For the AF filter design, different choices of the spatial gain and filter matrices (i.e. amplification factor) can be applied to the received signal at the relay station. For linear AF relay: blinded, zeros forcing (ZF) relay and, successive interference cancellation (SIC), matched filter (MF), QR relay named after QR-decomposition) are listed as examples improves the performance. Therefore, a comparative study will be presented in this thesis with the simulations and the proposed channel models.

1.3 Contributions of This Work

The main contributions of this thesis are as follows:
A realistic outdoor spatial statistical clustered (OSSC) channel model that is concurrent with the (SCM) model has been implemented in the simulation of MIMO Relay AF systems. The proposed model includes a detailed channel model and accounts for various real cellular propagation environments. It incorporates both line of sight (LOS) and non-line of sight (NLOS) channel components. It captures both scattering effects and path loss as a function of distance. The model aligns with models adopted by standards bodies such as the Third Generation Partnership Project

(3GPP) SCM model. A main objective of this research is to apply a realistic propagation channel model that can fully characterize the correlation properties to MIMO relay systems.

The Urban Hata model has been used in the path loss calculations implemented in the channel model. Most of the literature uses the exponential decay for the path loss, which is less accurate when compared with the Urban Hata model.

Coverage analysis is presented for different configurations of MIMO Relay under realistic channel model. In this work, the impact of channel model selection on link performance of systems employing ULA and UCA configurations is investigated. In addition, Characteristics of channel capacity versus azimuth orientation of UCA antenna are analyzed and compared with those of ULA. Moreover, the channel capacity is investigated under various realistic scenarios applying uniform and water-pouring power allocation schemes.

Linear filter design for multi-user MIMO-relay downlink systems with precoding beamforming was discussed. This part addresses the filter design and user selection issues for the downlink of a multi-user MIMO-relay system. To eliminate inter user interference, the filter design is based on the singular value decomposition (SVD) or Matched Filter (MF) of the first step and Liner Precoding such as block-diagonalization (BD) for the second design issue. Simulations are presented for different techniques. Also, Relay MU-MIMO precoding schemes are simulated and compared.

1.4 Outline of Thesis

This thesis is organized as follows:

Chapter 1 presents an introduction; objectives and contributions of the thesis are presented.

Chapter 2 gives some background on MIMO and multi- hop relaying systems, some discussion of the important performance measures, overview of relevant prior work, and brief discussion of the wireless standards that include MIMO and relaying. Also a survey on the most important developments in the area of MIMO channel modeling is provided along with comparisons that highlight the differences and limitations for each model.

Chapter 3 MIMO models developed within wireless standard are also presented. Then, the outdoor stochastic spatial clustered (OSSC) channel model is presented. An analytical expression for the spatial fading correlation function for MIMO channels is developed for both ULA and UCA antennas. The spatial fading correlation function is a function of angular spread, angle of incidence, PAS distribution and distance between elements that are dependent on the array geometry. Comparative results on the spatial fading correlation for both the ULA and UCA are presented.

Chapter4 discusses the Cooperative amplify-and-forward MIMO relay system is investigated. The chapter presents a comparative view of varies proposed link scenarios to study the effect relay location and coverage on the system performance under different power allocation techniques. In the presented model, a modified realistic SCM stochastic propagation channel model is used assuming the cases of existence and none existence of low rank line-of-sight communication for outdoor open space (Jiang 2006). The channel is modeled for multi- clusters scattering environment

which means that the signal will be transmitted with Angle of Departure (AoD) and will arrive at the receiver from multiple Angles of Arrival (AoA) each with angle spread (AS) that is a measure of the angle displacement due to the non-LOS propagation. The used relay has multiple antennas at both transmitting and receiving sides. The variation of the angle spread at the transmitter, relay and receiver is addressed as well. Also, different number multiple antennas in source, relay and destination nodes are considered.

Chapter 5 presents different relay filter matrix designs with linear precoding schemes that are studied based on channel state information known at the amplify and forward MIMO relay location. First Blind, singular value decomposition (SVD) and Matched filter designs are compared. Then the relay is designed for multiuser MIMO destination with Linear precoding techniques including channel inversion, minimum mean squared error (MMSE) criterion and block diagonalization (BD) and TH beamforming. The numerical simulation compare different designed for bit error rates and sum rate capacity.

Chapter 6 presents some overall conclusions from our work, and discusses some possible future work.

Chapter 2

Survey of MIMO Relay AF Modeling, Capacity investigations and Channel Models

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Chapter 2

Survey of MIMO Relay AF Modeling, Capacity investigations and Channel Models

2.1 Introduction:

MIMO Relay Amplify and Forward communication system could be considered as the evolution of Multi User MIMO communications system. The introduction of the MU-MIMO systems was accompanied by great expectations about the increased channel gains. These predictions were unrealistic due to the underlying channel model, power assumptions and how well the transmitter can track the receiver (Goldsmith 2002). The same can be said about the introduction of the MIMO Relay systems, which is divided into two main categories, Amplify and Forward scheme and decode and forward scheme (Fan 2007). A general overview about the MIMO Relay AF systems will be provided in this chapter. The topics will include the modeling approaches of the MIMO Relay AF systems. The introduction of the relay node in the communication system will not only affect the coverage range but more system resilience can be detected. The presence of the channel state information will have a great impact on the system capacity. Recent studies on this topic will be presented. Channel modeling for the MIMO Relay AF systems differs from normal MIMO systems in considering the geometrical location of the relay node (Jiang 2006). A review of a system model for the MIMO Relay AF system including the RN location will be presented. Enhancing

the overall link capacity via precoding has been a hot topic recently. Precoding helps reduce the interference caused by other users in the MU MIMO systems. An over view of different precoding technique will be presented along with their implementation cost as well.

2.2 MIMO Relay AF Modeling Approaches

Improving the performance of infrastructure-based networks can be achieved by introducing relays. This helps in increasing the coverage area and exploiting spatial diversity. To better understand the relay systems, more system parameters should be included in its modeling. The channel modeling usually focuses on the Rayleigh channel model, which is basically a non-line-of-sight (NLOS) model. Including the line-of-sight (LOS) components will improve the modeling process. This has been the focus of the work presented in (Jiang 2008). Another approach to studying the MIMO Relay systems is to compare the antenna distribution of relay systems. Two scenarios are possible, multi relay scenario where multiple relays are used each equipped with one antenna or multi antenna single relay system. In the multi antenna relay, one relay is used that is equipped with multiple antennas (Hwang 2010). The case of multiple relay systems, relay selections emerges as a new tool to optimize the system capacity and throughput. Selection schemes were introduced in (Li 2010). The basic MIMO Relay AF system is presented in figure 2.1. The system notation has been used in several literatures, the transmitter is being referred to as the source, S. the receiver as destination; D and the relay uses R.

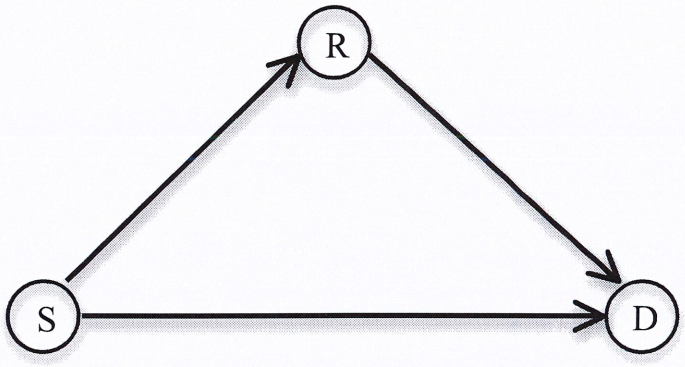


Figure 2.1, Basic MIMO relay system

2.2.1 Classifications of MIMO Relay Schemes

Spatial diversity gains motivate the shift towards cooperative relay networks from normal MIMO networks. As normal MIMO systems fail to provide spatial diversity due to the confined space, which does not allow for more antennas to be placed in a device. Two main schemes are being followed in MIMO Relay networks, Amplify and Forward (AF) and Decode and Forward (DF). The AF scheme is considered the simplest of both as it involves blindly amplifying the received signal at the relay transceiver passing it to the destination. Hence the name analogue scheme applies to it as well. As the name indicates, DF is more complex as the received data at the relay is being reconstructed then relayed to the destination. A hybrid-relaying scheme has been introduced in (Fan 2007), it has been called filter, amplify and forward where the received data at the relay is being partially decoded. This hybrid relaying approach has been found to outperform the AF and nearly match performance of the DF provided Channel State Information (CSI) is available at the relay (Fan 2007). The availability of the CSI will prove critical in the performance of any MIMO Relay system as will be shown later by the ground breaking work in (Goldsmith 2002). To further exploit the

cooperative diversity, suboptimal relay selection schemes were introduced in (Fan 2007). It has been found that with more antennas available at the relay than the transmitter and receiver, the system performance gets enhanced. This hybrid scheme however needs a more complex relay compared with the simple AF need. A general analysis of the cooperative AF relay networks has been introduced in (Abdaoui 2010). A general analysis of MIMO Relay AF networks has been done, especially when having multiple antennas per node. The analysis introduced a unified system definition and divers model investigation. It falls short in expanding the channel model to include the line of sight and none line of sight components in the MIMO channel as done by (Jiang 2006). The work we present in the research will combine the comprehensive channel model introduced in (Jiang 2006) and the diverse MIMO Relay AF systems introduced in (Abdaoui 2010). Moreover, the exponential path loss model was used to account for the power loss on the links (Jiang 2006). We have used the Urban Hata model to account for that. Unlike the single relay systems, the virtual antennas system is indeed an attractive choice (Abdaoui 2010).

2.2.2 MIMO Relay System Definitions

Moving forward to the MIMO Relay AF systems, (Jiang 2006) introduced the Source-Relay-Destination system where there is no direct link between the Source and Destination. This is known as the two hop system as data is first transmitted from the source to the relay. This takes place in the first time slot. In the second time slot transmission happens between the relay and the destination. The naming convention S-R-D has been introduced earlier (Rohit, 2004). The motivation for adopting the S-R-D system is to proof test the channel modeling introduced in (Jiang

2006) which accounts for the relay location in calculating the system capacity. The Relay Node (RN) has been accounted for by multiplying the square root of received power at RN by its channel matrix (Jiang 2006). The work in (Rohit, 2004) is among the earliest done on cooperative diversity. Working on a simple configuration, the two Relay techniques AF and DF were studied. The study concluded that with proper deployment of time division multiple access protocols higher degrees of spatial diversity could be achieved (Rohit 2004). The work presented in (Zhao 2004) focuses on MIMO Relay AF networks. It starts by making all RN participate in communicating the data between S and D. As this is a suboptimal approach, two routing approaches were developed based on the channel state information, CSI, and power allocation. Eventually intelligent power allocation and relay selection leads to an enhanced system performance.

2.3 MIMO Relay AF System Capacity formulation

The dual nature of the uplink, or Multiple Access (MAC) channel of the MIMO system and its downlink, or Broadcast channel (BC), this duality means that the analysis results for any link applies for the other link as well (Yang, W. Y., Kang, C. G., & Cho, Y. S., 2010). Our discussion will be restricted to the BC hereafter. Figure 2.2 provides a basic presentation of a Multiuser, MU-MIMO BC channel, with k users.

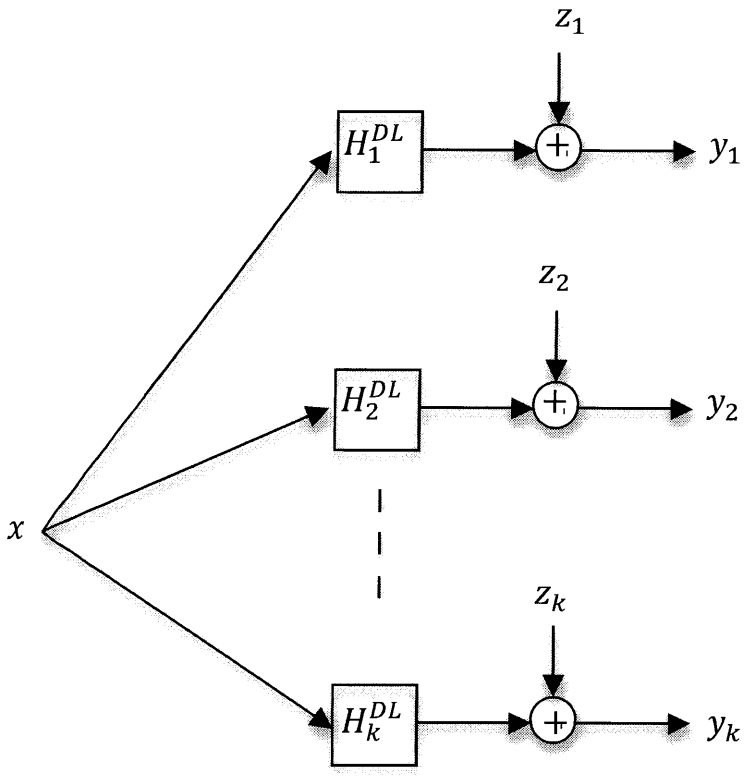


Figure 2.2, MU-MIMO BC channel with k users

The capacity of the MU-MIMO Relay AF system is described in equation 2.1.

$$C = log_2 det(I + (AR_x A^H)(BR_n B^H)^{-1}) \quad (2.1)$$

where A & B are derived from the channel matrix. The received data must be in the shape of equation 2.2.

$$y = Ax + Bn \quad (2.2)$$

2.3.1 Channel State Information knowledge effect on the System Capacity

The time varying nature of the MIMO channels makes it essential for the transmitter to have a certain level of knowledge of the CSI before Data transmission takes place (Zhao 2011). The degree of knowledge of the CSI and its location in the MIMO Relay AF system has been the work of (Sheng 2007). The work in (Goldsmith 2002) presented a detailed breakdown of the CSI level of knowledge and location effect on the multi user MIMO systems. There can be a perfect CSI or a partial CSI; it can be at the transmitter, CSIT or at the receiver, CSIR. The optimum condition for a MIMO Relay AF system is to have a perfect CSIT, however partial CSIT and CSIR would still keep a lot of issue unresolved like the MU-MIMO ergodic capacity. The work presented by (Shi 2007) developed practical feedback systems that require partial CSI. This has been developed along with precoding technique to cancel out interference. The precoding work will be presented later in this chapter.

2.3.2 Physical Characteristics effect on the MU-MIMO System Capacity

The physical design of the antenna system and the RN location effects were the center of the work presented in (Gomadam 2007). Eventually all these elements play a major role in determining the expected capacity gains. The work in (Sheng 2007) reflected the Angle of Arrival, AoA and Angle of Departure, AoD effects on the MIMO system capacity as well. These effects along with the SNR were thoroughly investigated in our work. In (Jiang 2008) the presence of the Line Of Sight link in the S-D link has been studied.

2.3.3 Downlink Uplink Duality

Another major area in the study of MU-MIMO systems is the dual nature of the MIMO Broad Cast (downlink) and multiple Access (MAC) channels (Goldsmith 2002). The dual nature of the BC and MAC channels means simply that whatever results gained in the study of one link can be extended to the other one. So it is enough to study the BC channel for example to know the MAC channel without undergoing the same study approaches. All the work done hereafter will be on the MIMO BC channel.

2.4 Interference Cancelation Precoding Techniques

MU-MIMO communication systems suffer from users interference as they share the same frequency in BC and MAC channels. To counter fight this interference problem, precoding at the transmitter is used. The work in (Gomadam 2008) looks after different Precoding techniques to cancel out interference in MU-MIMO systems. These results can be extended to MIMO Relay AF systems. The concept behind precoding is to multiply or encode the data stream at the transmitter with a special key. Every user's data stream is multiplied with a unique key. On the receiver side, the key is used to cancel out the received data stream of the other users and to boost the signal strength of the target data stream. Thus, precoding serves two purposes eliminate unwanted data and magnify the power of the needed data. The way precoding is done is however where engineering a good precoding technique counts. As it might sound, precoding multiple data streams with unique codes not only mathematically involved but also needs a lot of processing power. Four

precoding techniques will be investigated. The studied techniques are the Dirty Paper Coding (DPC), the Channel Inversion (CI), the Block Diagonalization (BD) and Tomlinson-Harashima (TH) precoding.

2.4.1 Dirty Paper Coding

DPC is the optimum precoding technique and the most involved one when looking at the processing power needed. The concept of DPC is simply to produce an interference free transmission. It does so by subtracting the potential interferences, i.e. other user's data streams, before transmission. This requires full CSI knowledge by the transmitter. LQ decomposition is implemented in DPC. The channel BC matrix can be LQ decomposed as shown in 2.3. By transmitting $Q^H x$ at the receiver Q effectively eliminates the interference caused by the other data streams. The below 3 users system helps visualize the DPC steps.

$$H^{DL} = \underbrace{\begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix}}_{L} \underbrace{\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}}_{Q} \tag{2.3}$$

The LQ decomposition is used to decompose the BC channel matrix. The received signal is the transmitted encoded data streams multiplied by the channel matrix of the system plus their corresponding noise as shown in 2.4

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \underbrace{\begin{bmatrix} H_1^{DL} \\ H_2^{DL} \\ H_3^{DL} \end{bmatrix}}_{H^{DL}} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \tag{2.4}$$

$$\tilde{x} = Q^H x \tag{2.5}$$

Where $H_u^{DL} \in \mathbb{C}^{1\times 3}$ is the channel matrix for the individual user. And $\{q_i\}_{i=1}^{3} \in \mathbb{C}^{1\times 3}$ are orthonormal row vectors. Expanding the equations

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \underbrace{\begin{bmatrix} H_1^{DL} \\ H_2^{DL} \\ H_3^{DL} \end{bmatrix}}_{H^{DL}} Q^H x + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \tag{2.6}$$

Expanding and solving for Q results in 2.7.

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -\frac{l_{21}}{l_{22}} & 1 & 0 \\ -\frac{l_{31}}{l_{33}} + \frac{l_{32}}{l_{33}}\frac{l_{21}}{l_{22}} & -\frac{l_{32}}{l_{33}} & 1 \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \end{bmatrix} \tag{2.7}$$

The above precoding matrix allows us to rewrite 2.6 as shown in 2.8.

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ -\frac{l_{21}}{l_{22}} & 1 & 0 \\ -\frac{l_{31}}{l_{33}} + \frac{l_{32}}{l_{33}}\frac{l_{21}}{l_{22}} & -\frac{l_{32}}{l_{33}} & 1 \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \tag{2.8}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} l_{11} & 0 & 0 \\ 0 & l_{22} & 0 \\ 0 & 0 & l_{33} \end{bmatrix} \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \\ \tilde{x}_3 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}$$

Hence the precoding matrix Q^H is found to be as below.

$$\begin{bmatrix} 1 & 0 & 0 \\ -\frac{l_{21}}{l_{22}} & 1 & 0 \\ -\frac{l_{31}}{l_{33}}+\frac{l_{32}}{l_{33}}\frac{l_{21}}{l_{22}} & -\frac{l_{32}}{l_{33}} & 1 \end{bmatrix} = \begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix}^{-1} \begin{bmatrix} l_{11} & 0 & 0 \\ 0 & l_{22} & 0 \\ 00 & 0 & l_{33} \end{bmatrix} \quad (2.9)$$

The aforementioned complexity of the DPC was the main motive to propose less complex algorithms even if some performance is compromised. However, DPC remains the method of precoding the data such that the effect of the interference can be canceled subject to some interference that is known to the transmitter (Yang, W. Y., Kang, C. G., & Cho, Y. S., 2010). (Jindal, N., & Goldsmith, A. 2005) established that the sum-rate capacity of the MIMO BC channel achievable by DPC is at most min (M, K) times larger than the maximum achievable sum rate via TDMA. Where M stands to the number of antennas per users and K stands for the number of active users. The work done in (Gomadam 2008) looks into less complex precoding techniques that approach the performance of the DPC as an acceptable compromise. Another approach to a suboptimal DPC was the focus of the work done by (Saradka, B., Bhashyam, S., & Thangaraj, A., 2011). They worked on a zero-forcing DPC precoding technique. It forms a suboptimal approach to the DPC precoding. The ZF-DPC was designed using trellis shaping and low Density Parity Check codes for the MIMO BC channel.

2.4.2 Channel Inversion

Channel Inversion also known as zero forcing refers to the process where the transmitted data stream is multiplied by a weight matrix prior to its transmission. This weight matrix is designed to balance the channel gain over the transmitted time interval; hence it is a linear precoding technique. Figure 2.3 explains this concept symbolically.

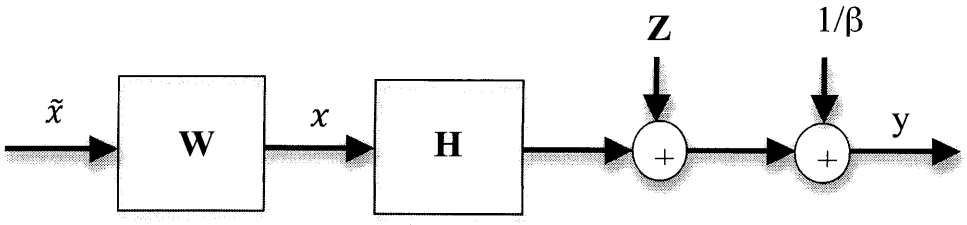


Figure 2.3, Channel Inversion linear precoding

Where W stands for the weight matrix, $W \in \mathbb{C}^{N_T \times N_T}$, H the channel matrix $H \in \mathbb{C}^{N_R \times N_T}$ is the system's channel matrix. 1/β is a constant designed to meet the total transmitted power constraint. Actually, this power constraint is present in all of the MIMO relay system equations as it dictated the gain introduced by the relay. Its formula however differs based on the system configuration. For our case here of CI, the Beta value is given as shown in equation 2.10. The precoded symbol vector x can be presented as shown in equation 2.11. Where N_T stands for the number of antennas at the transmitter and N_R stands for the receiver antennas count.

$$\beta = \sqrt{\frac{N_T}{Tr(H^{-1}(H^{-1})^H)}} \tag{2.10}$$

$$x = W\tilde{x} \tag{2.11}$$

Having introduced all the parameters, it is essential that the weight matrix is introduced as shown in equation 2.12. The weight matrix design determines the type of precoding.

$$W_{ZF} = \beta H^{-1} \tag{2.12}$$

In our case here it is the channel inversion precoding also known as Zero Forcing (ZF) precoding. This is a linear precoding as the parameter β is a constant, i.e. creating the weight matrix is a linear operation. A variation of the ZF precoding is generated when the creation of the weight matrix is done based on Minimum Mean Square Error technique, MMSE as shown in 2.13.

$$\begin{aligned} W_{MMSE} &= \beta \times arg_W min\, E\{\|\beta^{-1}(HW\tilde{x} + z) - \tilde{x}\|^2\} \\ &= \beta \times H^H \left(HH^H + \frac{\sigma_Z^2}{\sigma_x^2} I \right)^{-1} \end{aligned} \tag{2.13}$$

Joint precoding and suboptimal algorithms are recent approaches proposed to utilize MMSE based precoding for MIMO Relay AF systems. Source and relay precoders were designed while adopting the MMSE criterion at the destination in the work presented by (Wu, C., Chung, W., & Chen, C., 2013). Their proposed method is based on diagonalizaing the MSE matrix via SVD. This is a suboptimal approach aiming at reducing the precoders' complexity. Selecting particular structures of the precoding and amplifying matrices can diagonalize the Mean Square Error (MSE) matrix. This solution works out best when the SD power is higher than the SR link. The original problem of MMSE precoding is being a highly non-convex problem. The approach presented

in (Yi, H., Zou, J., Luo, H., & Yu, H., 2011) attempts solving this problem by decoupling it into three sub problems. Introducing an iterative algorithm to repeatedly optimize preorders and receivers did this. Their proposed algorithm outperformed standard approaches in terms of bit error rate and mean square error values. The work of (Aditya, S., Rajeshwari S. S, & Giridhar, K., 2012) introduced a joint precoding between the source and the relay. The proposed scheme required the knowledge of the second order statistics of the interference. The interference suppression was based on MMSE, the scheme proved robust even under low SINR.

2.4.3 Block Diagonalization

In Block Diagonalization precoding approach the interference from other user signals only, is canceled in the process of precoding. Then various signal detection methods can be used to cancel out the inter-antenna interference for each user. The precoding matrix must be constructed in a way to allow only the user information to emerge after decoding having all other signals suppressed. This is done by forcing the W matrix to be in the null space of the channel matrix of the system. The equations below help visualizing the concept. Looking at the receiver's end, the BD received signal looks as shown in 2.14.

$$\begin{aligned} y_u &= H_u^{DL} \sum_{k=1}^{K} + z_u \\ &= H_u^{DL} W_u \tilde{x}_u + \sum_{k=1, k \neq u}^{k} H_u^{DL} W_k \tilde{x}_k + z_u \end{aligned} \tag{2.14}$$

Where Wu stands for the precoding matrix for the uth user taking this form, $W_u \in \mathbb{C}^{N_B \times N_{M,u}}$. The channel Matrix between the BS and the uth user takes this form, $H_u^{DL} \in \mathbb{C}^{N_{M,u} \times N_B}$. Again, all the analysis done is for the Broad Cast BC link. However, the same results apply for the Multiple Access Channel MAC as the dual nature of both channels allows this assumption (Jafar, S. A., Gomadam, K. S., & Huang, C., 2007). Looking back at 2.14 the precoding matrix must be block-diagonalized so that only the uth user traffic is available after multiplying with the precoding matrix at the receiver and the other data streams, i.e. interference, is eradicated by the precoding matrix.

$$H_u^{DL} W_k = 0_{N_{M,u} \times N_{M,u}}, \forall u \neq k \tag{2.15}$$

With this condition in 2.15 being true, the received signal in 2.14 becomes interference free as shown below.

$$y_u = H_u^{DL} W_u \tilde{x}_u + z_u, u = 1,2, \dots, K \tag{2.16}$$

The task now is to construct the precoding matrix $\{W_k\}_{k=1}^{K}$ that must satisfy 2.16. This is done by constructing a system channel matrix for all the users except the user of interest. Once this matrix is constructed, and you have to imagine the complexity of this approach as the BS needs to be aware of the full CSI for all the users. Once this matrix is constructed, the precoding matrix is generated by satisfying the below condition in 2.17.

$$\tilde{H}_u^{DL} W_k = 0_{(N_{M,total} - N_{M,u}) \times N_{M,u}}, u = 1,2, \dots, K \tag{2.17}$$

Hence the precoding matrix must lie in the null space of the BD system channel matrix. So decimating the u^{th} user channel matrix from the system channel matrix creating a BD system channel matrix comes first in creating the precoding matrix. Then the precoding matrix has to lie in the null space of that BD system channel matrix. This has to be done for every user in the system. This iterative computation in generating the BD system channel matrix for each user and finding a solution in its null space to create a precoding metric motivated the search for less complex approaches which are based on the BD algorithm. (Morato, M., Chen, Y., Yuen, C., & Lei, Z., 2011) proposed two practical distributed algorithms that are based on block diagonalization technique. The proposed schemes eliminate the need of iterative computations, and hence can be implemented without information exchange between multiple base stations. But the need for CSI is still essential for this approach. Furthermore suboptimal solution has been proposed that requires only partial channel state information to be available at each base station. Simulation results showed that the proposed algorithm approaches the performance of its counterpart in the literature without the need of iterative computation to create BD system channel matrix for each user. Simulation results showed that the knowledge of CSI plays an important role on the system throughput for distributed MIMO systems. (Hwang, J., Lee, K., Sung, H., & Lee, I., 2010) proposed two (AF) relaying schemes, which maximized the sum-rate for the interference channel with multiple source-destinations. Since the formulated optimization problem is not a convex or concave in general two approaches were attempted to solve the interference cancelation in MIMO relay AF systems. First an iterative scheme was introduced which provides a local optimal solution. The proposed scheme iteratively searches an optimum relay matrix by

deriving the gradient of the sum-rate and applying the gradient descent algorithm. Next, in order to reduce the computational complexity of the iterative scheme, a BD method was introduced which utilizes the MMSE criterion with singular value decomposition (SVD) based rate maximization. The proposed iterative scheme achieved a near optimal sum-rate for the given channel model as shown by simulations. The MMSE based BD with the rate maximization approaches the local optimal sum-rate at high signal-to-noise ratio (SNR) regime.

2.4.4 Tomlinson-Harashima Precoding

Decision Feedback Equalization (DFE) is used in MIMO systems on the receiver side. To reduce the peak or average power usage on these DFE, which suffers from error propagation the TH precoding was introduced. The original idea of TH precoding in DFE is to cancel the post-cursor ISI in the transmitter, where the past transmit symbols are known without possibility of errors. In fact, it requires a complete knowledge of the channel impulse response, which is only available by a feedback from the receiver for time-invariant or slowly time varying channel (Yang, W. Y., Kang, C. G., & Cho, Y. S., 2010). Minimizing the peak or the average power of the DFE is achieved by encoding the transmitted signal; i.e. data stream from a set of symbols. Once the data stream is encoded, it can be transmitted and reconstructed at the receiver after being shaped to control its transmitted power. The encoding method ensures that the resulting symbols, called the expanded symbols, require minimum power for transmission. Equation 2.18 describes a typical expanded symbol formula.

$$c = x + 2A.m \tag{2.18}$$

Where x is the data stream, A is an even integer given by $A = \sqrt{M}$ similar to a Pulse Amplitude Modulation codebook. The constellation; $\{-(A-1), -(A-3), \ldots, -3, -1, 1, 3, \ldots, (A-3), (A-1)\}$ is used to map the data stream and encoding it into the expanded symbol. In order to reduce the peak power, m in 2.18 must be chosen to minimize the magnitude of c. At the receiver side, the data stream is recovered via a symmetric modulo operation as defined in 2.19.

$$x = mod_A(c) \triangleq c - 2A\lfloor (c + A)/2A \rfloor \tag{2.19}$$

(Lei Zhang, Yunlong Cai, Rodrigo C. de Lamare, and Minjian Zhao, 2014) proposed a design of robust transceivers with TH precoding for MIMO relay AF based on a multi-branch (MB) strategy. The robustness of the proposed scheme is based on the system being able to endure errors in its CSI. The MB strategy employs successive interference cancellation (SIC) on several parallel branches which are equipped with different ordering patterns so that each branch produces transmit signals by exploiting a certain ordering pattern. For each parallel branch, the proposed robust nonlinear transceiver design consists of TH precoding at the source along with a linear precoder at the relay and a linear minimum-mean-squared-error (MMSE) receiver at the destination. By taking the channel uncertainties into account, the source and relay precoders are jointly optimized to minimize the mean-squared-error (MSE). Simulation results demonstrate that the proposed MB-TH precoding scheme is capable of alleviating the effects of CSI errors and improving the robustness of the system. (Xing, G., Xia, M., Gao, F., & Wu, Y., 2011)

proposed a robust transceiver design with TH precoding for MIMO relaying AF systems. At source node, TH precoding was adopted to mitigate the spatial inter-symbol-interference (ISI). However, due to its nonlinear nature, TH precoding is very sensitive to channel estimation errors. In order to reduce the effects of channel estimation errors, a joint Bayesian robust design of THP at source, linear forwarding matrices at relays and linear equalizer at destination is proposed. The performance advantage of the proposed robust design over non-robust design was demonstrated by simulation results.

2.5 Conclusions:

MIMO Relay AF systems capacity and precoding techniques were studied. The nature of the MU-MIMO systems introduces new limits on the capacity analysis. However, the capacity analysis of the MIMO Relay systems has been standardized based on the general MIMO Relay system configurations. The ease of capacity calculation is subject to forming the received signal in a standard format. All the capacity analysis must follow the route of shaping the received signal into a standard format then considering the power constraints of the system. Then using the standard capacity equation follows. User interference is an added factor in considering the system capacity. As all users share the same uplink and downlink, interference cancelation techniques were introduced to mitigate this interference. Four main interference cancelation techniques were presented. The complexity and power needs for these techniques motivated the research for suboptimum approaches for interference cancelation. This field is a promising field to study. Later in chapter 5 we will present a comparison study between the main interference cancelation techniques.

Chapter 3

The MIMO Relay AF system Channel Model Implementations

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Chapter 3

The MIMO Relay AF system Channel Model Implementations

3.1 Introduction:

The introduction of the RN in the MU-MIMO systems thus transferring it into MIMO Relay systems added more constrains on adapting the proper channel model. The Line of Sight, LOS, channel components tend to negatively affect channel matrix as they tend to have more dominance over None Line of sight NLOS components. This results in reducing the rank of the matrix. This eventually leads to a lower capacity value of the system. Most literature focuses on the Rayleigh channel model (Jiang 2006). This channel model overestimates the channel capacity values. A more realistic channel model has been adopted in our work in one that accounts for LOS and NLOS components. Moreover, it accounts to the RN location and position as it affects the MIMO Relay AF system capacity. In implementing the channel model three levels of complexity were adopted. A simple channel model accounting for the system capacity, path loss and RN location has been adopted as the basic model. A correlation channel model followed this to account for the antennas correlation. The most realistic channel model implemented is the Outdoor Stochastic Spatial Clustered, (OSSC) channel model. The OSSC channel model is an extension to the correlation channel model where more channel elements were added. The

added parameters include the AoA, AoD at the three S, R & D nodes. The Angle Spread, AS has been added as well. On the receiver side, the mobility of the Mobile Stations has been accounted for as well.

3.2 Channel Modeling Approach

Extending the coverage area of a given wireless network can be done by introducing relays to the network structure. This improvement in the performance of infrastructure based network by increasing their coverage area and exploiting the spatial diversity has been a hot topic in research recently. The main focus of the existing literatures has been on studying the various methodologies to obtain better channel performance. However, little attention is paid to the channel modeling for relays. The Rayleigh channel model has been the most accepted channel model for the relay systems (Jiang 2006). This model however, holds in the case where the relay lies in the non-line-of-sight (NLOS) scenario of both the source and the destination. The channels between the source and relay, and the relay and destination are considered as the full rank multiple-input multiple-output (MIMO) channels. Maintaining a full rank for these channels is a goal by itself in MIMO communications, as the lower the rank leads to a lower capacity of the given system. The effect of the location of the relay on the system performance is usually ignored in the analysis; this is why it has been one topic addressed in our work. (Jiang 2006) investigated the power and location optimization for decode-and-forward relay network, but the fading coefficient of the channel is still assumed to be distributed according to Gaussian distribution. However, to maximize the coverage, the relay is typically placed in the LOS scenario of the source (Tsai 2007). Therefore, the Rayleigh channel model is no longer suitable to analyze practical relay channels. In addition, since there

is LOS component propagating from the source to relay, in the case of the MIMO communication, the channel between the relay and the source is correlated. Hence the capacity performance of the whole system degrades, and it is necessary to use techniques such as cross-polarized antenna or optimal power allocation to improve the performance in the channel. (Holakouei 2009) studied the channel modeling for a simple two-hop single relay system.

3.1.1 MIMO Relay AF Channel Model Considerations

When adopting the channel model for the simulation, some key factors had to be included in the channel model. These factors would contribute towards having a more realistic channel model with a room for control for some parameters. Thus we started with the simple channel model to test for correctness. Then the correlation channel model gave a room to control the antenna correlations in the three links, SR, SD and RD. The OSSC is the most realistic channel model where the correlation is calculated based on the rice steering matrix. The AoA, AoD and AS were sourced from the 3GPP-SCM channel model tables. The path loss calculations were based on the Urban-Hata model (Young 2010) as described in the next section.

3.1.2 Path Loss implementation

The work presented in (Jiang 2006) though detailed in channel modeling, it used the exponential decay as its path loss model. The Hata model being the most popular is more accurate as well. Thus it has been adopted in our work to account for the path loss in the simulation.

3.1.3 The Urban Hata Model

The Okumura model has been extended to cover the various propagation environments, including urban, suburban, and open area, which is now known as the Hata model. In fact, the Hata model is currently the most popular path loss model (Young 2010). For the height of transmit antenna, h_{TX}[m], and the carrier frequency of f_c[MHz], the path loss at distance d [m] in an urban area is given by the Hata model as:

$$PL_{Hata,U}(d)[dB] = 69.55 + 26.16\log f_c \ldots \\ \ldots -13.28\log h_{TX} - C_{RX} + (44.9 - 6.55\log h_{TX})\log d \quad (3.1)$$

Where

h_{TX} $[m]$ is the transmitter height in meters
d is the direct distance between the transmitter and the receiver in meters
C_{RX} is the correlation coefficient of the receive antenna, which depends on the size of coverage. For small to medium-sized coverage, C_{RX} is given as:

$$C_{RX} = 0.8 + (1.1\log f_c - 0.7)h_{Rx} - 1.56\log f_c \quad (3.2)$$

Where

$h_{Rx}[m]$ is the receiver's height in meters.
f_c is the carrier frequency in MHz

the Hata model for Urban areas was adopted in our work throughout.

3.3 Simple channel model with path loss via the Hata model

The first channel model used in the simulation was the simple channel model. The main reason for adopting this model though other models were used later was to test for correctness. This model takes account of the Line of sight (LOS), and No line of sight (NLOS) components of the MIMO channel (Venugopal 2005). The case were all three stations S, R and D have the same number of antenna elements, which is denoted by M As shown in (Jiang 2006) has been adopted. The channel matrix for a point-to-point channel link can be written as:

$$H = \sqrt{Power_{received}}\left(\sqrt{\frac{K}{K+1}}H_{LOS} + \sqrt{\frac{1}{K+1}}H_{NLOS}\right) \quad (3.3)$$

Where the power received stands for the power received at the received side of a given link. And, K is the Rician K-factor, which is related to the propagation condition and the distance between transmitter and receiver (Jiang 2006).

$$K = 13 - 0.03d(dB) \quad (3.4)$$

Where d is the direct distance between the transmitter and receiver.

H_{LOS} represents the contribution of the LOS components in the channel. The specific distance between transmitter and receiver and the configurations of the antennas determines it.

H_{NLOS} takes into account the influence of the scattering components during the propagation. The entries of H_{NLOS} are assumed to be zero-mean unit-variance complex Gaussian random variables.

K is assumed to be 0 dB in the NLOS case, while in the LOS case, K is often larger than 0 dB, hence H shows Rician fading characteristics. Note that time correlation and spatial correlation are not considered in the model. All three links of relay system can be modeled the same way. The spatial correlation is however considered in the next two models.

3.4 Correlated channel model

The correlated channel model incorporates the antennas spatial correlation in the channel capacity calculations. The user controls the correlation values. This allowed us to study the effect of varying correlation on the system capacity. The model has been presented in (Mangoud, 2008).

$$H = \sqrt{Power_{received}}\left(\sqrt{\frac{K}{K+1}}H_{LOS} + \sqrt{\frac{1}{K+1}}R_t^{1/2}H_{NLOS}R_r^{1/2}\right) \quad (3.5)$$

Where $R_t^{1/2}$ represents the antenna correlation of the transmitter and $R_r^{1/2}$ represents the antenna correlation at the receiver. All the other parameters would still the same as the simple channel model.

3.5 Outdoor Stochastic Spatial Clustered Channel Model

The most realistic channel model used in our work is the outdoor stochastic spatial clustered (OSSC) channel model. The covered elements in this model include the geometrical antenna configurations, the AoA, AoD and the Mobile Stations (MS) movements as well. An illustration of the wave propagation for spatial channel model employing ULA array is shown in Figure 3.1. The OSSC channel model is given in equation 3.6.

$$H = \sqrt{Power_{received}}\left(\sqrt{\frac{K}{K+1}}v(\theta_r) + \sqrt{\frac{1}{K+1}}R_t^{1/2}H_{NLOS}R_r^{1/2}\right) \quad (3.6)$$

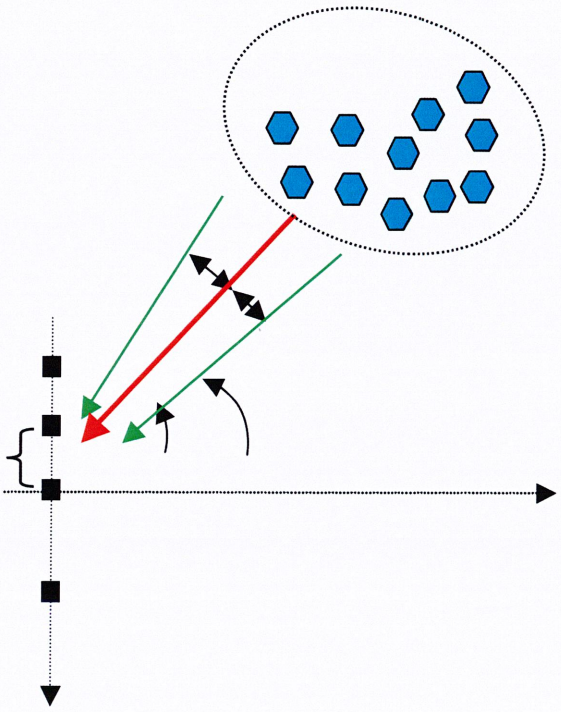


Figure.3.1, Wireless communication system employing ULA array

The Receiver *steering vector* $\mathbf{v}(\theta_r)$ for specific arriving plane wave in a ULA M elements UCA can be written as ;

$$\mathbf{v}(\theta_r) = \begin{bmatrix} v_1(\theta_r) \\ v_2(\theta_r) \\ v_3(\theta_r) \\ \vdots \\ v_M(\theta_r) \end{bmatrix} = \begin{bmatrix} 1 \\ e^{j2\pi\frac{D}{\lambda}\sin(\zeta)\sin(\theta_r)} \\ e^{j2\pi\frac{2D}{\lambda}\sin(\zeta)\sin(\theta_r)} \\ \vdots \\ e^{j2\pi\frac{(M-1)D}{\lambda}\sin(\zeta)\sin(\theta_r)} \end{bmatrix} \tag{3.7a}$$

where D is the antenna element spacing, ζ is the elevation angle, and θ_r is the AoA at received antenna array. For simplicity, only the azimuth angles are considered in the propagation geometry ($\zeta = 90^{o}$). Similarly, Figure 3.2 shows a wireless communication system employing a UCA array with M evenly spaced receive elements.

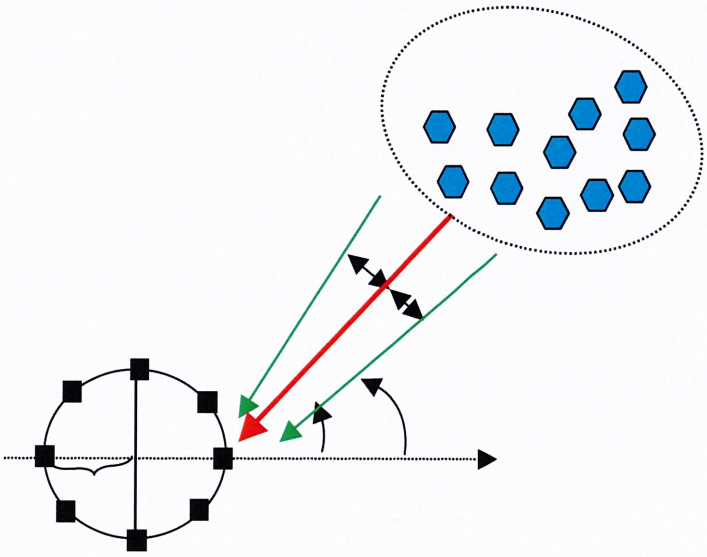


Figure 3.2, Wireless Communications System employing UCA array

The array steering vector $\mathbf{v}(\theta_r)$ for a single received plane wave in a UCA can be written as (Umrani, A. W., Guan, Y. L., & Umrani, F. A., 2019).

$$\mathbf{v}(\theta_r) = \begin{bmatrix} v_1(\theta_r) \\ v_2(\theta_r) \\ \vdots \\ v_M(\theta_r) \end{bmatrix} = \begin{bmatrix} e^{j2\pi\frac{R}{\lambda}\cos(\theta_r-\varphi_1)} \\ e^{j2\pi\frac{R}{\lambda}\cos(\theta_r-\varphi_2)} \\ \vdots \\ e^{j2\pi\frac{R}{\lambda}\cos(\theta_r-\varphi_M)} \end{bmatrix} \tag{3.7b}$$

where R is the circular radius of the antenna array, and φ_m is the phase excitation of mth element in azimuth plane.

The spatial fading correlation function $\mathrm{R}_s(np, mq)$ between two channels $h_{n,p}$ and $h_{m,q}$ for a MIMO channel can be defined as ;

$$\mathrm{R}_s(np, mq) = E\left[h_{n,p}h_{mq}^*\right] \tag{3.8}$$

where $h_{n,p}$ is the multipath channel impulse response for the pth transmit antenna at the nth receive antenna elements. Subsequently, $\mathrm{R}_s(np, mq)$ can be written as

$$\begin{aligned} \mathrm{R}_s(np, mq) &= E\left[v_n(\theta_s^{\mathrm{Rx}})v_p(\theta_s^{\mathrm{Tx}})v_m^*(\theta_s^{\mathrm{Rx}})v_q^*(\theta_s^{\mathrm{Tx}})\right] \\ &= \int_{\theta_s^{\mathrm{Tx}}}\int_{\theta_s^{\mathrm{Rx}}} v_n(\theta_s^{\mathrm{Rx}})v_p(\theta_s^{\mathrm{Tx}})v_m^*(\theta_s^{\mathrm{Rx}})v_q^*(\theta_s^{\mathrm{Tx}})\, p(\theta_s^{\mathrm{Tx}}, \theta_s^{\mathrm{Rx}})d\theta_s^{\mathrm{Tx}}d\theta_s^{\mathrm{Rx}} \end{aligned} \tag{3.9}$$

where $v_n(\theta_s^{\mathrm{Rx}})$ and $v_m(\theta_s^{\mathrm{Rx}})$ are the array response for nth and m^{th} receiving antennas and s^{th} scatterer path at the receiver side, while, $v_p(\theta_s^{\mathrm{Tx}})$ and $v_q(\theta_s^{\mathrm{Tx}})$ are the array response for p^{th} and q^{th} transmitting antennas and s^{th} scatterer path at the transmitter side, and $p(\theta_s^{\mathrm{Tx}}, \theta_s^{\mathrm{Rx}})$ is the joint probability density function of AOD and AOA. For a ULA, $v_i(\theta_s^y)$ can be expressed as

$$v_i(\theta_s^y) = e^{j2\pi\frac{D(i-1)}{\lambda}\sin(\theta_s^y)} \tag{3.10}$$

and for a UCA, $v_i(\theta_s^y)$ can be written as

$$v_i\left(\theta_s^y\right) = e^{j2\pi\frac{R}{\lambda}\cos(\theta_s^y - \varphi_i)} \tag{3.11}$$

where $i \in \{n, m, p, q\}$ and $y \in \{\text{Tx}, \text{Rx}\}$. Since θ_s^{Tx} and θ_s^{Rx} are statistically independent, (3.9) can be written as

$$\begin{aligned} &\mathrm{R}_s(np, mq) \\ &= \int_{\theta_s^{\text{Tx}}} v_p(\theta_s^{\text{Tx}}) v_q^*(\theta_s^{\text{Tx}})\, p(\theta_s^{\text{Tx}}) d\theta_s^{\text{Tx}} \int_{\theta_s^{\text{Rx}}} v_n(\theta_s^{\text{Rx}})\, v_m^*(\theta_s^{\text{Rx}}) p(\theta_s^{\text{Rx}}) d\theta_s^{\text{Rx}} \\ &= \mathrm{R}_{\mathrm{S}}^{\text{Tx}}(p, q)\mathrm{R}_{\mathrm{S}}^{\text{Rx}}(n, m) \end{aligned} \tag{3.12}$$

where $p(\theta_s^{\text{Tx}})$ and $p(\theta_s^{\text{Rx}})$ are the PDFs of AoD and AoA, respectively. $\mathrm{R}_{\mathrm{S}}^{\text{Tx}}(p, q)$ is the spatial correlation due to transmit antennas, and $\mathrm{R}_{\mathrm{S}}^{\text{Rx}}(n, m)$ is the spatial correlation due to receive antennas. Both $p(\theta_s^{\text{Tx}})$ and $p(\theta_s^{\text{Rx}})$ are known as the Power Azimuth Spectrum (PAS). In (Y. S. Cho, J. Kim, W. Y. Yang and C. Kang, 2010), it is shown that the pattern of PAS depends mainly on the distribution of the locally- scattered components. In general, enormous amounts of locally-scattered components are observed by the MT in all different environments. Therefore, its PAS usually follows a uniform distribution. However, for the access point (AP) there are different PAS distributions (e.g. uniform, truncated Gaussian and truncated Laplacian) are observed depending on the characteristics of terrain, which is usually shown to have a small angular spread (AS), AS (σ) is defined as the standard deviation of the PAS distribution in degrees as shownin Figures 3.1, 3.2. Figure 3.3 shows the PDF for the three PAS distributions with the central angle of incidence=0° and AS=20°.

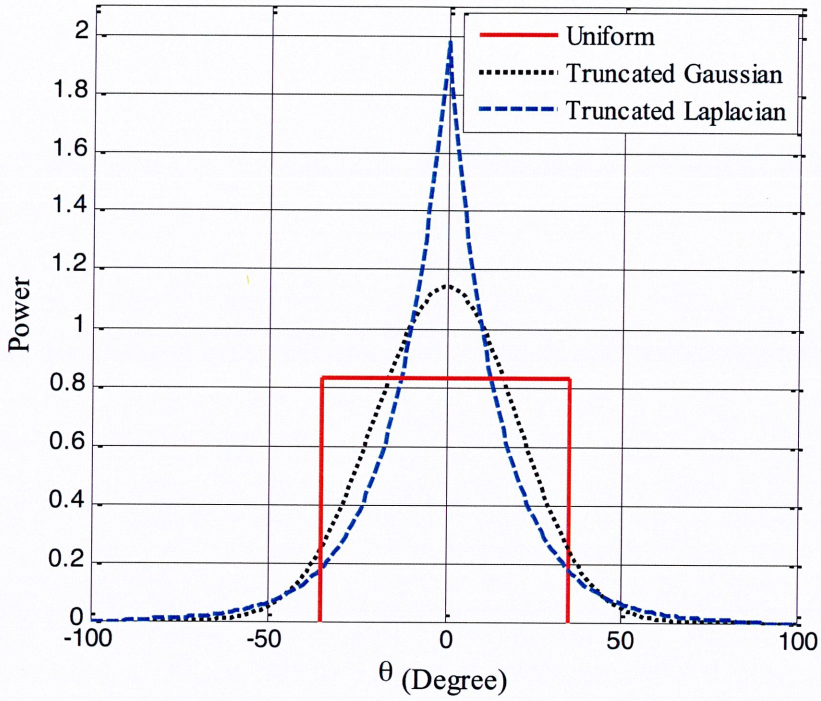


Figure 3.3, PAS distributions (θ = 0°, σ = 20°) comparisons

In this research, the truncated Laplacian PAS distribution at the BS is considered, because it is the best fit to measurement results in urban and rural areas, as revealed in (Abderrazek Abdaoui, 2010). Also, due to reciprocity of uplink and downlink communications, only the uplink spatial correlation function is presented. Consequently, for the s^{th} scattering path on the uplink, θ_s^{Tx} is the AoD at the MT and θ_s^{Rx} is the AOA at the AP. Both $\theta_s^{\text{Tx}}$and θ_s^{Rx} are random variables. θ_s^{Tx} is assumed uniformly distributed over $[0,2\pi]$. A uniform distribution for θ_s^{Tx} is expressed as

$$p(\theta_s^{\text{Tx}}) = \begin{cases} \dfrac{1}{2\pi} & -\pi \le \theta_s^{\text{Tx}} \le \pi \\ 0 & \text{otherwise,} \end{cases} \tag{3.13}$$

and θ_s^{Rx} has a truncated Laplacian PAS distribution, which can be expressed as

$$p(\theta_s^{\mathrm{Rx}}) = C_l e^{-a|\theta_s^{\mathrm{Rx}} - \theta_r|} \quad , -\pi + \theta_r \leq \theta_s^{\mathrm{Rx}} \leq \pi + \theta_r \tag{3.14}$$

where θ_r is the central AoA, and C_l is a normalization factor can be found by

$$\int_{-\pi}^{\pi} C_l e^{-a|\theta_s^{\mathrm{Rx}} - \theta_r|} \, d\theta_s^{\mathrm{Rx}} = 1 \tag{3.15}$$

which gives

$$C_l = \frac{a}{2(1 - e^{-a\pi})} \tag{3.16}$$

and a is a positive decaying factor which is related to the angle spread. Specifically, as a increases the angle spread decreases. The angle spread σ of the Laplacian distribution is defined as

$$\sigma = \frac{2}{a^2} - \frac{2ae^{-a\pi}}{1 - e^{-a\pi}} \left(\frac{\pi^2 a + 2\pi}{a^2} \right) \tag{3.17}$$

Using (3.17) the uplink spatial correlation can be written as

$$\mathrm{R}_s(np, mq)^u = \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(p, q)^u \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(n, m)^u \tag{3.18}$$

where

$$\begin{aligned} \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(p, q)^u &= \int_{\theta_s^{\mathrm{Tx}}} v_p(\theta_s^{\mathrm{Tx}}) v_q^*(\theta_s^{\mathrm{Tx}}) \, p(\theta_s^{\mathrm{Tx}}) d\theta_s^{\mathrm{Tx}} \\ \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(n, m)^u &= \int_{\theta_s^{\mathrm{Rx}}} v_n(\theta_s^{\mathrm{Rx}}) \, v_m^*(\theta_s^{\mathrm{Rx}}) p(\theta_s^{\mathrm{Rx}}) d\theta_s^{\mathrm{Rx}} \end{aligned} \tag{3.19}$$

In (J. Salz and J. H. Winters, 1994), it is shown that $\mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(p, q)^u$ with θ_s^{Tx} uniformly distributed over $[0,2\pi]$ for a ULA can be expressed as

$$\mathrm{R_s^{Tx}}(p,q)^u = I_0\left(Z_l{}^{\mathrm{Tx}}\right) \tag{3.20}$$

where

$$Z_l{}^{\mathrm{Tx}} = \frac{2\pi(p-q)D_t}{\lambda} \tag{3.21}$$

In (J. Tsai and B. D. Woerner, Nov. 2001), it is shown that $\mathrm{R_s^{Tx}}(p,q)^u$ with θ_s^{Tx} uniformly distributed over $[0,2\pi]$ for a UCA can be expressed as

$$\mathrm{R_s^{Tx}}(p,q)^u = I_0\left(Z_c{}^{\mathrm{Tx}}\right) \tag{3.22}$$

where

$$Z_c{}^{\mathrm{Tx}} = \sqrt{Z_{1,\mathrm{Tx}}^2 + Z_{2,\mathrm{Tx}}^2} \tag{3.23}$$

and

$$\begin{aligned} Z_{1,\mathrm{Tx}} &= 2\pi\frac{R_t}{\lambda}\left[\cos(\varphi_p) - \cos(\varphi_q)\right] \\ Z_{2,\mathrm{Tx}} &= 2\pi\frac{R_t}{\lambda}\left[\sin(\varphi_p) - \sin(\varphi_q)\right] \end{aligned} \tag{3.24}$$

In (J. Salz and J. H. Winters, 1993), it is shown that the real and imaginary parts of receive spatial correlation between the nth and mth antenna element for a ULA with a truncated Laplacian AoA distribution as follows

$$\begin{aligned} &\mathrm{Re}\{\mathrm{R_s^{Rx}}(n,m)^u\} \\ &\quad = I_0\left(Z_l{}^{\mathrm{Rx}}\right) \\ &\quad + 4C_l\sum_{k=1}^{\infty} a^2\frac{(1-e^{-a\pi})}{a^2+4k^2} I_{2k}\left(Z_l{}^{\mathrm{Rx}}\right)\cos\left[\left(2k(\theta_r)\right)\right] \end{aligned} \tag{3.25}$$

$$\mathrm{Im}\{R_S^{Rx}(n,m)^u\} = 4C_l \sum_{k=0}^{\infty} a \frac{(1+e^{-a\pi})}{a^2+(2k+1)^2} I_{2k+1}(Z_l{}^{Rx}) \sin[(2k+1)(\theta_r)]$$

where

$$Z_l{}^{Rx} = \frac{2\pi(n-m)D_r}{\lambda} \tag{3.26}$$

In (J. Tsai and B. D. Woerner, Nov. 2001), it is shown that the receive spatial correlation nh and mth antenna element for a UCA with a truncated Laplacian AoA distribution can be expressed as

$$\begin{aligned}\mathrm{Re}\{R_S^{Rx}(n,m)^u\} &= I_0(Z_c{}^{Rx}) \\ &+ 4C_l \sum_{k=1}^{\infty} a^2 \frac{(1-e^{-a\pi})}{a^2+4k^2} I_{2k}(Z_c{}^{Rx}) \cos[(2k(\theta_r + \alpha^r))] \\ \mathrm{Im}\{R_S^{Rx}(n,m)^u\} &= 4C_l \sum_{k=0}^{\infty} a \frac{(1+e^{-a\pi})}{a^2+(2k+1)^2} I_{2k+1}(Z_c{}^{Rx}) \sin[(2k+1)(\theta_r+\alpha^r)]\end{aligned} \tag{3.27}$$

where $Z_c{}^{Rx}$ is related to the antenna spacing and α^r is the relative angle between the nth and mth antenna element, that are defined as

$$\begin{aligned} Z_c{}^{Rx} &= \sqrt{Z_{1,Rx}^2 + Z_{2,Rx}^2} \\ Z_{1,Rx} &= 2\pi \frac{R_r}{\lambda}[\cos(\varphi_n) - \cos(\varphi_m)] \end{aligned} \tag{3.28}$$

$$Z_{2,\mathrm{Rx}} = 2\pi \frac{R_r}{\lambda}[\sin(\varphi_n) - \sin(\varphi_m)]$$

$$\sin(\alpha^r) = \frac{Z_{1,\mathrm{Rx}}}{\sqrt{Z_{1,\mathrm{Rx}}^2 + Z_{2,\mathrm{Rx}}^2}}$$

$$\cos(\alpha^r) = \frac{Z_{2,\mathrm{Rx}}}{\sqrt{Z_{1,\mathrm{Rx}}^2 + Z_{2,\mathrm{Rx}}^2}}$$

The OSSC channel model utilizes the Kronecker model that described in (3.3). Thus, the OSSC channel model can be represented as

$$\mathbf{H} = \mathbf{R}_{\mathrm{Rx}}^{1/2}\mathbf{H}_{iid}\mathbf{R}_{\mathrm{Tx}}^{1/2} \tag{3.29}$$

where $\mathbf{R}_{\mathrm{Tx}}$ and $\mathbf{R}_{\mathrm{Rx}}$ can be computed as follows

$$\mathbf{R}_{\mathrm{Tx}} = \begin{bmatrix} \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(1,1) & \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(1,2) & \dots & \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(1,M_t) \\ \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(2,1) & \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(2,2) & \dots & \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(2,M_t) \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(M_t,1) & \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(M_t,2) & \dots & \mathrm{R}_{\mathrm{s}}^{\mathrm{Tx}}(M_t,M_t) \end{bmatrix}$$

$$\mathbf{R}_{\mathrm{Rx}} = \begin{bmatrix} \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(1,1) & \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(1,2) & \dots & \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(1,M_r) \\ \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(2,1) & \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(2,2) & \dots & \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(2,M_r) \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(M_r,1) & \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(M_r,2) & \dots & \mathrm{R}_{\mathrm{s}}^{\mathrm{Rx}}(M_r,M_r) \end{bmatrix} \tag{3.30}$$

3.6 Simulation assumptions

To further analyze the position effect of the relay, we simulate with 2 pairs of cross-polarized patch antennas at the source, relay and the destination. We apply the widely used assumption in the simulation, (Lei Jiang, 2006). The source-relay distance d_{SR} and relay-destination distance d_{RD} are normalized with respect to the source-destination distance d_{SD} when calculating the path loss. The transmit power is set as 10 Watt. The element spacing for source is 4λ, and the spacing for both the relay and

the source is assumed to be 0.5λ. Intuitively, the relay should lie within the right semi circle with the source at the center, which radius is determined by d_{SD}, i.e., $0 < d_{SR} < d_{SD}$, and $-\pi/2 < \theta_S < \pi/2$. θ_S is the angle between source-relay link and source-destination link. The Ricean K factor is assumed as K = 13−0.03d (dB) as in (Yi Zhao, 2004). Furthermore, we assume that the polarizations of all the antennas at the source, relay and destination are perfectly matched, i.e., $\theta p = 0$. The capacity of the relay channel with 2 pairs of cross-polarized patch As most literature focuses on better methods on enhancing the channel performance, in (Holakouei 2009). The focus was on redefining the channel model to include the line of site as well as none line of site components. The Rayleigh channel model is widely used in modeling the relay systems as done in (Lei 2011). If the Relay Node lies in the LOS between the BS and the MS's then this model wouldn't hold. Thus, the channel model adapted in (Holakouei 2009); combines the LOS and NLOS components in the channel model. Table 4.4 lists the channel models and their differences.

Table 3.1
Summary of the used Channel Models

Channel Model	Simulated Parameters
Simple Channel Model	The Path loss via Hata Model The channel matrix elements, random variables
Correlation Channel Model	The Path loss via Hata Model The channel matrix elements, random variables The Ricean K factors LOS and NLOS components Antenna correlation, Fixed Value
OSSC Channel Model	The Path loss via Hata Model The channel matrix elements, random variables The Ricean K factors LOS and NLOS components Antenna correlation, Rice Steering Matrix Antenna Configuration, ULA and UCA MS movement, speed assumed 1.2 KM/h

3.7 Conclusions

Channel modeling implementations is one of the major contributions of our work. Integrating the path loss in the channel model is the main contribution regarding the channel modeling. The need to integrate the path loss in the channel model was motivated by the introduction of the relay and the need to investigate the effect of the relay position on the system capacity.

Three channel models were studied and implemented in chapters four and five. The simplest channel model incorporates the path loss only. It has been introduced to test for correctness against published work. The antenna correlation has been incorporated in the second channel so that antenna correlation can be investigated under set conditions. The last model introduced was based on the outdoor Stochastic Spatial Channel Model allowing the most realistic channel changes to influence the system capacity.

Chapter 4

MIMO Relay AF capacity Analysis and Cooperative diversity

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Chapter 4

MIMO Relay AF capacity Analysis and Cooperative diversity

4.1 Introduction:

Diversity gain is one of two reasons making the MIMO systems attractive. Having more uncorrelated antennas can literally increase the link capacity as we increase the number of antennas. However, This gain of the MIMO systems has its physical limitation as any given set can have a finite number of antennas. Having more antennas increases the diversity gain till the point where the antenna correlation dominates, hence defeating the diversity gain advantage. So there must be a tie point between the number of antennas and the diversity gain achieved. The other reason would be beamforming gains. This works out by directing the signal from one antenna array at the transmitter to that at the receiver. In this chapter the working model used in investigating the MIMO Relay AF capacity will be introduced. This model will be used in evaluating the diversity gains of the MIMO Relay AF systems. The general capacity calculations for the MIMO Relay AF networks will be derived from the general capacity equation to the cases used in the simulation work. We will start with a generalized MIMO Relay AF system capacity description. Then we will show the detailed derivation of one scenario used in the analysis. Other scenarios will be used as well to construct a broad understanding of the relay system in general. But first let us look into a proper way of modeling a general MIMO Relay AF system.

4.2 Survey of Cooperative Relaying System Modeling Approaches

The flagship work done in (Nishimorii 2012), Laneman et al, provided a fundamental analysis of cooperative relaying systems. It showed that AF schemes provide full diversity gains. This however, did not come at a free cost as the advantage of the diversity gains came on the expense of spectral efficiency and advanced coding to separate and reconstruct the received signal at the receiver. Thus, diversity gains came at the cost of repetition coding and rate increase. Although their work focuses on single-antenna terminals, the resulting analysis is equally expandable to include distributed multi-antenna systems. The previous work gave momentum to raise the expectation of the MIMO system. This was realized by the work done by (Rohit 2004), on virtual antenna arrays. Neighboring terminals cooperate by forming a virtual array; space-time block codes provide the required orthogonality of superimposed signals. Acting as active scatterers, a recent study has shown that relay nodes can enhance the MIMO transmission by increasing the rank of the MIMO Channel. The work presented her looks at analyzing different AF MIMO configurations and comparing their outputs. More specifically we will be looking in the effect of changing the antenna structure on the overall system capacity. All the previous work implemented Uniform Linear Array of antennas; the case of Uniform Circular Array of antennas has been studied in our case .The effect of the Relay Node location on the system capacity is another contribution in the investigation of the MIMO Relay AF systems. However, before we start looking into various systems, let us agree on a unified system description first as shown next.

4.3 Research contributions

The investigation study carried out aimed at understanding the effect of different system parameters on the overall system capacity. For that purpose and to have a fair comparison the total transmitted power has been fixed to 10 Watts for all the cases. The outdoor Stochastic Spatial Clustered Channel Model; OSSC channel Model, has been used in all the simulations. The Hata Model has been used in calculating the power dissipation in the Communication systems studied. More comparative studies were carried out where all the three systems were compared against each other keeping the upper and lower bounds, i.e. a MIMO and SISO systems. The channel model parameters and the antenna structure parameters like the antenna spacing and the antenna structure has been studied. The changes in the antenna parameters has been focused on the BS and RN as the MS's as changes on the MS's would be possible but might not be feasible due to the physical limitations of the MS's. The power allocation ration between the direct link and the relay links is another interesting area of study for the MIMO Relay AF system. As the total transmission power at the BS has been fixed for all the studied cases, the ratio of the power going to the direct link and the relay link has been studied. This is a feasible approach as dividing or directing the transmitted power is a possible approach for controlling the system capacity. Changing the antenna structure affects the system capacity. This has been verified by implementing ULA and UCA antenna configurations at BS and RN. The antenna spacing is another factor, which has been considered in the study as well.

4.4 MIMO Relay AF System Description

BS MS h_{relay} H_{RD}

We study a general cooperative scheme as depicted in figure 4.1, h_{source} where we allow all terminals to be equipped with multiple antennas. The $h_{destination}$ overall system has been designed to be as close to a realistic system as possible, thus scatterers were included in all the signal paths. The logical representation d_{SR} of the analyzed d_{RD} variation will be shown on case-by-case basis. d_{SD}

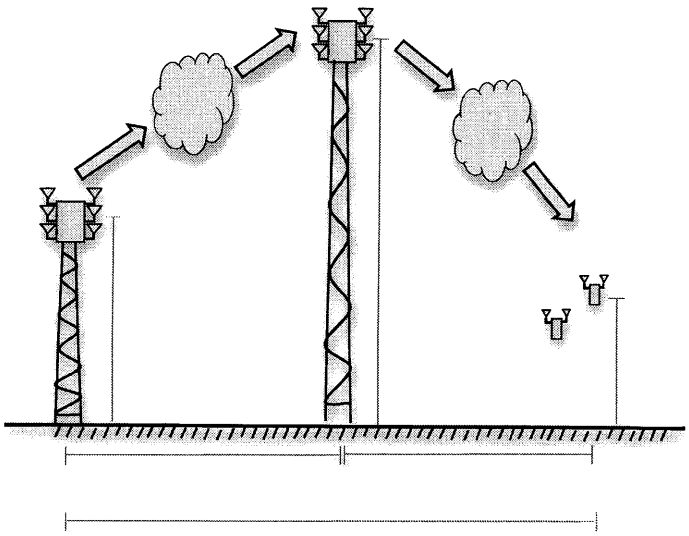


Figure 4.1, MIMO relay AF system model

Where the MIMO Relay AF model parameters are defined below.

BS: the Base Station equipped with the mTx transmitting antennas.

RN: the Relay Node equipped with mRel relay antennas.

MS's: the Mobile Stations acting as destination or receivers.

M_{Tx}: total number of transmitting antennas

M_{Rn}: total number of Relay Node antennas

M_{Rx}: total number of receiving antennas for all the Mobile Stations

H_{SR}: channel matrix between the Source and the Relay Node

H_{RD}: Channel Matrix between the Relay Node and the Destination, i.e. the Mobile Stations.

Scatterers: surrounding obstacles acting on the transmitted signal causing it to scatter, diffract and refract.

d_{SR}: direct distance between the Source Base Station and the Relay Node in meters.

d_{RD}: average direct distance between the Relay Node and the destination Mobile Stations in meters.

d_{SD}: average direct distance between the Source Base Station and the destination Mobile Stations in meters, set at 1000m.

h_{SOURCE}: height of the source Base Station in meters, set at 12m.

h_{RELAY}: height of the Relay Node in meters, set at 32m.

$h_{DESTINATION}$: average height of the Mobile Station in meters, set at 2m.

f_c: system's center frequency in MHz, set at 2530 MHz.

K: number of users, i.e. Mobile Stations

P_s: transmitter power at the source in Watts, set at 10 W.

V_o: average velocity of the Mobile Stations in m/s, set at 1.2 ms^{-1}

spacing_s: source's inter antenna spacing relative to the system's frequency wavelength λ set at 4λ.

spacing_r: relay node's inter antenna spacing relative to the system's frequency wavelength λ set at 0.5λ.

spacing_d: the mobile stations' inter antenna spacing relative to the system's frequency wavelength λ set at 0.5 λ.

So these are the physical parameters of the MIMO Relay AF system that we will analyze. Next we will look into the theoretical modeling of the system.

4.4.1 MIMO Relay AF System Modeling

Here we will discuss how the MIMO Relay AF protocol works. We will start with the two-hop system, as it is a special case of the general MIMO Relay AF system. As the direct link between the source and destination is missing, this causes the transmission to takes place over two phases between the BS and the MS's. This takes place while the Relay Node is relaying the signal. In the first phase, the source transmits signals intended for the destination in a broadcast manner. All relays and the destination receive faded noisy versions of these signals. In the second phase, the relays retransmit a processed version of their received signals to the destination, and the destination combines the signals received in the two phases. The processing in this MIMO Relay AF case is just a linear amplification added to the received signal at RN. Discussing the scalability of the MIMO Relay AF, one need to consider the theoretical constrains first. The initial constraint, which will face scaling up the network by adding multiple Relay Nodes, is orthogonality. In contrast to conventional RF repeaters, small-sized terminals are not capable of receiving and transmitting simultaneously at the same frequency due to hardware imperfections (e.g. oscillations). Hence, relays must be assigned orthogonal resources for their transmit and receive paths. For purposes of exposition, we assume that such separation is performed in the time domain; another approach would be to use frequency relaying where the relays receive and transmit in different frequency bands. While it is of no concern for our theoretic analysis which of these methods is chosen, it is crucial to note the important consequences of assigning orthogonal sub-channels. Consider time-division relaying as an example. Moving to the direct transmission, this is the general case of the MIMO Relay systems where we have three links.

They are the source to the relay, the relay to the destination and the source to the destination. The source transmits K symbols in a period T to the destination. For relay transmission that achieves the same end-to-end delay, the source must transmit its K symbols in a period of T=2, which is followed by the relay's transmission of these K symbols in the second half period. As a consequence, the spectral efficiency of the individual links must at least be doubled compared to that of the direct system. This holds in the same way for frequency relaying: there, available bandwidth instead of time is shared among the two phases. The impact of such a rate increase is often neglected. The case where no direct link is available between the BS and the MS's is a special case though. In such cases the entire communication is being divided into two phases; the first is BS to RN and the second is RN to MS. This results in increasing the transmission rate and reducing the system capacity as the spectral efficiency drops by half.

Energy Normalization is another constraint in the simulated system environment. Simply put, the total consumed energy of the relay system does not exceed that of the corresponding direct system, this is to maintain a fair comparison between the direct and relay systems. We note that this is a strict and conservative constraint; allowing the relays to add additional power can then only increase the attractiveness of cooperation. In our continuous-time channel model the source transmits with power P over a period T in the case of direct transmission. For relay transmission, the source first broadcasts with power P over a period of T=2; in the second phase, the relays use again a maximum total power of P over T=2. In calculating the power received at the relay nodes and at the mobile stations, the Urban Hata model has been used. As this study case is restricted to Amplify and forward relay, then we would need two types of

relay operation. The first type is the amplifying relays, which simply amplify their received signals essentially acting as active reflectors. This provides diversity gains, and can be understood as enhancing the rank of the MIMO channel matrix. Most of the proposed systems employ such amplifying relays. And these relays are used in systems implementing one relay node only. Increasing the number of relay nodes requires complex coding, which is a difficult problem (if not impossible) to solve as requires transmitting orthogonal waveforms from the relays. The special case of two relay nodes can be solved using the distributed Alamouti system, which brings us to the second type of relays, the coding relays. These are relays that can employ orthogonal coding techniques to enhance the diversity order of the system. An example is the distributed Alamouti method proposed in, where two relays retransmit in an amplify-and-forward manner, and one of the relays additionally conjugates and negates the signal.

4.4.2 Unified System Description:

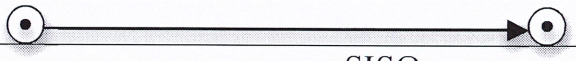
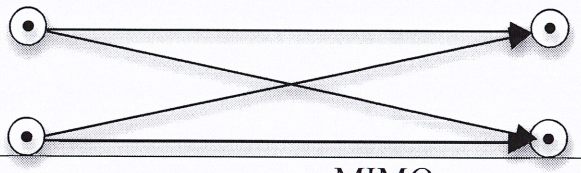
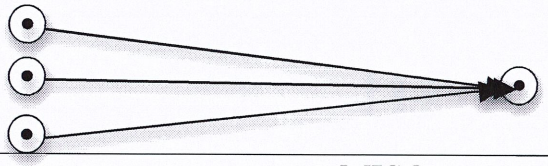
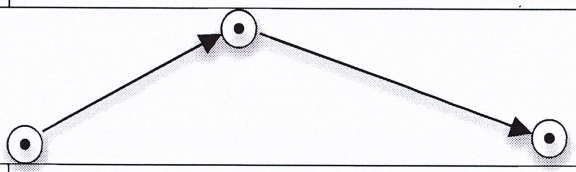
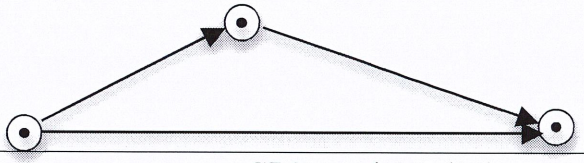
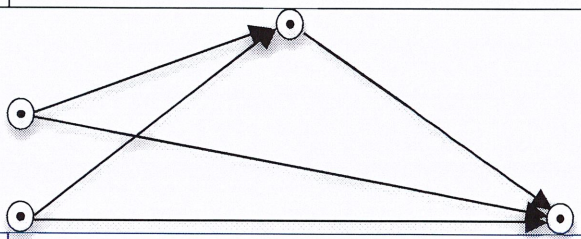
As we will discuss different MIMO Relay AF systems let us first agree on a unified system description as used in. The system will be referred to as p. Four parameters will be used to describe the subject system. The number of relays M will indicate how many distinct relay nodes are being implemented in the system. These relays will be equipped with m_{rel} antennas. The Base station will be equipped with m_{Tx} antennas and the Mobile stations total number of antennas will be referred to as m_{Rx}. This shown system description method is being elaborate in describing most of the system parameters. However it has few shortcomings. For instance, it assumes that all the relay nodes do have the same number of antennas, which is a fair assumption but should

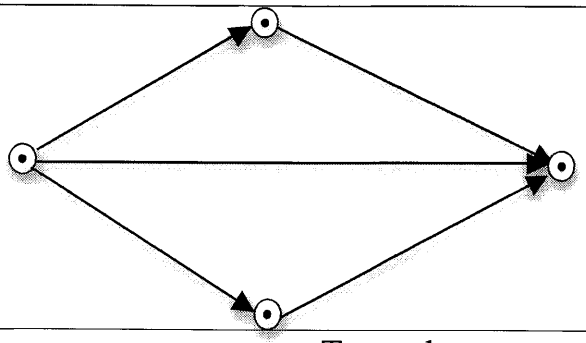
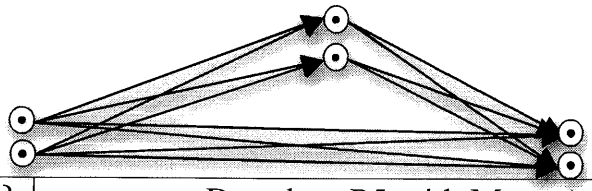
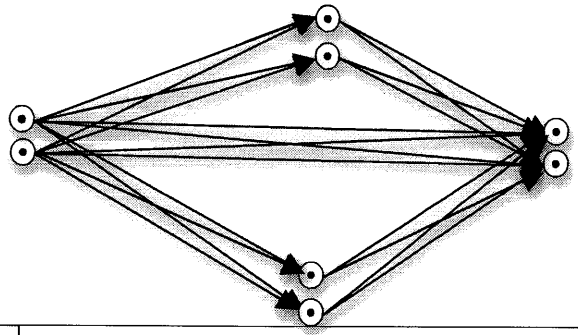
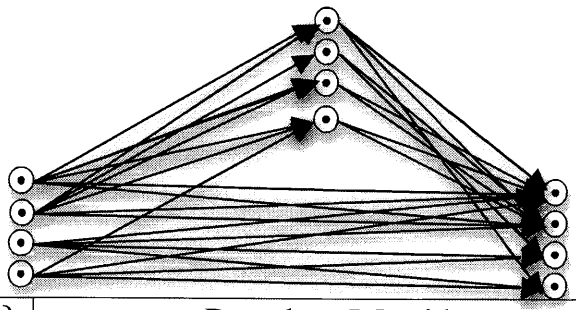
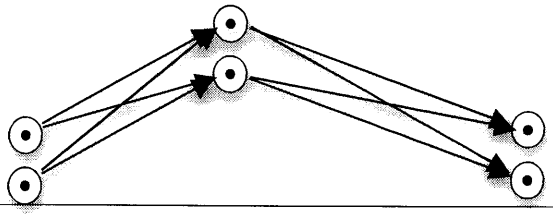
not always be true. Another example is that it assumes that the direct link between the BS and MS's is always there. Our first model violates this assumption. But aside from these two points, the system description used here is sufficient for our analysis. So the system description form used is $p = \{M, m_{Tx}, m_{rel}, m_{Rx}\}$.

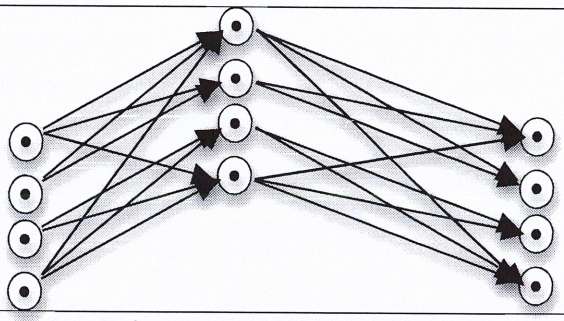
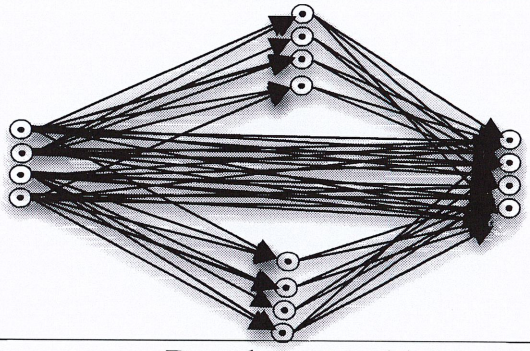
4.4.3 MIMO Relay AF Studied Systems

Based on the Antenna number and Relay configurations, ten different variations of the MIMO Relay AF systems were studied. As a benchmark; three none Relay systems were used to compare the system performance against. Hence, the full set of systems comprises of thirteen systems. The systems were named P1 through to P13. Table 4.1 lists all the systems used with a brief description. The systems will be represented symbolically later. The total number of antennas used in any given system was the criteria for paring them for comparison. This and the number of relays as well were the two basic selection conditions for comparing any two systems. The first three systems were used as a benchmark to provide a base line for all the comparisons.

Table 4.1
Summary of the studied MIMO Relay AF systems

System	$\{M, m_{Tx}, m_{rel}, m_{Rx}\}$
$P1$	
	{0,1,0,1} SISO
$P2$	
	{0,2,0,2} MIMO
$P3$	
	{0,3,0,1} MISO
$P4$	
	{1,1,1,1} No Direct Link between Source and Destination
$P5$	
	{11,1,1} SRD and SD links
$P6$	
	{1,2,1,1} Two transmitting antennas and one Relay

*P*7		
	{2,1,1,1}	Two relays
*P*8		
	{1,2,2,2}	Based on P5 with More Antennas
*P*9		
	{22,2,2}	Based on P7 with More Antennas
*P*10		
	{1,4,4,4}	Based on P5 with More Antennas
*P*11		
	{1,22,2}	No Direct Link between Source and Destination

$P12$		
	{1,4,4,4}	No Direct Link between Source and Destination
$P13$		
	{2,4,4,4}	Based on P7 with More Antennas

The systems presentation will be followed by the system discussion. The discussion will include the system modeling leading up to its capacity investigation. The Bench Mark systems P1, P2 and P3 were selected to present the upper capacity bounds of the studied systems with a similar number of antennas. The first MIMO Relay AF system model,$p_{4noSD} = \{1,1,1,1\}$, is a two hop MIMO Relay AF system without a direct link between the BS and the MS. Adding the direct link leads to the second model,$p_5 = \{1,1,1,1\}$. The noSD subscript for p1 indicates the lack of the direct link between the source and the destination. Adding a second relay node leads to the third studied model, $p_7 = \{2,1,1,1\}$. Another variation to the basic MIMO Relay AF systems is to add more antennas at the transmitter. This resulted in $p_6 = \{1,2,1,1\}$. All the subsequent MIMO Relay AF systems are based on the three basic systems, namely $p_4, p_5 \& p_7$. More antennas were simply added to these

systems to account for correlation and different antenna structure analysis.

4.4.4 Mathematical modeling of the studied systems

The mathematical analysis of the MIMO Relay AF models will be introduced next. This analysis will lead to the capacity evaluation of any given MIMO Relay AF system. It will include systems P4, P5 and P7. The rest of the models should follow the same steps. The final capacity formulas will be presented after words. All the MIMO Relay AF systems consist of the Source Node, S, the Relay node, R, and the Destination Node, D. the nodes are communicating over their respected channels. H_{SD} is the channel between the source and the destination, H_{SR} is the channel between the source and the Relay and H_{RD} stands for the channel between the Relay and the destination. The relay introduces a relay gain to the system; G this gain is the ratio of the power transmitted by the relay to that received at the relay. The labels were indicated on the three systems in figures 4.2, 4.3 & 4.4.

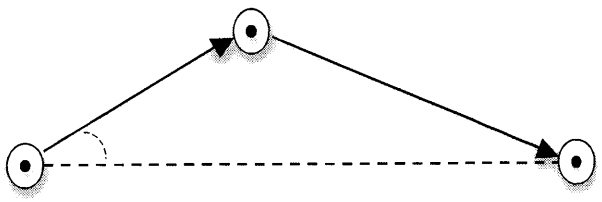


Figure 4.2, Detailed model $p_{4noSD} = \{1,1,1,1\}$

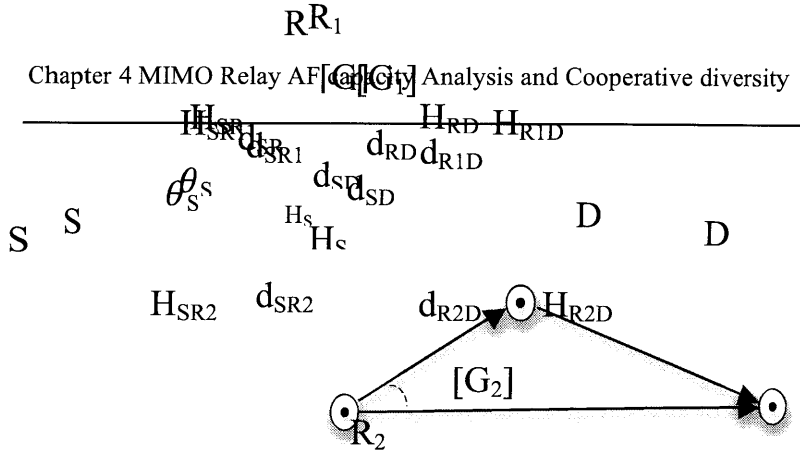


Figure 4.3, Detailed model $p_5 = \{1,1,1,1\}$

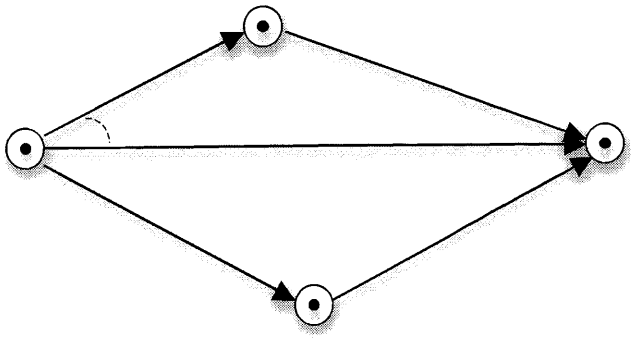


Figure 4.4, Detailed model $p_7 = \{2,1,1,1\}$

4.5 General Capacity Analysis of MIMO Relay AF systems

Before we start analyzing individual systems let us agree on the common ground between all the systems and on a common capacity calculation method for them. As shown previously, the MIMO Relay AF network can be described using the form below.

$$Y = Ax + Bn \qquad (4.1)$$

Where "A" and "B" are system Matrices, x stands for the transmitted data vector and n stands for the noise. The strength of the formula in equation 4.1 is realized when using this form to express the system capacity as

shown in equation 4.2 and the task of finding out any system capacity d_{SR} d
reduces θ_S to finding out the system matrices A and B and the correlation
S D
matrices R_x and R_n.

$$C = log_2 det(I + (AR_X A^H)(BR_n B^H)^{-1}) \qquad (4.2)$$

Where;

A is a system matrix describing the attenuation and changes affecting the transmitted data.

Rx is the auto correlation of the transmitted data signal

B is the second system matrix acting on the noise

Rn is the noise power at the receiver

$(.)^H$ is the conjugate transpose operator.

So equation 4.2 is the standard formula in all literature reviewed being used to calculate the capacity of any given MIMO Relay AF system. In comparing different systems, the task reduces to putting the system in a form similar to equation 4.1. Using equation 4.2 can use this result to estimate the system capacity. The next part works on finding out the system matrixes for each of the three models used to compare their performance.

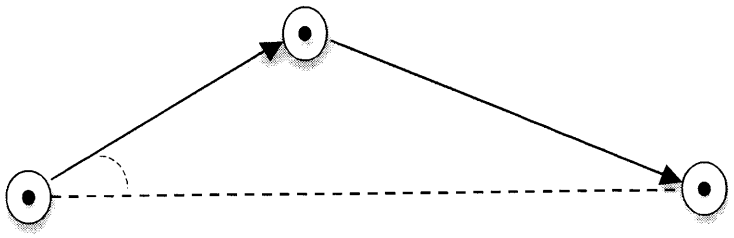


Figure 4.5, Detailed model of $p_{4noSD} = \{1,1,1,1\}$

So let us derive the A and B system Matrices for the MIMO Relay AF system displayed in figure 4.5. The analysis will be based on the receiver's prospective of the transmitted data. That is, standing at the receiver's end, how does the transmitted data get through the RN and channel to the transmitter. As the model in hand is the two hop MIMO Relay AF model, then two points need to be clarified here. The first point is that each of the MS's will receive one stream of data coming from the RN only. And the second point is that the data is received over two time slots as it hops from the BS to the RN in the first time slot and from the RN to the MS's in the second time slot. The received data at the RN can be modeled as equation 4.3,

$$y' = H_{SR}x + n_1 \tag{4.3}$$

Where y' is the noise at the RN, the gain introduced by the Amplify and Forward relay node has a positive real value named G. This amplification factor acts on the received signal at the RN and gets carried to the destination MS's as shown below.

$$y = H_{RD}Gy' + n_2 \tag{4.4}$$

Rearranging;

$$y = H_{RD}G(H_{SR}x + n_1) + n_2 \tag{4.5}$$

Expanding;

$$y = H_{RD}GH_{SR}x + H_{RD}Gn_1 + n_2 \tag{4.6}$$

So at the receiver, i.e. MS's, there is one stream of data being received which is described in equation 4.6. Reshaping it into the standard form as in equation 4.1, 4.6 becomes as shown next.

$$y = [H_{RD}GH_{SR}]x + [H_{RD}G \quad I]\begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{4.7}$$

So the system matrices A and B are easily found to be as:

$$A = [H_{RD}GH_{SR}] \tag{4.8}$$

$$B = [H_{RD}G \quad I] \tag{4.9}$$

And their transpose pairs are:

$$A^H = [H_{SR}^H G^H H_{RD}^H] \tag{4.8}$$

$$B^H = \begin{bmatrix} G^H H_{RD}^H \\ I \end{bmatrix} \tag{4.9}$$

$$AA^H = [H_{RD}GH_{SR}][H_{SR}^H G^H H_{RD}^H] = H_{RD}GH_{SR}H_{SR}^H G^H H_{RD}^H \tag{4.10}$$

$$BB^H = [H_{RD}G \quad I]\begin{bmatrix} G^H H_{RD}^H \\ I \end{bmatrix} = (I + H_{RD}GG^H H_{RD}^H) \tag{4.11}$$

$$R_x = E\{xx^H\} = (P_0/m_{T_x}).I_{m_{T_x}} = P_0/(2m_{T_x}) \tag{4.12}$$

$$R_n = E\{nn^H\} = \sigma_n^2 \tag{4.13}$$

So if we lump up equations, 4.10, 4.11, 4.12 and 4.13 into 4.2 equation 4.14 will emerge as the capacity equation of the two-hop MIMO Relay AF system. This equation has been used in (Holakouei, R 2009).

$$C = 0.5 \log_2 \det\left\{I + \frac{P_o}{2N_S\sigma_n^2} H_{RD} G H_{SR} H_{SR}^H G^H H_{RD}^H \times \left(I + H_{RD} G G^H H_{RD}^H\right)^{-1}\right\} \quad (4.14)$$

4.5.1 The Gain Matrix

As this is a non-regenerative relay channel, the total transmitted power in two time slots is restricted to P0. Thus the amplification factor is selected to satisfy this constrain as below:

$$g = \sqrt{\frac{P_0}{\frac{P_o}{2N_s}\|H_{SR}\|_F^2 + 2N_R\sigma_n^2}} \quad (4.15)$$

where the Gain matrix is a diagonal matrix with the diagonal elements being g and the Frobenius norm or the Hilbert–Schmidt norm. The latter term is often reserved for operators on Hilbert space. This norm can be defined in various ways:

$$\|A\|_F = \sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}|a_{ij}|^2} = \sqrt{trace(A^*A)} \quad (4.16)$$

Where A* denotes the conjugate transpose of A, σi are the singular values of A, and the trace function is used. Then G matrix is defined as:

R

H_{SR} d_{SR} d_{RD} H_{RD}

θ_S d_{SD}

S $[G] = H_S \begin{bmatrix} g & 0 & 0 & \\ 0 & g & 0 & \cdots \\ 0 & 0 & g & \\ \vdots & & & \ddots \end{bmatrix}_{m_{T_X} \times m_{R_X}}$ D (4.16)

Next we look at P5.

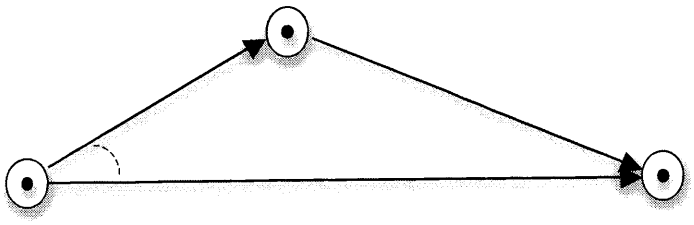


Figure 4.6, Detailed model of $p_5 = \{1,1,1,1\}$

The introduction of the direct link between the source, and the destination, leads to the realization of the second simulated system. The new system communicates over two time slots in the initial transmission but then the Mobile Stations will receive data from the source directly and the relay nodes. Hence the initial transmission delay's effect on the system's spectral efficiency is negligible. The system matrices are driven in a similar manner as done with the first system.

In the first transmission phase; phase I the destination receives the data stream coming from the source:

$$y_1 = H_{SD}x + n_{SD} \tag{4.17}$$

At the relay, the data received can be modeled as below:

$$r_1 = H_{SR}x + n_{SR} \tag{4.18}$$

The data stream received at the destination coming from the relay node can be represented as below:

$$y_2 = H_{RD}Gr_1 + n_{RD} \tag{4.19}$$

$$y_2 = H_{RD}G\{H_{SR}x + n_{SR}\} + n_{RD} \tag{4.20}$$

$$y_2 = H_{RD}GH_{SR}x + H_{RD}Gn_{SR} + n_{RD} \tag{4.21}$$

$$Y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} H_{SD} \\ H_{RD}GH_{SR} \end{bmatrix} x + \begin{bmatrix} I & 0 & 0 \\ 0 & H_{RD}G & I \end{bmatrix} \begin{bmatrix} n_{SD} \\ n_{SR} \\ n_{RD} \end{bmatrix} \tag{4.22}$$

$$A = \begin{bmatrix} H_{SD} \\ H_{RD}GH_{SR} \end{bmatrix}, A \in \mathbb{C}^{2m_{R_x} \times Mm_{rel}} \tag{4.23}$$

$$B = \begin{bmatrix} I & 0 & 0 \\ 0 & H_{RD}G & I \end{bmatrix}, B \in \mathbb{C}^{2m_{R_x} \times (2m_{R_x} + Mm_{rel})} \tag{4.24}$$

$$P_l = \frac{P}{m_{T_x}} \sum_{i=1}^{m_{rel}} \sum_{k=1}^{m_{Tx}} \left| \left[H_l^{(1)} \right]_{i,k} \right|^2 + m_{rel}N \tag{4.25}$$

$$g_l = \sqrt{\frac{P/M}{P_l}} \tag{4.26}$$

Next we look at P7.

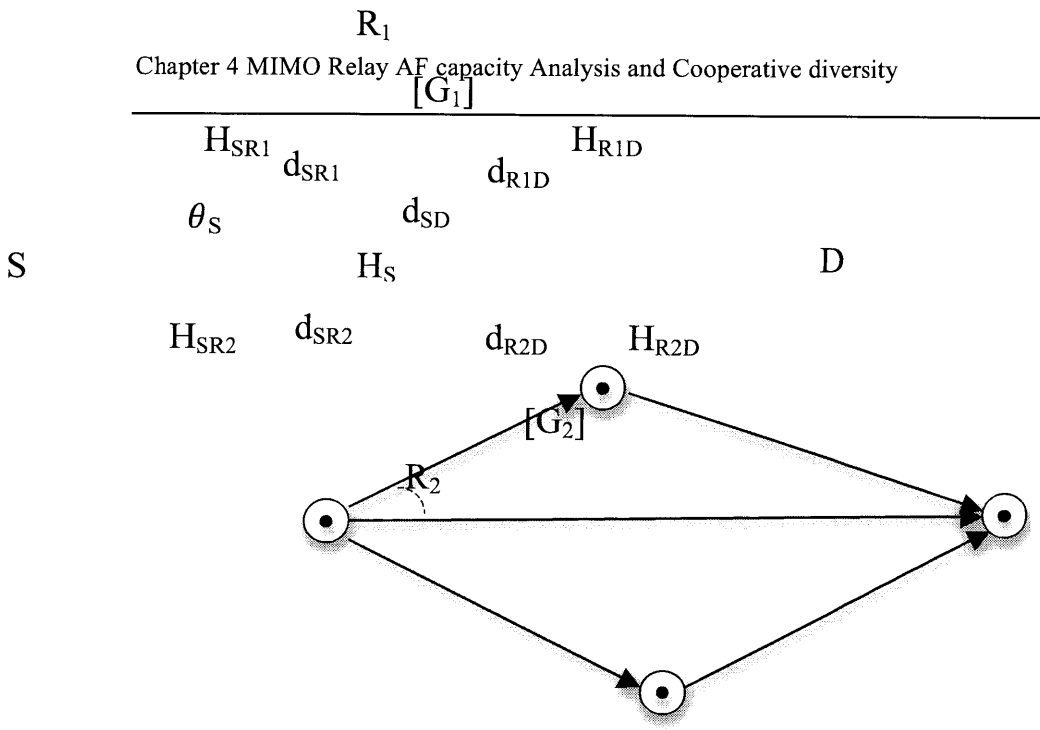


Figure 4.7, Detailed model of $p_7 = \{2,1,1,1\}$

Adding another Relay Node to P5 brings us to P7. The addition of more relay nodes should, intuitively, increase the overall system capacity as the correlation between the MIMO antennas decrease since they are further apart. However, this advantage is being faced with the orthogonal codes hard limits. The problem of finding orthogonal codes for more than two relay nodes is difficult if not impossible to find. The current solution for the two relay nodes is using the distributed Alamouti system. Focusing on just one symbol period, we note that we can again divide transmission in two phases. In the second phase, one of the two relays retransmits a conjugated and negated version of the. Hence our analysis will not include adding more relay nodes, as it is not feasible right now. But looking at the bright side, this hard limit opens the way for future work in looking in to more orthogonal codes.

$$Y = \begin{bmatrix} y_0 \\ y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} H_{SD} \\ H_{R1D}G_1H_{SR1} \\ H_{R2D}G_2H_{SR2} \end{bmatrix} x + \begin{bmatrix} I & 0 & 0 & 0 \\ 0 & H_{R1D}G_1 & 0 & I \\ 0 & 0 & H_{R2D}G_2 & I \end{bmatrix} \begin{bmatrix} n_{SD} \\ n_{SR1} \\ n_{SR2} \\ n_{RD} \end{bmatrix} \quad (4.27)$$

This is under the assumption that.

$$n_{R1D} = n_{R2D} \quad (4.28)$$

$$g_l = \sqrt{\frac{P/2}{\left|h_r^{(1)}\right|^2 P + N}} \qquad forr \in \{1,2\} \quad (4.29)$$

Applying a similar analysis to P6 will lead to its capacity equation matrices listed in the below table.

Table 4.2
Summary of the capacity equations of systems P4, P5, P6 & P7

p_i	A Matrix	B Matrix	Gain Factor
p_4	$[H_{RD}GH_{SR}]$	$[H_{RD}G \quad I]$	$\sqrt{\frac{P_0}{\frac{P_0}{2N_s}\|H_{SR}\|_F^2 + 2N_R\sigma_n^2}}$
p_5	$\begin{bmatrix} H_{SD} \\ H_{RD}GH_{SR} \end{bmatrix}$	$\begin{bmatrix} I & 0 & 0 \\ 0 & H_{RD}G & I \end{bmatrix}$	$\sqrt{\frac{P/M}{P_l}}$
p_6	$\begin{bmatrix} H_{S1D} & H_{S2D} \\ H_{RD}GH_{S1R} & H_{RD}G_2H_{S2R} \end{bmatrix}$	$\begin{bmatrix} I & 0 & 0 \\ 0 & H_{RD}G & I \end{bmatrix}$	$\sqrt{\frac{P/M}{\frac{P}{2}(\|h_{S1R}\|^2 + \|h_{S2R}\|^2) + N}}$
p_7	$\begin{bmatrix} H_{SD} \\ H_{R1D}G_1H_{SR1} \\ H_{R2D}G_2H_{SR2} \end{bmatrix}$	$\begin{bmatrix} I & 0 & 0 & 0 \\ 0 & H_{R1D}G_1 & 0 & I \\ 0 & 0 & H_{R2D}G_2 & I \end{bmatrix}$	$\sqrt{\frac{P/2}{\left\|h_r^{(1)}\right\|^2 P + N}} forr \in \{1,2\}$

For the other systems having the same configurations, the same capacity equations apply. The more antennas add to larger H matrix dimensions. The grouping of MIMO Relay AF systems is explained in the Table 4.3.

Table 4.3
Summary of the Studied Systems Groups

Group	Systems	Common Factor	Difference
Bench Mark	P1, P2 & P3	None Relay systems	Link Structure
G1	P4, P11 & P12	No SD link	1, 2 & 4 antennas per node
G2	P5, P8 & P10	Full MIMO Relay AF	1, 2 & 4 antennas per node
G3	P6	Two antennas at S	One model only
G4	P7, P9 & P13	Two Relay Nodes	1, 2 & 4 antennas per node

4.6 Channel Modeling Approach

Extending the coverage area of a given wireless network can be done by introducing relays to the network structure. This improvement in the performance of infrastructure based network by increasing their coverage area and exploiting the spatial diversity has been a hot topic in research recently. The main focus of the existing literatures has been on studying the various methodologies to obtain better channel performance.

However, little attention is paid to the channel modeling for relays. The Rayleigh channel model has been the most accepted channel model for the relay systems. This model however, holds in the case where the relay lies in the non-line-of-sight (NLOS) scenario of both the source and the destination. The channels between the source and relay, and the relay and destination are considered as the full rank multiple-input multiple-output (MIMO) channels. Maintaining a full rank for these channels is a goal by itself in MIMO communications, as the lower the rank leads to a lower capacity of the given system. The effect of the location of the relay on the system performance is usually ignored in the analysis; this is why it has been one topic addressed in our work. (Jiang 2006) investigated the power and location optimization for decode-and-forward relay network, but the fading coefficient of the channel is still assumed to be distributed according to Gaussian distribution. However, to maximize the coverage, the relay is typically placed in the LOS scenario of the source. Therefore, the Rayleigh channel model is no longer suitable to analyze practical relay channels. In addition, since there is LOS component propagating from the source to relay, in the case of the MIMO communication, the channel between the relay and the source is correlated. Hence the capacity performance of the whole system degrades, and it is necessary to use techniques such as cross-polarized antenna or optimal power allocation to improve the performance in the channel (Holakouei 2009).

4.7 Channel Model Implementation

Three channel models were implemented in the simulation studies as explained in chapter 3. The models differ by the amount of complexity included in each model to realize the real world model as close as possible. The purpose of having three levels of channel complexity is to

evaluate the effect of different parameters variations on the system's capacity. The first channel model used is the simple channel model. The second channel model used is the Correlation Channel Model. The third level of complexity is achieved via the OSSC channel model. Using this channel model in this simulation is one of the thesis contributions.

4.7.1 Simulation assumptions

To further analyze the position effect of the relay, we simulate with 2 pairs of cross-polarized patch antennas at the source, relay and the destination. We apply the widely used assumption in the simulation, (Jiang 2006). The source-relay distance d_{SR} and relay-destination distance d_{RD} are normalized with respect to the source-destination distance d_{SD} when calculating the path loss. The transmit power is set as 10 Watt. The element spacing for source is 4λ, and the spacing for both the relay and the source is assumed to be 0.5λ. Intuitively, the relay should lie within the right semi circle with the source at the center, which radius is determined by d_{SD}, i.e., $0 < d_{SR} < d_{SD}$, and $-\pi/2 < \theta_S < \pi/2$. θ_S is the angle between source-relay link and source-destination. The Ricean K factor is assumed as $K = 13-0.03d$ (dB) as in (Zhao 2004). Furthermore, we assume that the polarizations of all the antennas at the source, relay and destination are perfectly matched, i.e., $\theta p = 0$. The capacity of the relay channel with 2 pairs of cross-polarized patch

As most literature focuses on better methods on enhancing the channel performance, in (Holakouei, R. 2009). The focus was on redefining the channel model to include the line of site as well as the none line of site components. The Rayleigh channel model is widely used in modeling the relay systems as done in (Holakouei, R. 2009). If the Relay Node lies in the LOS between the BS and the MS's then this model

wouldn't hold. Thus, the channel model adapted in (Holakouei, R. 2009); combines the LOS and NLOS components in the channel model. Table 4.4 lists the channel models and their differences.

Table 4.4
Summary of the used Channel Models

Channel Model	Simulated Parameters
Simple Channel Model	The Path loss via Hata Model The channel matrix elements, random variables
Correlation Channel Model	The Path loss via Hata Model The channel matrix elements, random variables The Ricean K factors LOS and NLOS components Antenna correlation, Fixed Value
OSSC Channel Model	The Path loss via Hata Model The channel matrix elements, random variables The Ricean K factors LOS and NLOS components Antenna correlation, Rice Steering Matrix Antenna Configuration, ULA and UCA MS movement, speed assumed 1.2 KM/h This is the most math intensive model when carrying out the simulations.

4.8 MIMO Relay AF Capacity Investigations

Having introduced the MIMO Relay AF systems and the channel models used in the simulation, next the simulation approach will be explained. The capacity investigations aim at studying the advantages of the MIMO Relay AF systems over the MIMO systems. For this purpose three none relay systems where selected. A SISO, a MIMO and a MISO representing the upper and lower bounds of the investigated systems were used as benchmark systems. The SISO system represents the simplest transmission system having one antenna at the receiver, and one antenna at the transmitter. The MIMO system has two antennas at the receiver and two antennas at the transmitter. The MISO system has three antennas at the receiver and one at the transmitter. To test the upper and lower bounds of the benchmark systems, some of the MIMO Relay AF systems were built. To test for correlation and Antenna structure effect on the system capacity, more systems were introduced. Table 4.5 summarizes the different purposes of the MIMO Relay AF systems used.

4.8.1 Capacity Investigations Approach

The capacity investigation aims at studying the effect of changing some parameters of the studied systems on the overall system capacity. The standard parameters for any communications systems were included. This included the signal to noise ratio affect on the capacity and probability of outage. With the introduction of the OSSC channel model, more parameters were accessible for investigation. The Angle of Arrival, antenna structure and antenna array spacing were included in the capacity investigations. Having a relay system added more dimension to the communications systems.

Table 4.5
Capacity Investigations for different MIMO Relay AF systems

System	Simulation Role
P1, P2 & P3	Bench Mark Systems Upper and lower bounds for similar MIMO Relay AF systems antenna count
P4, P5, P6 & P7	MIMO Relay AF system capacity vs none Relay systems
P6, P8, P9, P10, P11, P12& P13	The effect of Correlation on the Capacity The effect of adding more antennas on the Capacity AoA variation on the Capacity
P10	Changing the antenna structure ULA vs UCA

The Relay Node location and the power allocation between the source to destination and source to relay links were new factors to be considered for the capacity investigations. The capacity investigations are listed in the next paragraphs with the results and conclusions found based on the simulation runs.

4.8.2 Results Validation

Comparing our work with the published work of (Herhold, P. E Zimmermann, E. & Fettweis, G. 2004) validates our results. Figure 4.8 shows the published work, our results are shown in figure 4.9. The aforementioned simulation assumptions and parameters were used to generate the curves in figure 4.9. The order of the curves is maintained,

although our channel realizations were limited to 500k realizations only. The Channel model used here is the simple channel model. This proofs that our model matches the original work against which we are validating. All the results after figure 4.9 were based on the same channel model but with added complexity to investigate different parameters effects on the system's capacity.

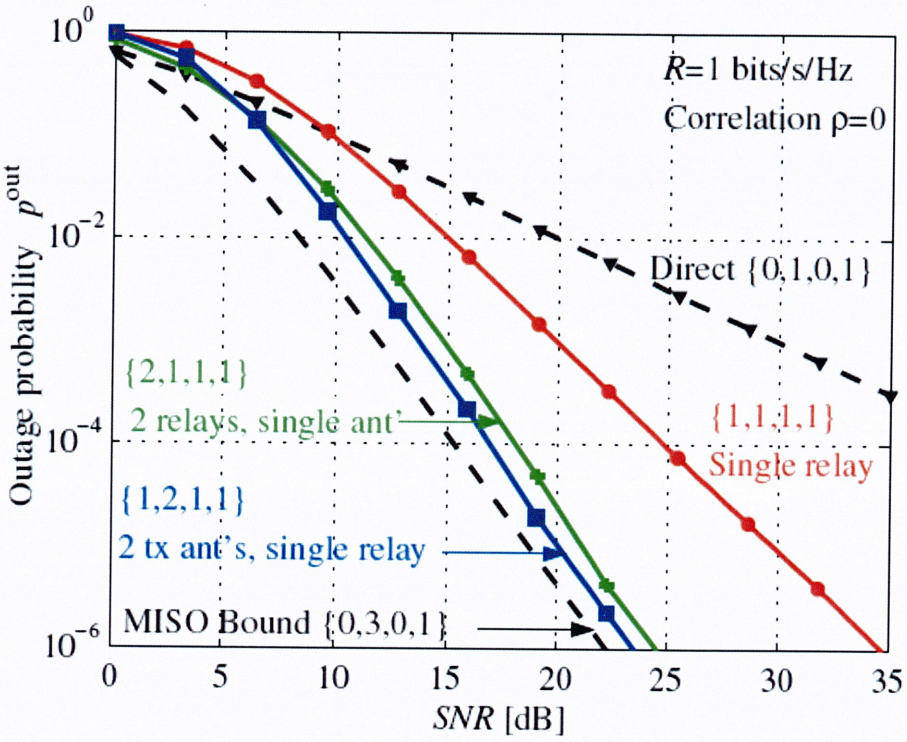


Figure 4.8, Outage probability versus SNR for P1, P3, P5, P6 & P7

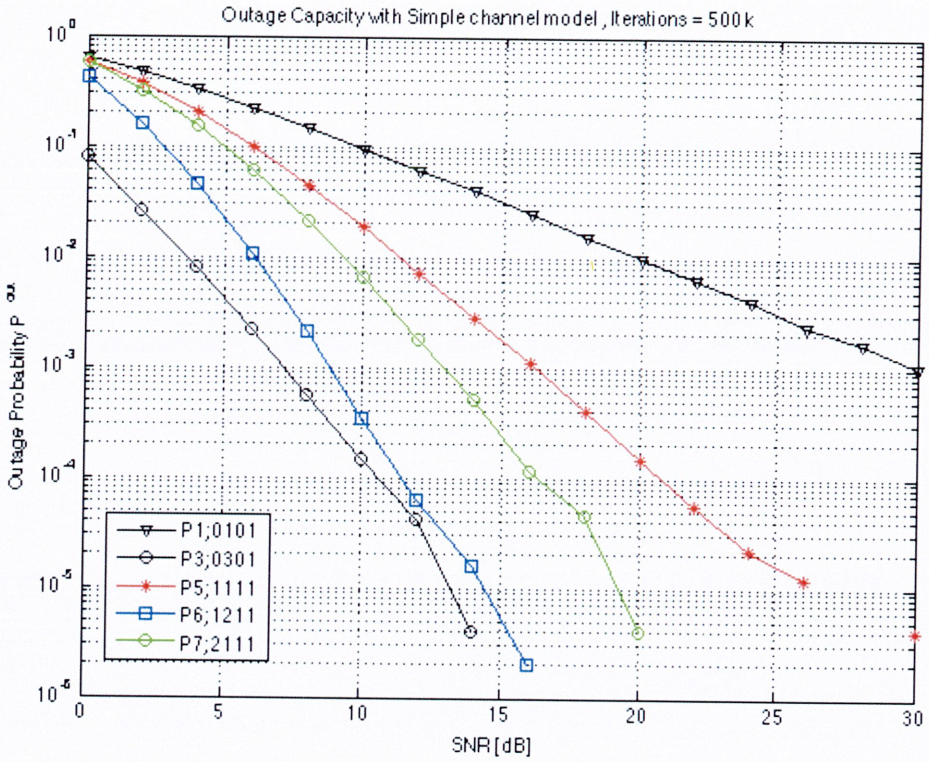


Figure 4.9, Outage probability versus SNR for P1, P3, P5, P6 & P7

4.8.3 Relay added resilience to MIMO systems.

Figure 4.10 shows the capacity curves of the systems P1, P3, P5, P6 & P7. The outage probability curves shown figure 4.11 include P1, P4 and P5. The interesting curves here are those of the SISO system compared with a MIMO Relay system with the same capacity, namely P1 and P5. Both systems do have the same capacity as their capacity curves run in parallel in figure 4.11. The outage probability curves reveal that the MIMO Relay system, i.e. P5 is more resilient when compared with the none SISO system P1, despite the fact that both systems do have almost the same capacity. This confirms that introducing a relay in a MIMO system provides increased link reliability.

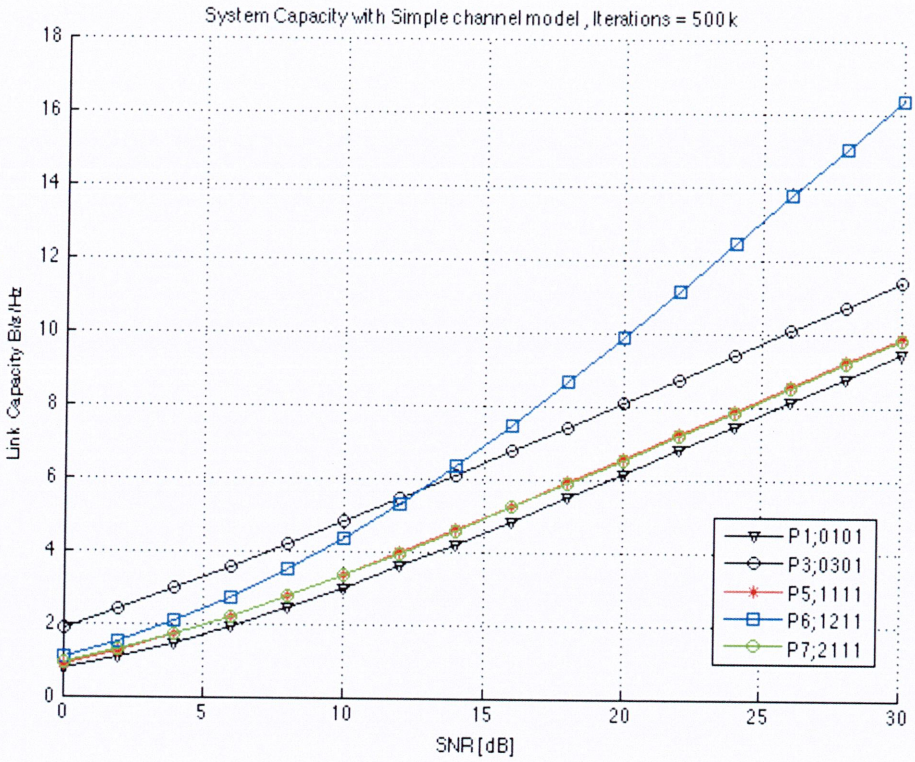


Figure 4.10, Capacity versus SNR for P1, P3, P5 P6 & P7 systems

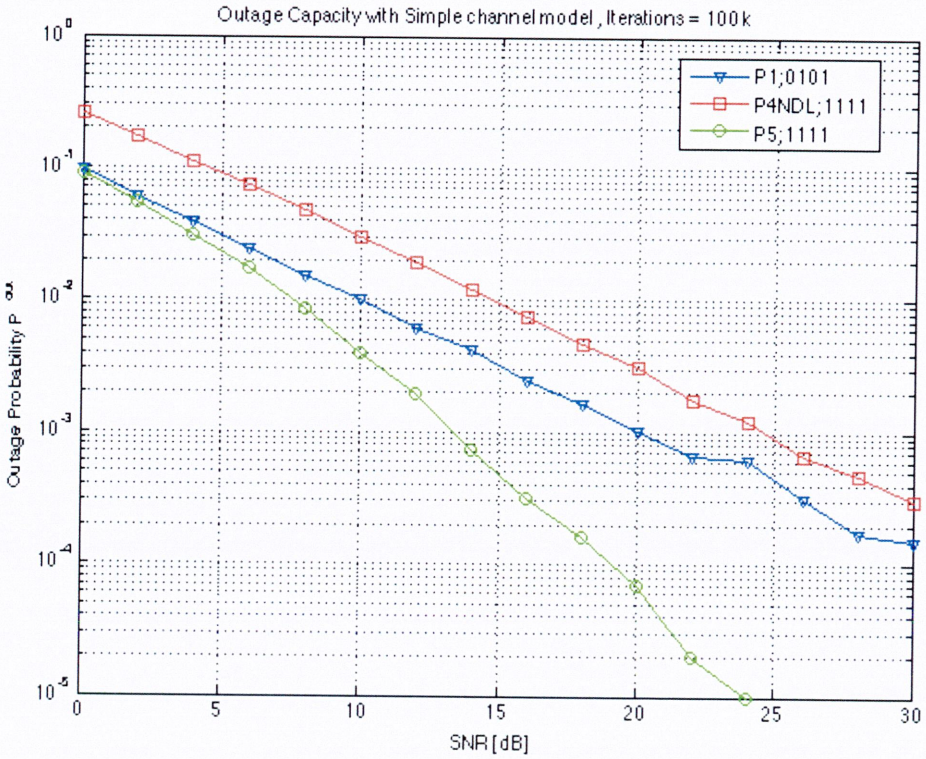


Figure 4.11, Outage capacity versus SNR for P1, P4 & P5 systems

4.9 Capacity Investigation with Different system Parameters

Design elements and system parameters were studied to verify their effect on the system capacity. The aim of this study is to define the optimal conditions to operate the MIMO Relay AF systems. The comparisons are carried among different MIMO Relay systems.

4.9.1 System capacity and outage probability comparisons

Figure 4.12 displays the outage probability curves of systems P1, P2, P3, P6 and P7. The single relay system, P6, outperforms the dual relay system P7 when comparing their resilience. Adding more antennas to

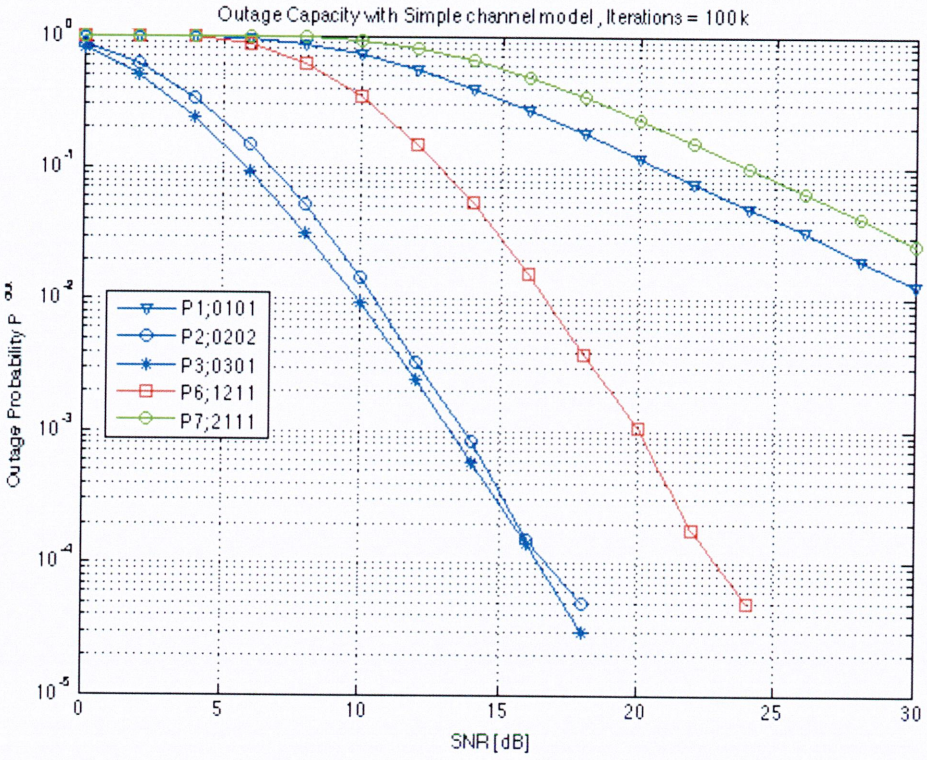


Figure 4.12, Outage probability versus SNR

the systems does not change the order of performance as shown in figure 4.13. Adding another antenna at each node converts P6 into P8, the same

can be said about P7 and P9. P8 outperforms P9 as clearly shown in figure 4.14. This favors a single relay system over a two-relay system assuming similar channel conditions for both systems.

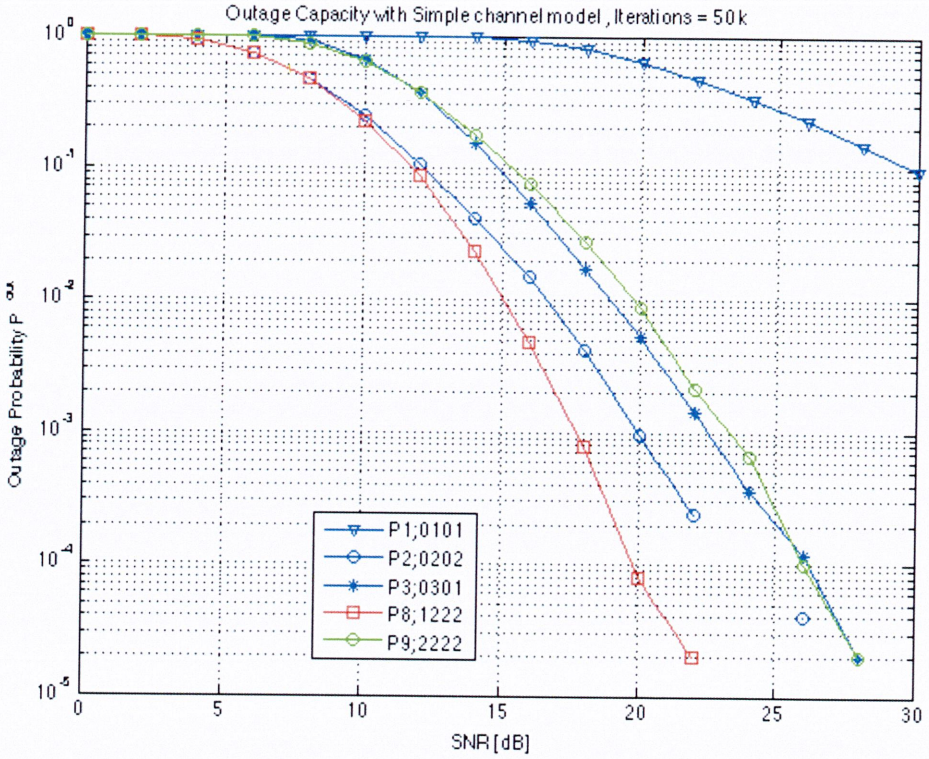


Figure 4.13, Outage probability versus SNR

Being a two-hope system, P4 will have the lowest capacity among the other systems as shown in figure 4.14. This is due to the fact that transmission happens over two time slots. The capacity curves of P5 and P1 coincide. But P5 shows a more resilience response in the outage curve as indicated earlier. The capacity curves of P6 and P7 hold the same order as shown in figure 4.15. Figure 4.16 indicates the advantage of a single relay over two relays, as P8's capacity is larger than P9's.

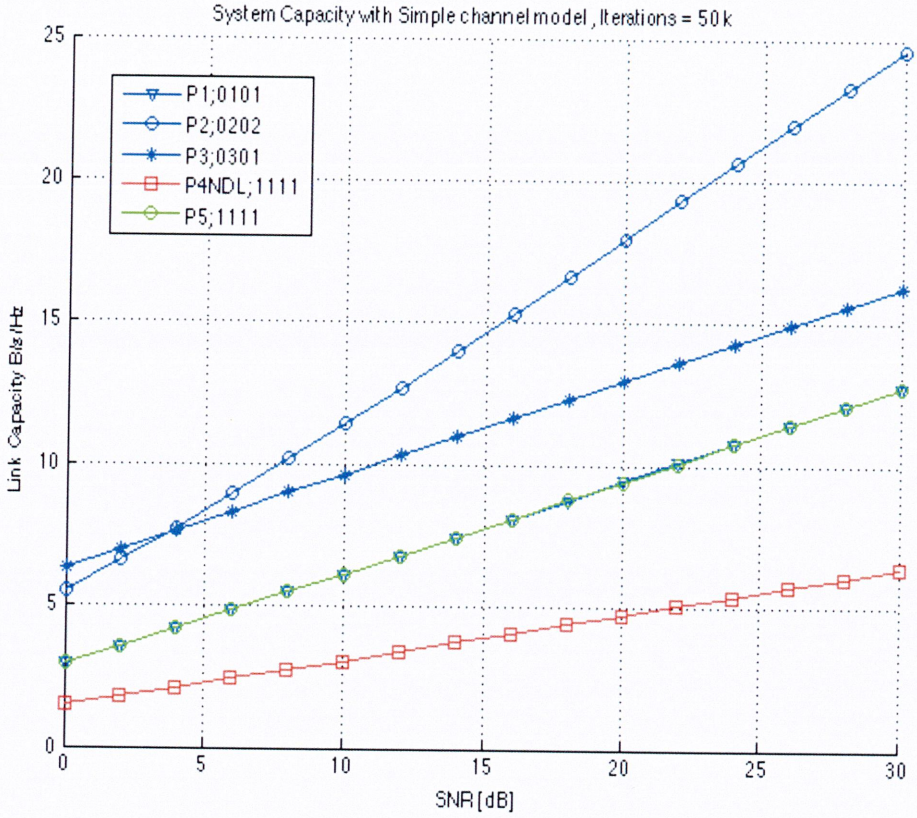


Figure 4.14, Capacity versus SNR for P1, P2, P3 P4 & P5 systems

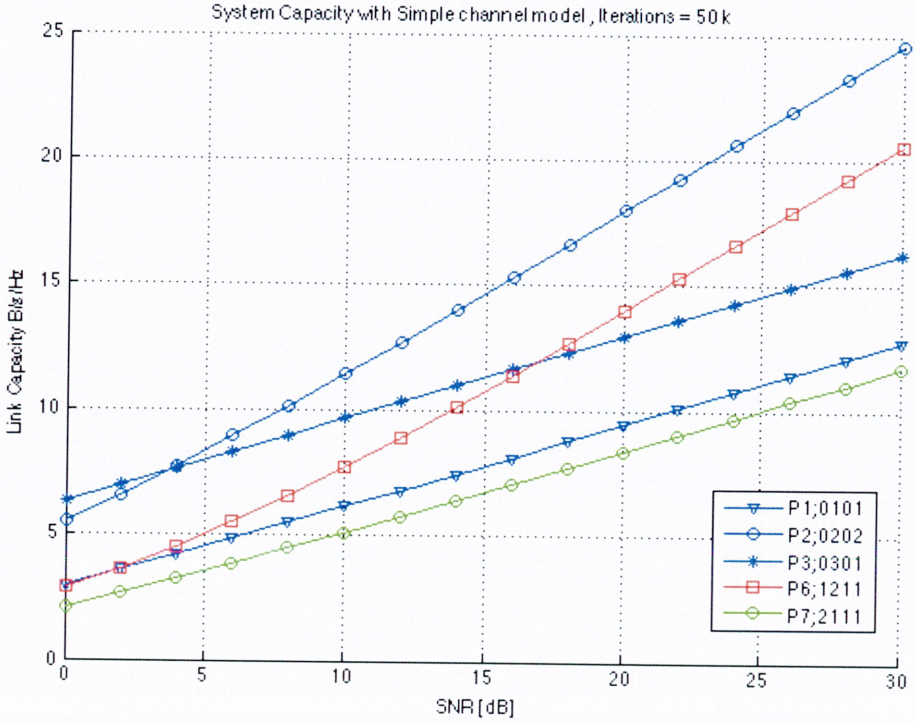


Figure 4.15, Capacity versus SNR for P1, P2, P3 P6 & P7 systems

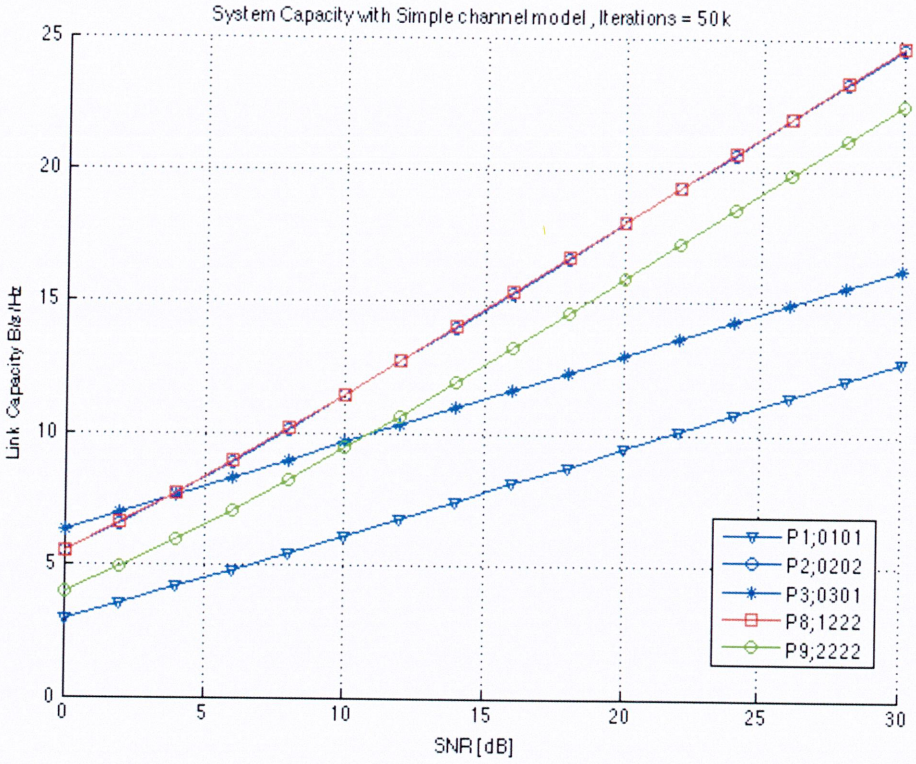


Figure 4.16, Capacity versus SNR for P1, P2, P3 P8 & P9 systems

4.9.2 Changing antenna parameters effect on system capacity

Studying the effect of antenna structure and parameters on the link capacity is the focus of this part of the simulations. The antenna correlation effect on the link capacity is evident in figure 4.17. The curves show how the capacity degrades as the correlation between the antennas increase. This simulation was done via the second channel model, i.e. the correlated channel model shown in equation 3.5. The degradation is similar to a normal MIMO system. The curves shown are limited to the direct link between the source and destination. The antenna spacing effect on the link capacity is shown in figure 4.18. These results were produced

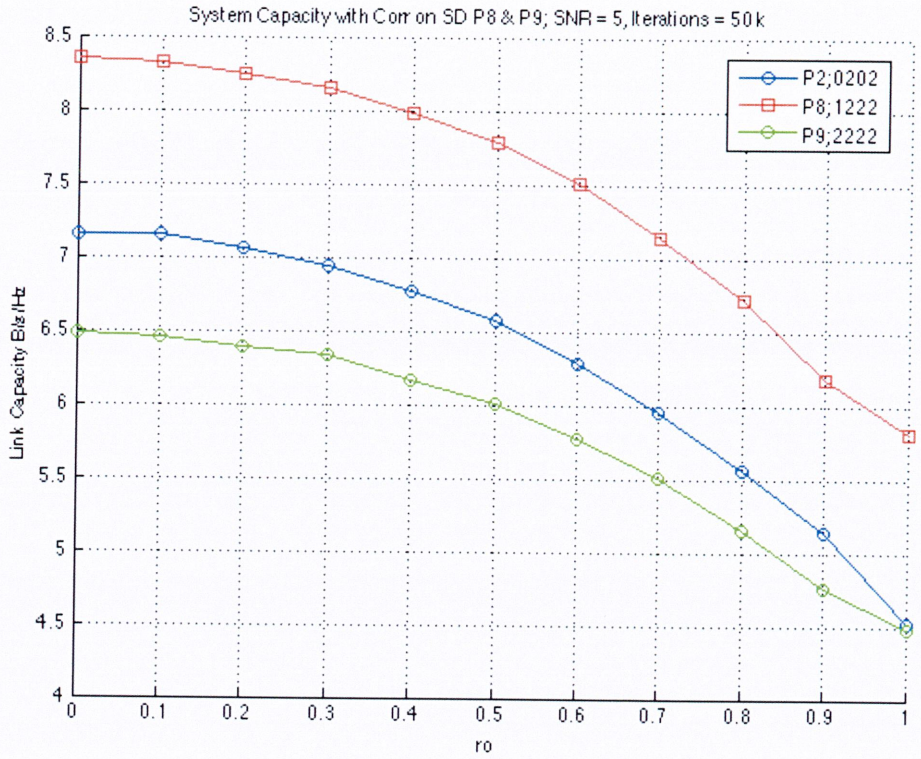


Figure 4.17, Capacity versus antenna correlation

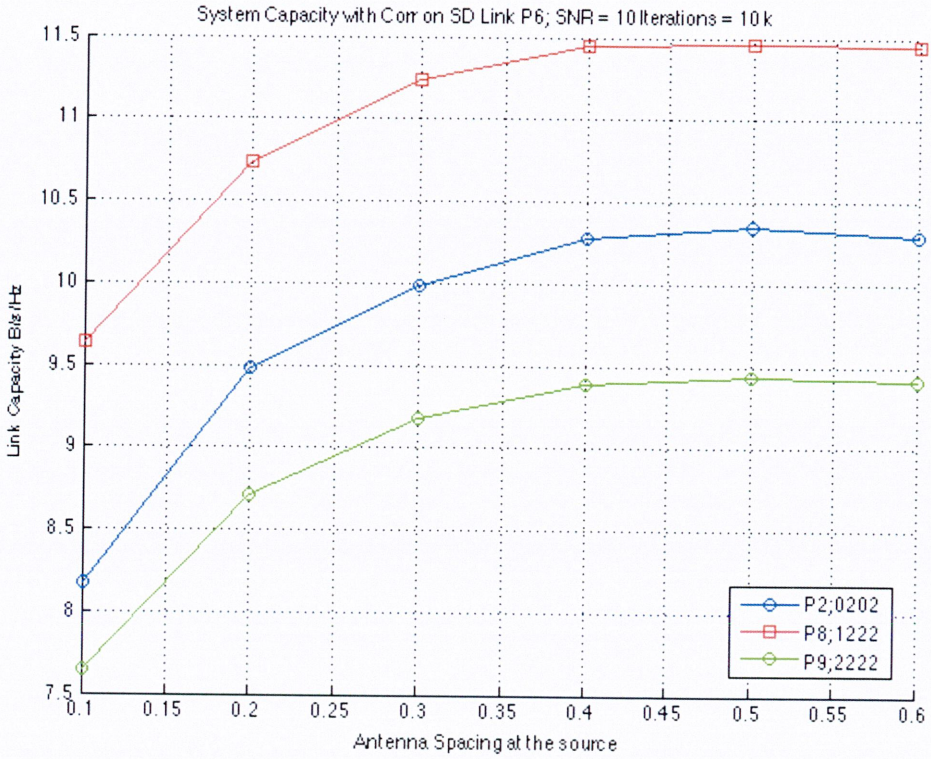


Figure 4.18, Capacity versus antenna spacing

Via the OSSC channel model. From the curves shown, it is clear that increasing the antenna spacing more than 0.4*Lambda will not affect the capacity positively. Increasing the number of antennas increases the threshold for antenna spacing as shown in figure 4.19 were 1.5*Lambda is the new threshold as the antenna per node doubled. System P8 and P10 share the same structure but P8 has two antenna per node, whereas P10 has four antennas per node. Uniform Linear Array is the antenna structure simulated in figure 4.19. Uniform Circular Array was simulated in figure 4.20. The curve shown there indicates that 1.5*Lambda is a good threshold though capacity keeps increasing slowly after that point.

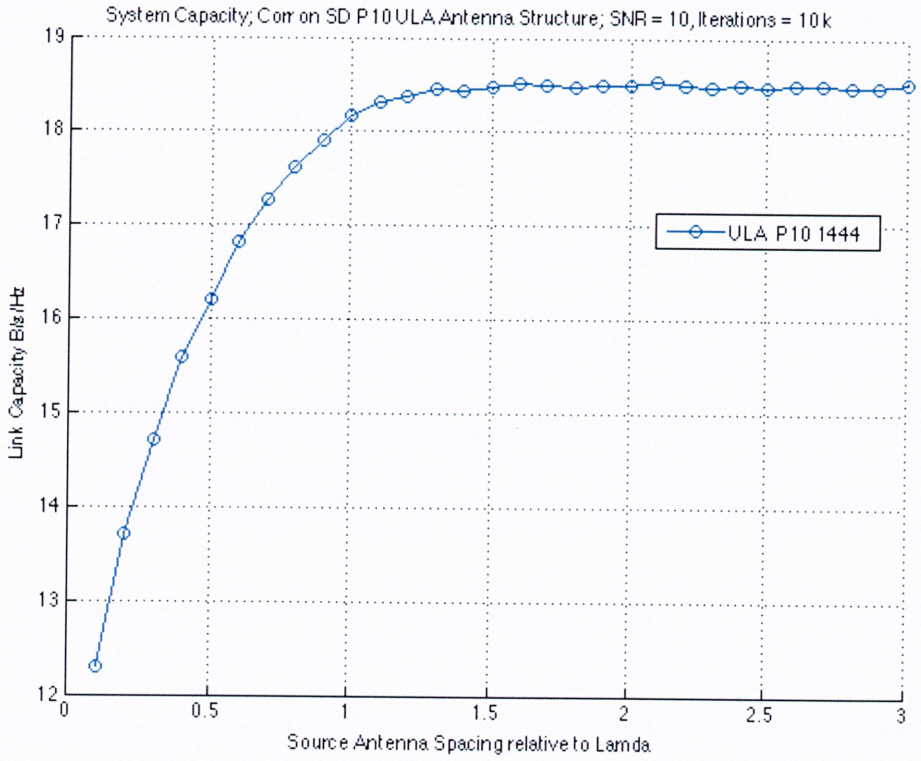


Figure 4.19, Capacity versus ULA antenna spacing

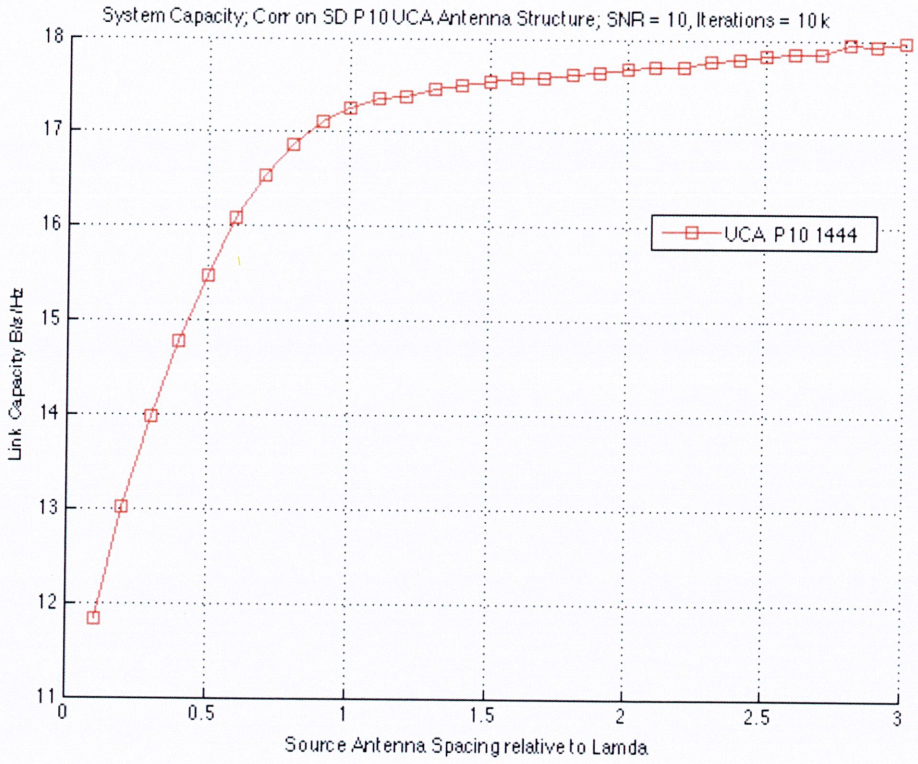


Figure 4.20, Capacity versus UCA antenna spacing

4.9.3 RN location and source power allocation effect on system capacity

The location of the Relay Node plays a major role in controlling the capacity of a MIMO Relay AF system. Basically, adding a relay node at the edge of the cell can increase the cell coverage. In this part of the simulations study, the optimum RN location was examined. As shown in figures 4.20 and 4.21, the RN is best located halfway between the source and destination. The source power allocation between the source-relay path and the source-destination path has a clear effect as shown in figure 4.22. In this simulation, the source-transmitted power is divided between the S-D link and the S-R link. As the ratio changes, so does the link capacity.

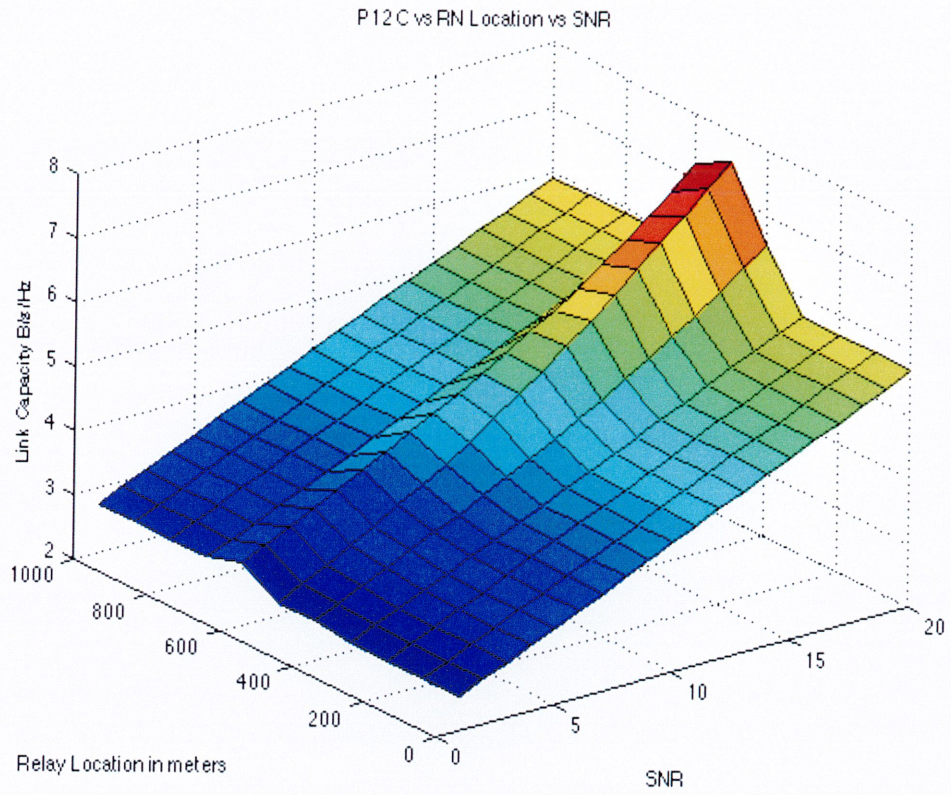


Figure 4.21. Capacity versus source antenna spacing

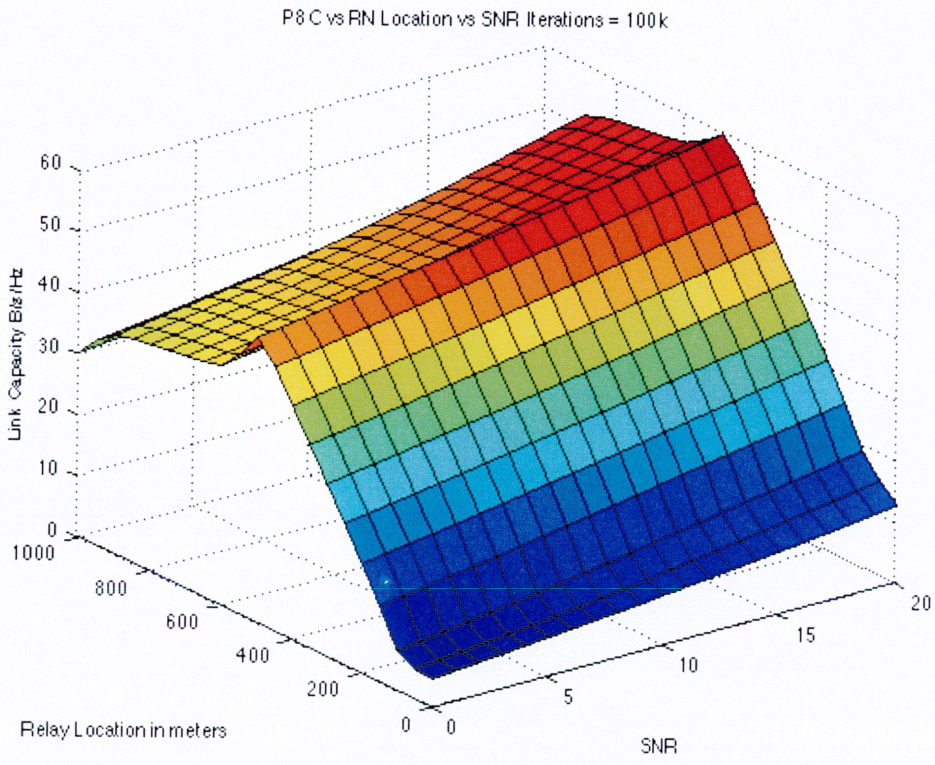


Figure 4.22, Capacity versus source antenna spacing

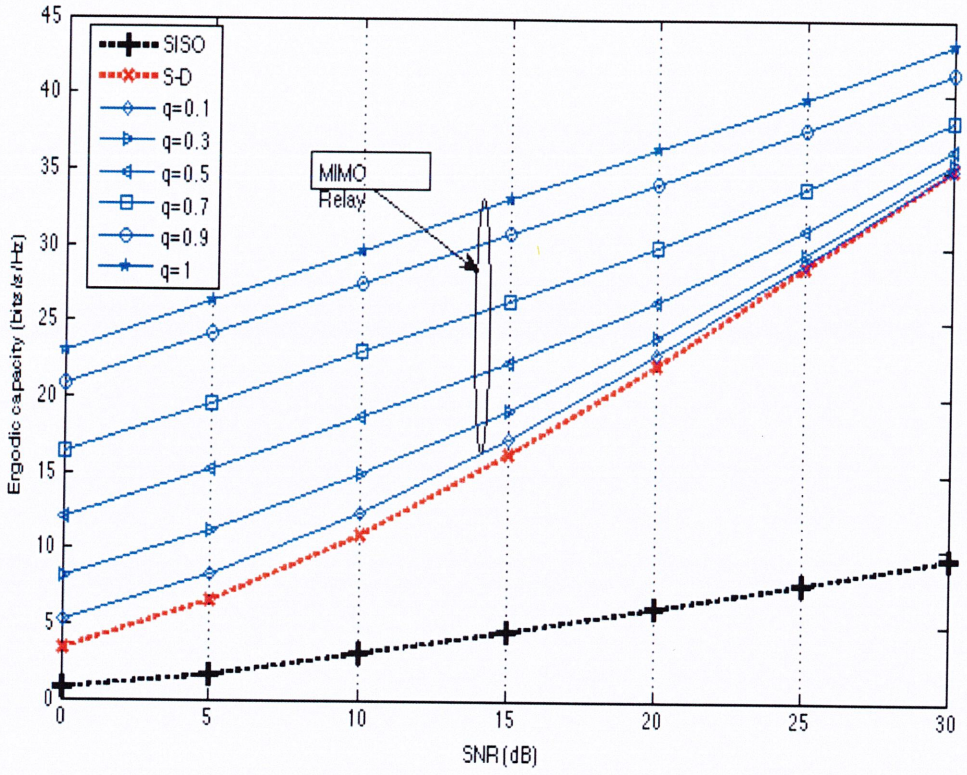


Figure 4.23, Ergodic Capacity versus SNR

4.10 Conclusion

Below is a summary of the finding noted from the capacity investigations of the MIMO Relay AF systems.

1- The MIMO Relay AF system does not have a capacity advantage over the MIMO systems. However, they are more resilience and outperform the MIMO systems in outage probability.

2- The MIMO Relay AF systems are more immune to system parameters changes on their source to relay and relay to destination links. Their most vulnerable link is the source to destination.

3- The antenna spacing affects the system capacity significantly when the spacing is less than a certain threshold. After this threshold, the antenna spacing does not affect the system capacity. For a ULA

antenna structure with two antennas the threshold antenna spacing is 0.4λ. A four antennas array has a higher threshold, 1.5λ. UCA antenna array has a different threshold for the same antennas count.

4- The Relay Node location significantly affects the system capacity for MIMO Relay AF systems. In general, the antenna should be place halfway through closer to the destination to maintain high system capacity.

5- Introducing the source to destination link enhances the system coverage over the two-hop AF system, i.e. P4.

Chapter5

Linear Filter Design for Multi-User MIMO-Relay with Precoding in Correlated Channel

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Chapter 5

Linear Filter Design for Multi-User MIMO-Relay with Precoding in Correlated Channel

5.1 Introduction

On the edges of a MIMO Network, Relay nodes (RN) can be used to extend the networks reach so it extends the network coverage. Alternatively, RN could be used as an alternative way of emulating a MIMO system by using RN as distributed antennas that have the potential to cooperate, thus relaxing the hardware complexity at the Base Station, (BS) and/or the User Terminal (UT). Relay techniques could be deployed in either of two methods, the one-relay case and multi-relay case. In the one-relay case, all the antennas are located and attached to the single relay, and in the multi-relay case, the multi-antennas are distributed indifferent relays. It has been shown theoretically that both types of systems are indeed equivalent in many aspects, disregarding the practical aspects. The amplification factor for the MIMO AF relay has been widely studied (Jiang, L. 2006). This work provided general analysis of cooperative amplify-and-forward relay networks with a united and comparative view of various proposed systems. Based on the first and second hop Channel State Information (CSI) a good investigation of the gain allocation of the AF relays has been done. Cooperative transmission schemes have been presented by (Jiang, L. 2006). Only simple AF relay without additional filter matrix is considered. The r^{th} diagonal component

of amplify gain matrix G is designed according to the r^{th} eigenvalue of the first and second hop channel respectively. This was presented in the work by (Qingyu, M. Osseiran, A. & Jiansong, G. 2008), where there is only one relay. They investigated the gain allocation in the multi-relay cases, where relay switch and selection is also compared. The choice of the spatial gain and filter matrices (i.e. amplification factor) applied to the received signal at the relay station has been widely investigated by (Abdaoui, A. 2010). Furthermore, substantial gains can be obtained in wireless relay and ad-hoc networks employing terminals with MIMO capability. Zeros forcing (ZF) relay and linear AF relay are listed as examples. However, due to the ZF operation, it requires that the number of antennas at each relay node is no less than that of source and destination node. The work presented by (Zhao, Y. 2004) discussed the blinded, MMSE and ZF relay. In the listed analysis, it is assumed that the CSI and signal can be known in all relays. A QR relay (named after QR-decomposition) is proposed in (Qingyu, M. 2008) where the performance is compared with ZF relay. The QR relay improves the performance since the destination can easily employ successive interference cancellation (SIC). Short term and long term SVD is discussed when the instantaneous or the average CSI of the first hop and second hop is available in relays. The basic idea of the filter design is that the overall MIMO channel is diagonalized at the RN. This allows to optimally choosing the gain coefficient for each eigenmode while fulfilling the transmitting power constraint. The above proposed SVD; ZF and MMSE relays were designated to optimize the one-relay case. The performance of the matched filter relay for the multi-relay case is analyzed where the source and the destination form a SISO system. The matched filter matrix is called maximum ratio combining (MRC) on receive and transmit beam

forming (TB). In (Qingyu, M. Osseiran, A. & Jiansong, G. 2008), various designs for the relay filter equalization matrices in the multi-relay case has been proposed and investigated

5.1.1 Filter Matrix Design Study approach

The work carried out in this part of the research looks at utilizing the OSSC channel model in our MIMO AF Relay model. The focus here is on the filter equalizers schemes. The gain allocation of AF relays in cooperative transmission schemes based on the first and second hop channel state information (CSI) is the target to be investigated. With the introduction of feedback into the link model, the filter matrix design (FMD) techniques could be implemented. The main assumption is that feedback is available at the transmitter and relay node. The channel state information, CSI, is available to transmitter hence allowing for the filter coefficients to be determined. The CSI helps the transmitter decide about the channel before sending out the signal. The signal is further engineered to counter effect interference from other channels. First the FMD techniques will be presented and explained. Then an implementation with a simple channel model will be demonstrated. Theoretically, the OSSC channel model is more realistic than the simple channel model and hence this will result in more realistic capacity values. Varying the antenna arrays as uniform linear array, ULA, and uniform circular array, UCA will be studied. The effect of changing the number of antennas at the transmitter, relay and receiver will be investigated as well.

5.2 Filter Matrix Design Implementation

As wireless channels behave randomly according to the given characteristics of fading and delay, it would seem rather more intelligent to know the channel before sending traffic over it. This is a well-known practice in SISO channels where for example, equalization is used. In MIMO channels the process is a little but complicated as another source of noise is present. Not only the transmitter has to account for white noise and maintain a high SNR to counter its effect. Adjacent transmitted signals are considered as an added noise source this is also known as fading correlation, as it presents an in reducing the throughput at the receiver. In the two-hop AF MIMO Relay, it is assumed that the data is transmitted over two phases. In the first time slot, the data is transmitted from the source to the relay node. In the second time slot, the data is transmitted from the relay to the destination after being amplified .Two schemes can ne used for AF MIMO, either simple AF uniform relaying without equalization or using CSI to amplify the signals and choose spatial gain and filter matrices with variable amplification factors according to the received signal at the relay station (Mangoud, 2009). The concept of Filter Matrix Design is to equalize the received signal at the relay by accounting for the adjacent MIMO channels before relaying it to its destination. This adds another level of encoding. The FMD work is done in the relay node by altering the gain matrix, G, to account for the channel changes. In this chapter, three techniques will be discussed Blind Amplify Relay, Singular Value Decomposition Relay; SVD and Matched Filter Relay. All the techniques used depend on the presence of the CSI at the relay node of both hops. The SR hop and the RD hop. Let us define the some variables before discussing the FMD techniques ahead.

G_{Relay} : is the basic Gain Matrix produced by the Relay Node

G_{FMD}: is the new Gain Matrix produced as a result of the implemented FMD technique that is either G_{BR}, G_{SVD} or G_{MF}

F_{SR}: is the first Filter Matrix calculated based on the Channel State Information of the Source to Relay wireless Channel Link

F_{RD} : is the second Filter Matrix calculated based on the Channel State information of the Relay to Destination wireless Channel Link.

5.2.1 Blind Amplify Relay

As the name suggests, Blind Amplify Relay is the simplest of all types. The received signal from the Source is amplified by the Relay and forwarded to the Destination. No channel state information is used in this technique making it the simplest of them all. Both the Filter Matrixes F_{SR} and F_{RD} are replaced with Identity matrixes. So that the new gain matrix becomes the original relay gain matrix multiplied by the two identity matrixes as follows:

$$G_{BA} = F_{SR} \cdot G_{Relay} \cdot F_{RD} \tag{5.1}$$

Where F_{SR} and F_{RD} are simply identity matrix with the dimension of the MIMO system;

$$F_{SR} = \begin{bmatrix} 1 & 0 & 0 & \\ 0 & 1 & 0 & \cdots \\ 0 & 0 & 1 & \\ & \vdots & & \ddots \end{bmatrix}_{M_S.N_R} \tag{5.2}$$

$$F_{RD} = \begin{bmatrix} 1 & 0 & 0 & \\ 0 & 1 & 0 & \cdots \\ 0 & 0 & 1 & \\ & \vdots & & \ddots \end{bmatrix}_{M_R.N_D} \tag{5.3}$$

5.2.2 Singular Value Decomposition Relay

Singular Value Decomposition, SVD aims at maintaining the gain matrix at a full rank. Thus, the Gain matrix is kept at its optimal value. This means that the gain coefficients are chosen in an optimal way for each eigenmode of the channel matrix. Implementation wise, this is the most complex as SVD calculations are mathematically involved due to matrix inversion and the basic decomposition calculations. The first hop channel matrix H_{SR} is decomposed into its singular values yielding three matrixes as follows:

$$H_{SR} \overset{SVD}{\Longrightarrow} U_{SR}.D_{SR}^{1/2}.V_{SR}^{H} \tag{5.4}$$

Similarly for the second hop, Relay to destination,

$$H_{RD} \overset{SVD}{\Longrightarrow} U_{RD}.D_{RD}^{1/2}.V_{RD}^{H} \tag{5.6}$$

Where H_{SR} is the Source to Relay complex channel matrix, U_{RS} and V_{SR} are unitary matrices

D_{SR} is a diagonal matrix; its diagonal elements are the singular values of the H_{SR} and the $(.)^H$ operator is the conjugate transpose operator. The Filter matrices are designed so that:

$$F_{SR} = (U_{SR})^H \tag{5.7}$$

And

$$F_{RD} = V_{RD} \tag{5.8}$$

Hence the Gain matrix becomes:

$$G_{SVD} = V_{RD} \cdot G_{Relay} \cdot (U_{SR})^{H} \tag{5.9}$$

5.2.3 Matched Filter

The Matched Filter Relay is the third technique discussed in this chapter. Basically the Filter is set to match the matched filter of the first and second hops of the Relay link. Equalization method is used to cancel out the channel differences. The first filter is set as the conjugate transpose of the first hop and the second filter is set as the conjugate transpose of the second hop. The channel state information is needed for both links in this method as well. However it is less math intensive when compared with the SVD relay. The Gain matrix becomes as follows:

$$F_{SR} = (H_{SR})^{H} \tag{5.10}$$

$$F_{RD} = (H_{RD})^{H} \tag{5.11}$$

$$G_{MF} = (H_{RD})^{H} \cdot G_{Relay} \cdot (H_{SR})^{H} \tag{5.12}$$

5.3 Filter Matrix Design Example

Now that the theoretical concept of the FMD in AF MIMO Relay has been discussed, let us show some implementation examples and compare their outcome.

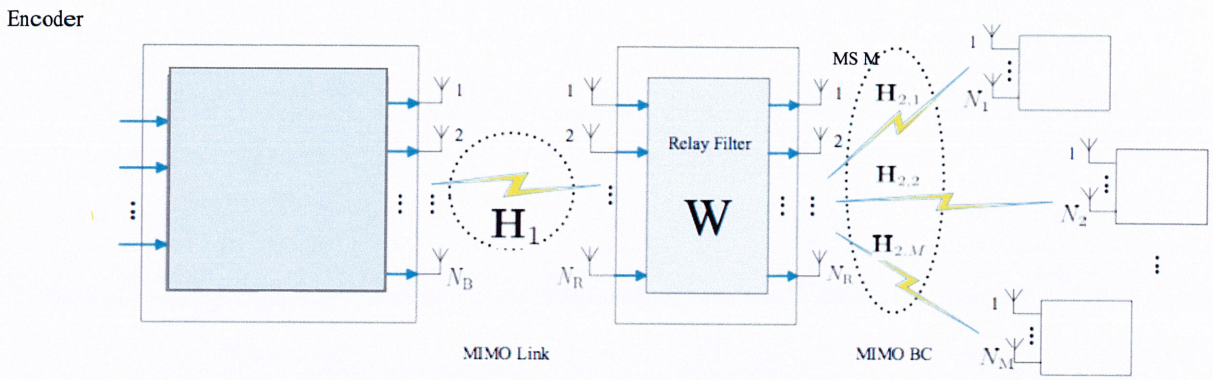


Figure 5.1, Illustration of MIMO Relay AF with Filter Matrix (G)

5.3.1. System model description

A typical MIMO Relay with FMD is shown in figure 5.1. Basically it shows a direct link AF MIMO Relay with 4 antennas at the transmitter, 4 antennas at the Relay Node, and two users at the destination each equipped with two antennas. The traffic will take the path of the source to the relay then the relay to the destination only. This setup is the two-hops system. Our analysis will cover the two-hop system and the system with the direct S-D link. A simple correlated channel model has been used first, the realistic Outdoor Statistical Correlated Channel Model, (OSSC) which has been presented in chapter 3 has been used. Capacity analysis versus SNR has been studied followed by coverage analysis with different FMDs. Assuming that the total transmit power at BS is equal to (P_t), and the power transmitted in SR and SD links are both equal ($P_t/2$). It is further assumed that relay node has the full knowledge of channel characteristics of the backhaul channel. This assumption is practical and often realized by sending pilot signals in real life communication systems. The common gain factor **g** of the Relay Station in the AF mode is as thus the amplification factor is selected to satisfy this constrain as below:

$$g = \frac{1}{Ms} trace((F_1F_2Hr)(F_1F_2H_{SR})^H + N_R(F_1F_2H_{SR}) \quad (5.10)$$

Where the Gain matrix is a diagonal matrix. The diagonal elements being g defined with squared Frobenius norm of the SR channel multiplied with relay filter matrix. The entries of noise vectors at the receiver side are independent zero mean complex Gaussian random variables. The variances of Noises are assumed to be time-uncorrelated. The received signal at MS of a narrowband AF relay channel can be written as

Case (1): SRD model without SD link

This is similar to chapter 4 and Equation (4.2) the capacity of such MIMO relay system is calculated as below.

$$C = log_2 det(I + (AR_XA^H)(BR_nB^H)^{-1}) \quad (5.10)$$

Where, A, B, R_x and R_n are as defined in (4.8, 9, 12 and 13)

Case (2) SRD-SD with SD link

$$C = log_2 det\left(I_{2Ms} + \frac{1}{Ms}(R_{n,AF},)^{-1} Ht\, Ht^H\right) \quad (5.11)$$

Where H_t is an Equivalent Channel matrix

$$H_t = \begin{bmatrix} H_{SD} \\ H_{RD}F1GF2H_{SR} \end{bmatrix} \quad (5.12)$$

and $R_{n,AF}$ The covariance correlation matrix of noise vector is

$$Rn, AF = \begin{bmatrix} Rn & 0 \\ 0 & \text{H\_RD} * \text{F1GF2} * \text{Rn} * (\text{F1GF2})' * \text{H\_RD}' + \text{Rn} \end{bmatrix} \quad (5.13)$$

5.3.2. Results validation

Before proceeding with our results let us validate our proposed model against a published work. The OSSC channel matrix is more realistic as explained earlier and thus the resulting system capacity should be less than that of the other model. We are validating our work against figure 5.2, this is the work presented by (Qingyu, M. Osseiran, A. & Jiansong, G. 2008). Three filter designs were simulated, Blind, Matched filter and SVD. The order of performance starts with the Blind filter then the SVD and the highest capacity gain was achieved via the matched filter. The simulated system is similar to our model in several aspects; the source destination separation being 1000 meter is an example. Similar to the validation work our results maintained the same order of performance. This is shown in figure 5.3, where the performance starts with the Blind filter followed by the SVD and the Matched filter formed the highest capacity gain. The remaining of the results was produced with our proposed models. To investigate the effect of antenna correlation on the order of the performance of the filter designs, the correlated channel model was used. The resulting curves are shown in figures 5.4 and 5.5. The figures show performance curves under different correlation conditions. The general capacity values differ slightly under different correlation conditions but the order of performance is maintained.

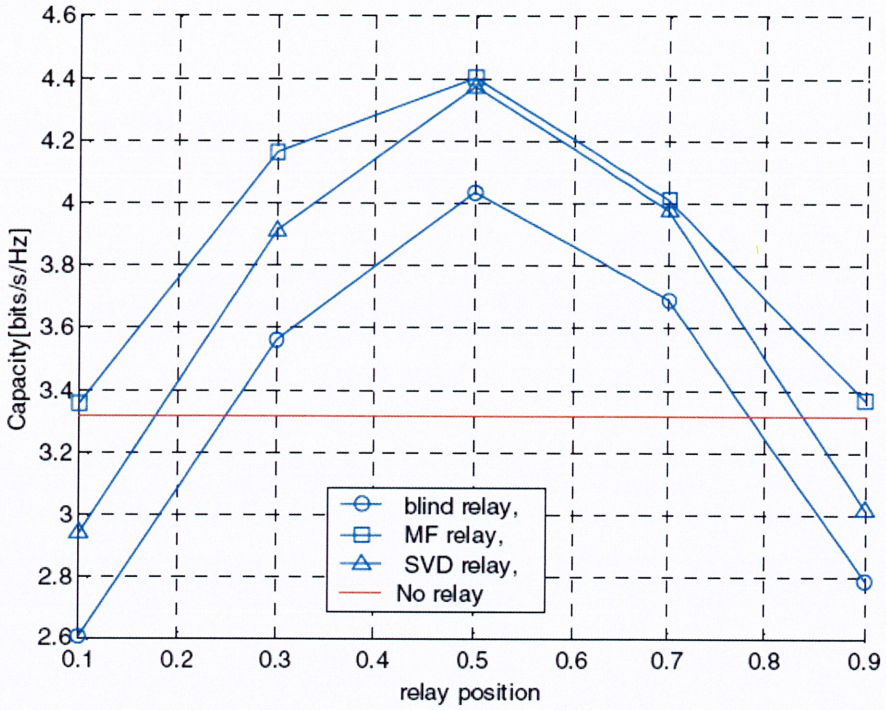


Figure 5.2, Capacity versus RN location for different filter designs

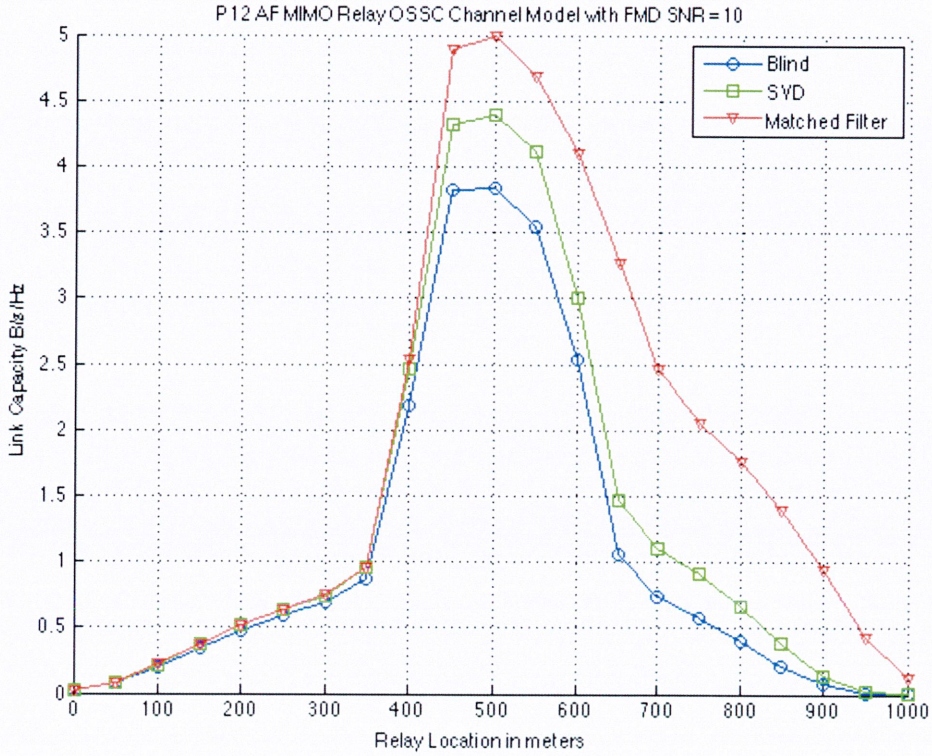


Figure 5.3, Capacity versus RN location for different filter designs

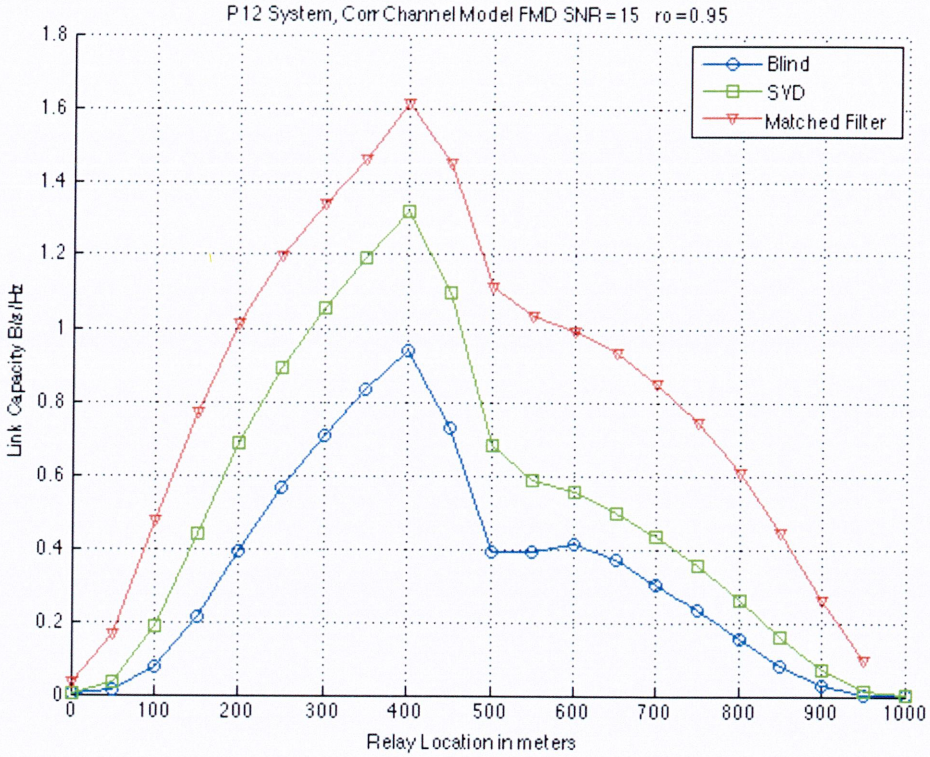


Figure 5.4, Capacity versus RN location, high antenna correlation

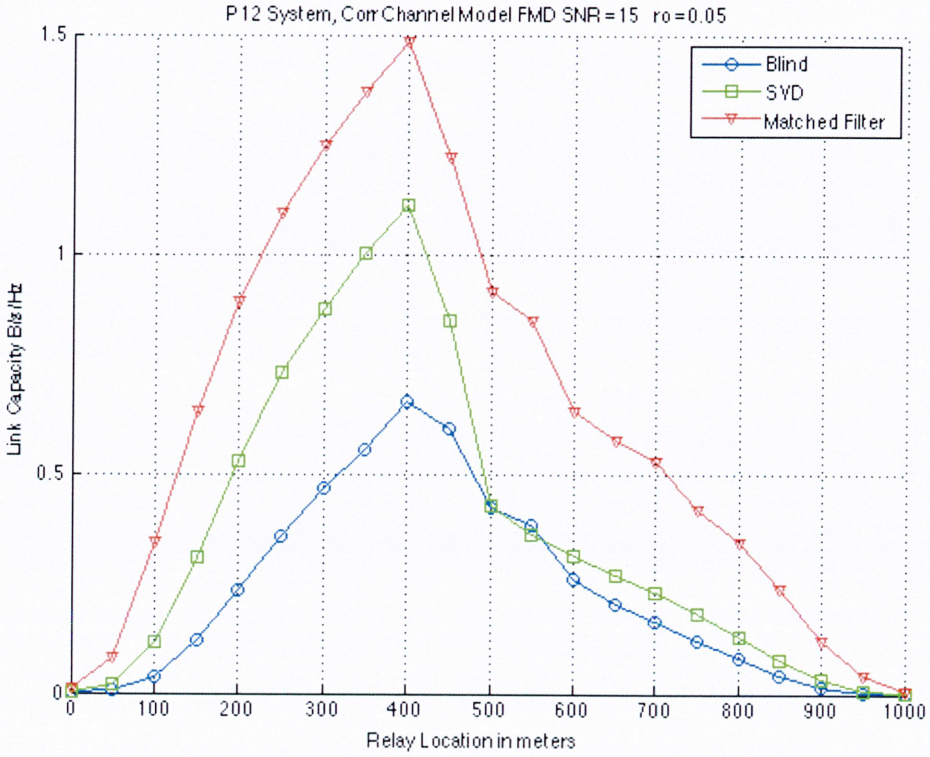


Figure 5.5, Capacity versus RN for low antenna correlation

5.3.3. Numerical Results

The Ergodic capacity of different FMD schemes was evaluated in correlated channel model in flat fading environments. First, the capacity vs. SNR are presented in figures 5.6,7,8 and 9 for case (1), SRD, and (2), SRD-SD, for Low SNR [0:10] and High SNR [10:20] ranges. The order of performance is yet maintained her with a little change of capacity values due to different system configurations.

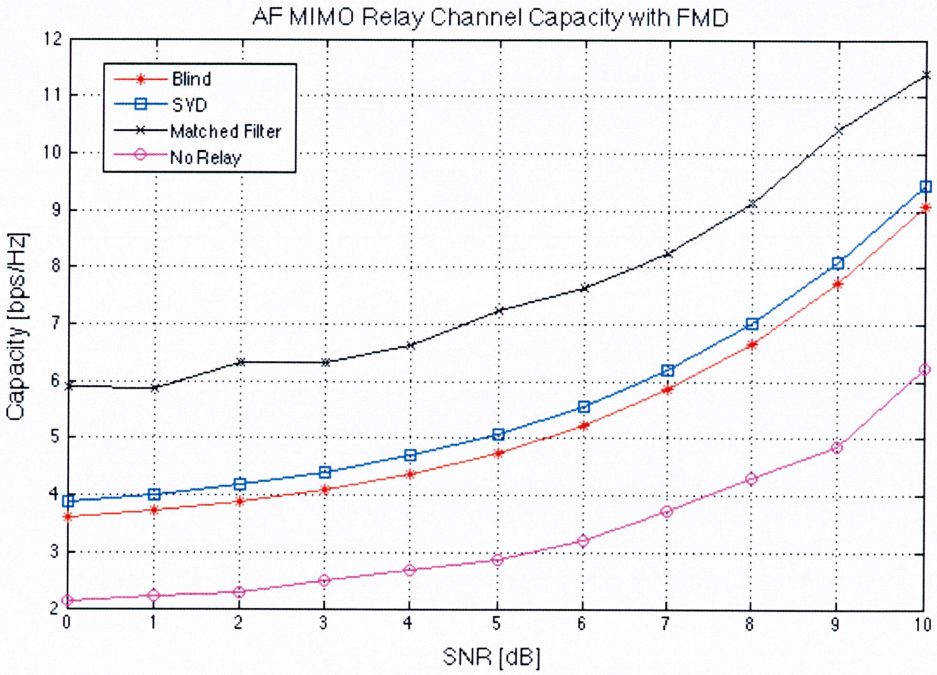


Figure 5.6, Capacity versus SNR; case (1)

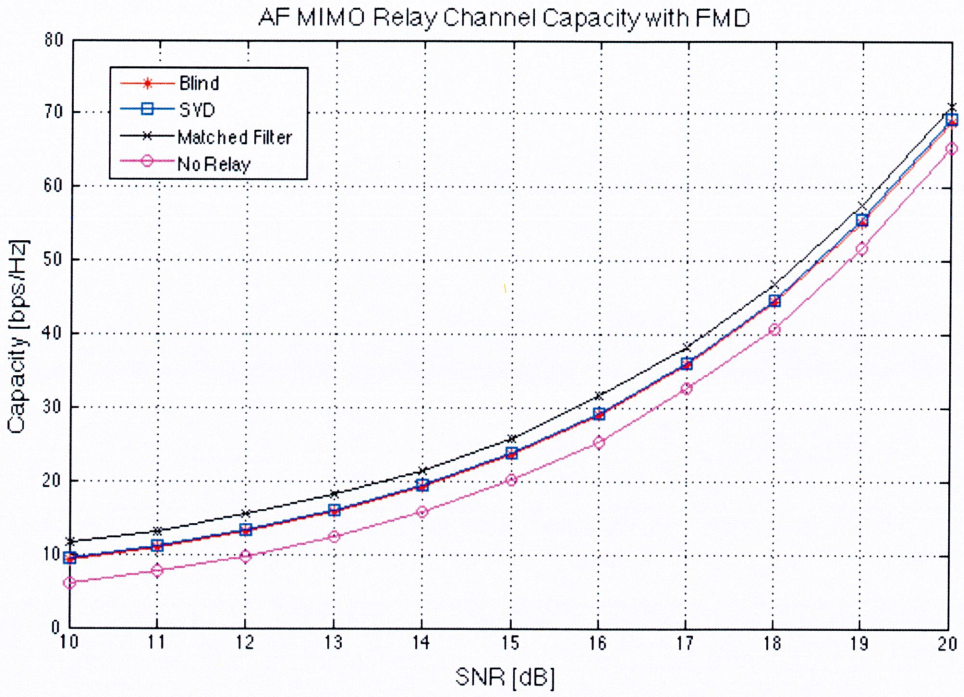


Figure 5.7, Capacity versus SNR; case (1)

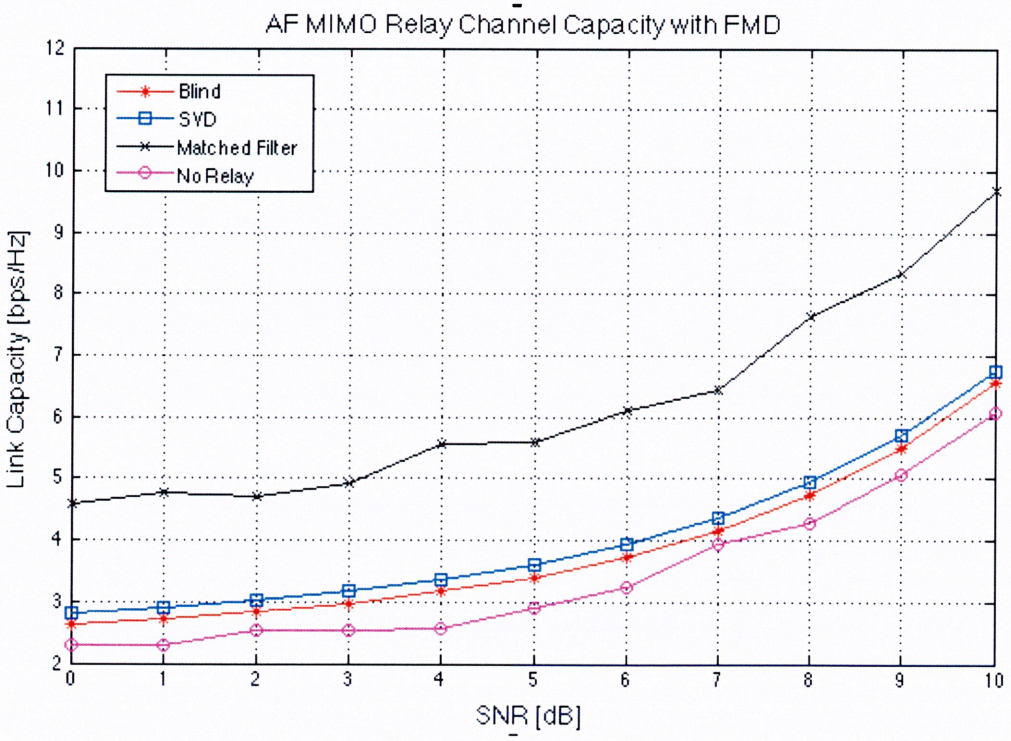


Figure 5.8, Capacity versus SNR; case (2)

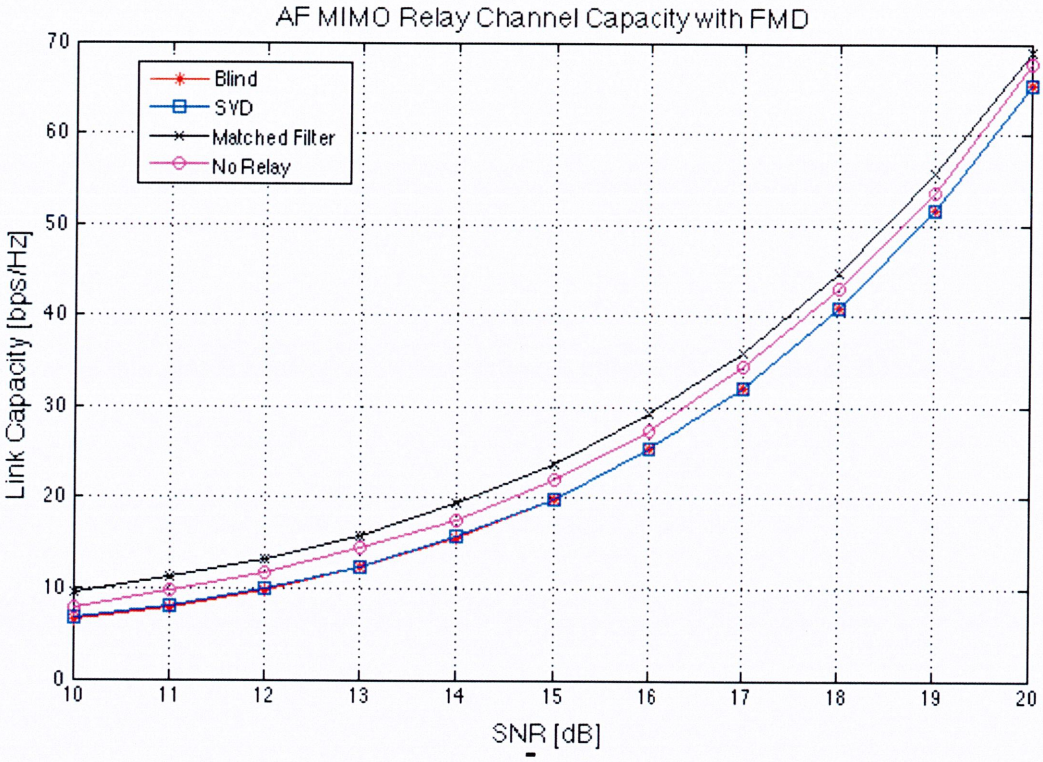


Figure 5.9, Capacity versus SNR; case (2)

5.4 Relay Design with Linear Precoding Multiuser MIMO

The previous work has been concerned with the general capacity of the MIMO Relay AF system. At the receiver end, multi user implementation tends to have its own issues, i.e. user interference. As all users share the same resources, multi user interference becomes an issue. To address that precoding is used.

5.4.1 MU-MIMO Relay System Description

This Section presents the numerical results for performance analysis of relay MU-MIMO with simple correlation channel model. Four liner-precoding techniques for MU-MIMO systems are. Here, a typical MU-MIMO environment is made up of a single relay serving multiple mobile

stations (MS). Each MS can have either one or more antennas. The relay is equipped with (N_r) antennas and each of the (K) mobile stations is equipped with (N_k) antennas. The end-to-end configuration can be described as a ($K.N_k x N_r$) MIMO system. All the coming work is based on the assumption that $K.N_k$ equals N_r. For detailed description of the four precoding techniques used, the reader is kindly referred to chapter 2. Displayed in figures 5.10 and 5.11 a comparison between CI and MMSE precoding techniques under an increasing number of users is presented. Clearly the simulation reveals the robustness of MMSE as compared to CI. The BER performance of the MMSE maintains its shape as more users enter the system. The case with the CI differs as the BER performance degrades as the system users double.

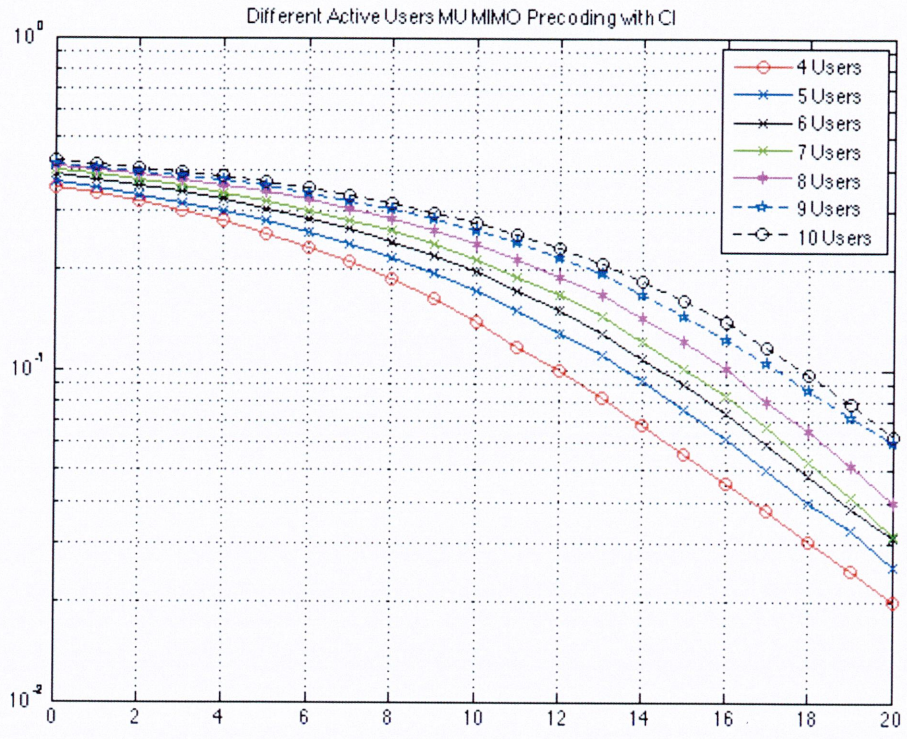


Figure 5.10, BER versus SNR Channel Inversion with precoding

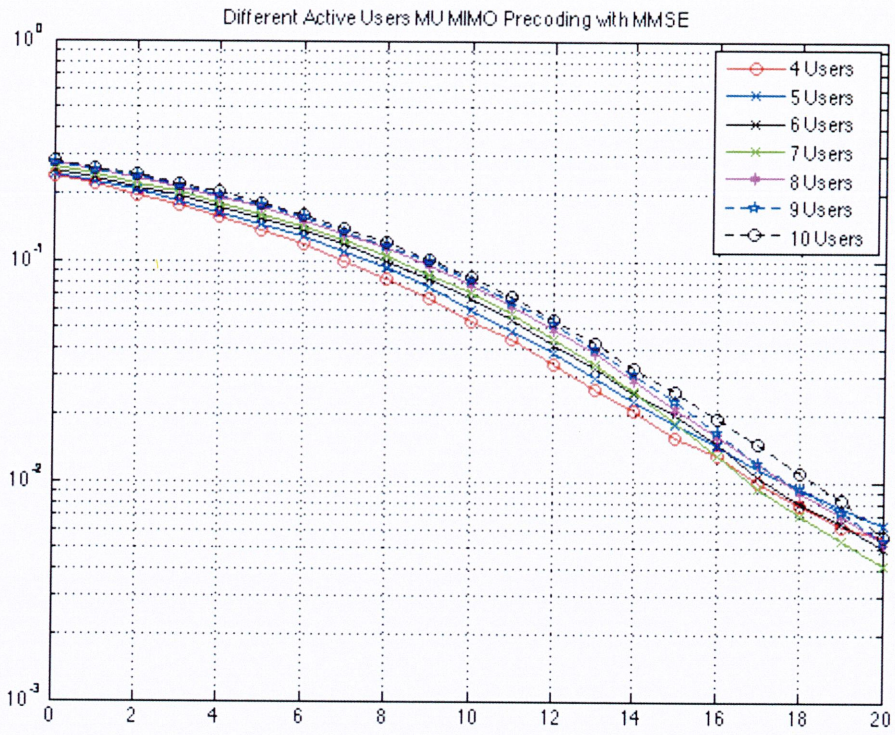


Figure 5.11, BER versus SNR MMSE precoding

The BD precoding BER performance displayed in figure 5.12 follows the same degradation as CI with a slower rate. DPC and TH precoding techniques in figures 5.13 and 5.14 show a strong BER performance as more users enter the system.

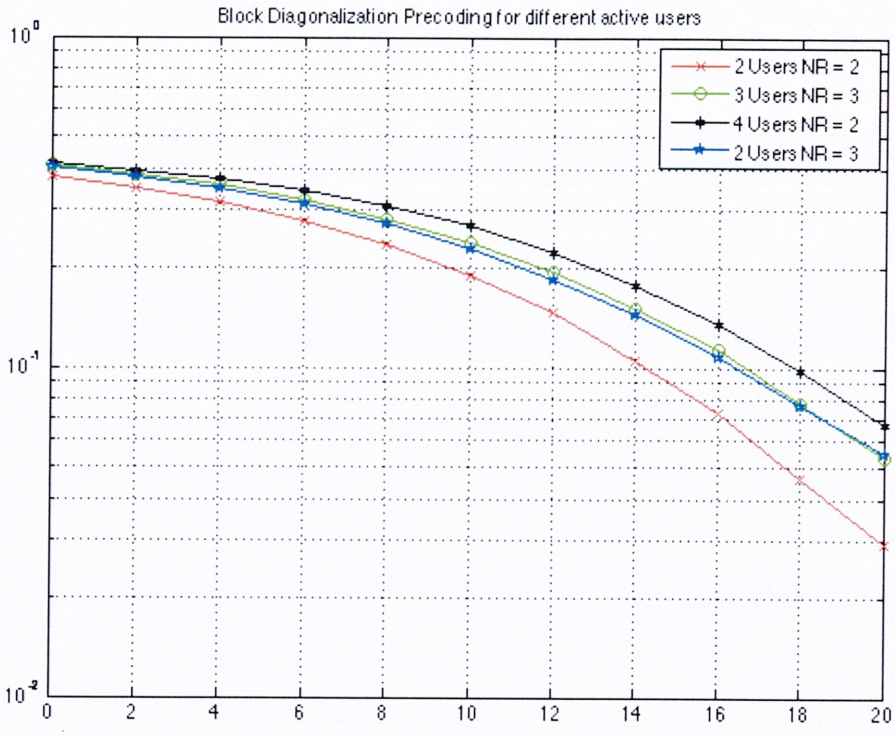


Figure 5.12, BER versus SNR BD precoding

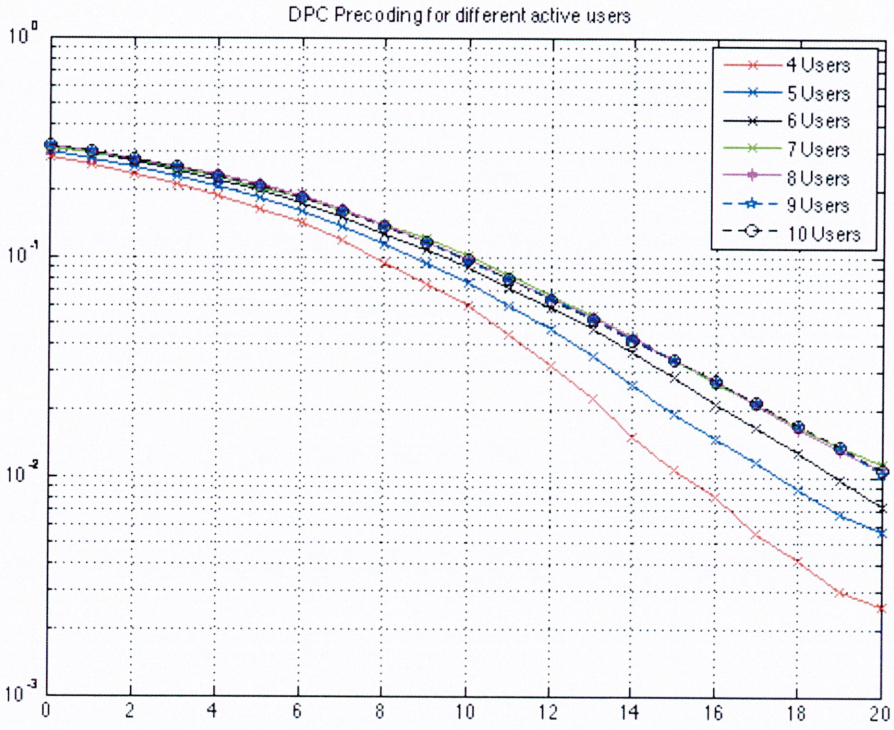


Figure 5.13, BER versus SNR DPC precoding

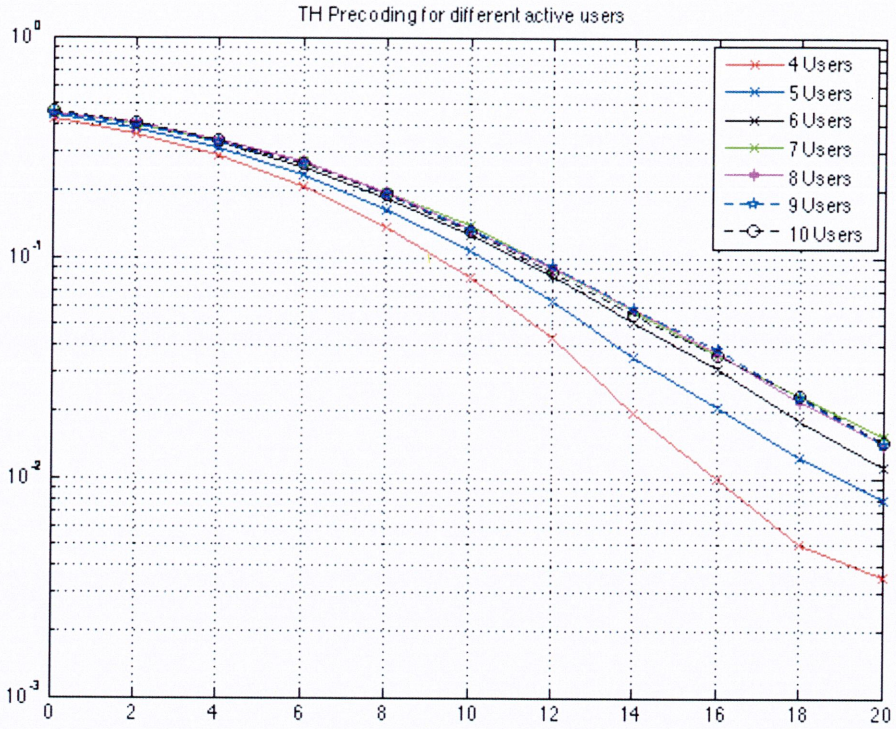


Figure 5.14, BER versus SNR TH precoding

5.4.2 Comparing Different Precoding Techniques

In this section different Precoding methods are being compared. Figures 5.15 through to 5.18 display a comparison between different precoding techniques. This aims at evaluating the BER performance under different system dimensions. In the below figure 4 by 4 MU-MIMO system has been implemented with different precoding. The MMSE precoding outperforms all the other schemes. TH and DPC seem to catch MMSE at higher SNR values. This indicates TH and DPC vulnerability for increasing SNR. Comparing figures 5.7 and 5.8 reveals that MMSE precoding BER improves with more users

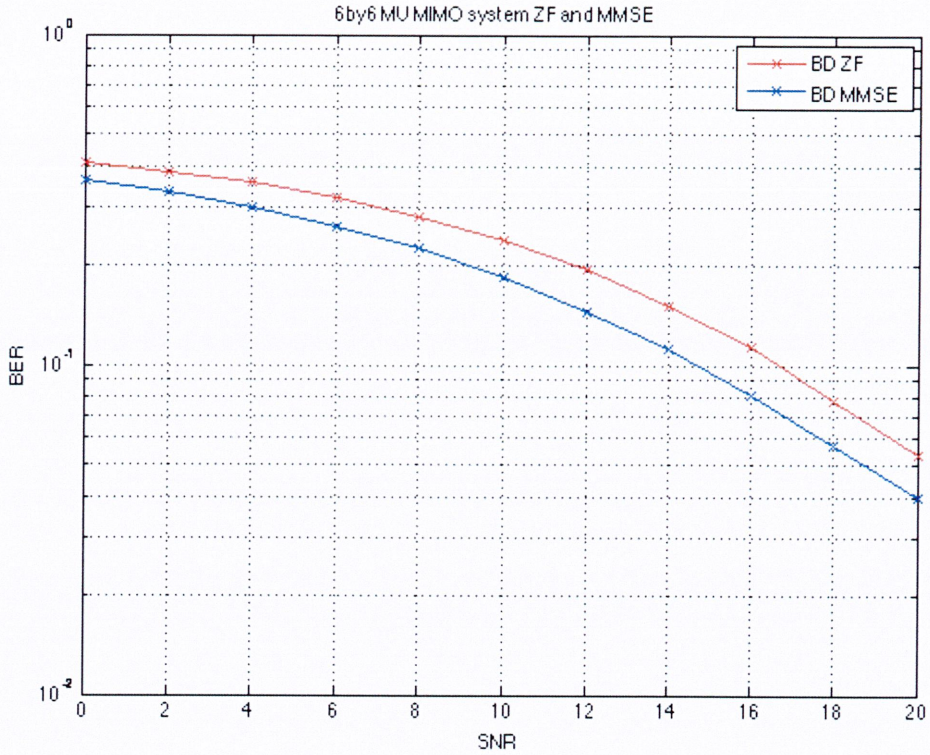


Figure 5.15, BER versus SNR, 6 users MMSE and CI/ZF precoding

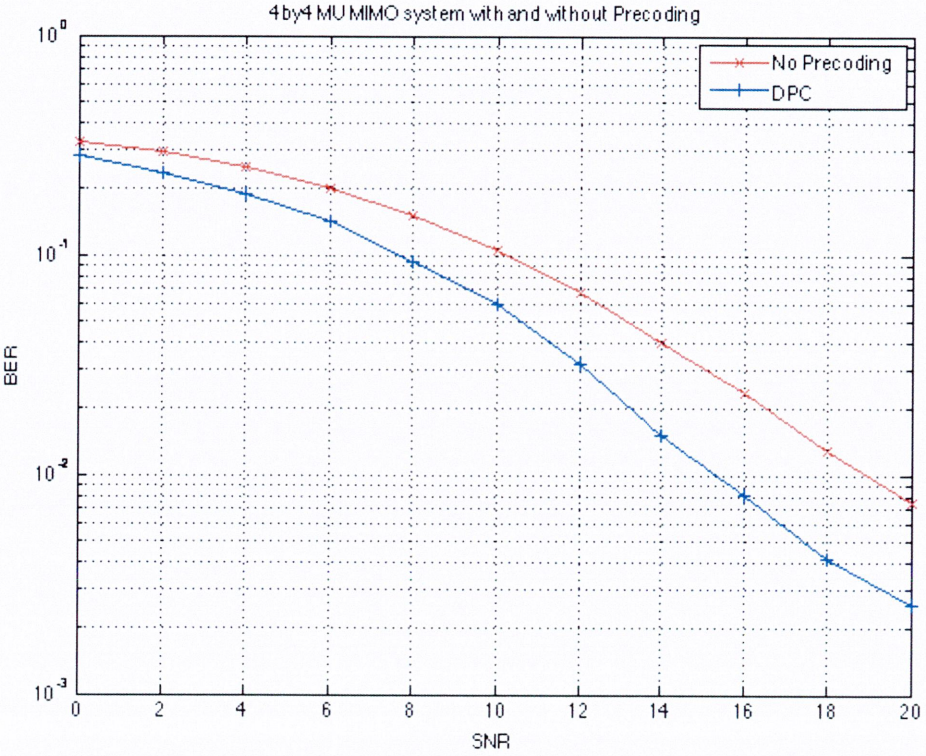


Figure 5.16, BER versus SNR

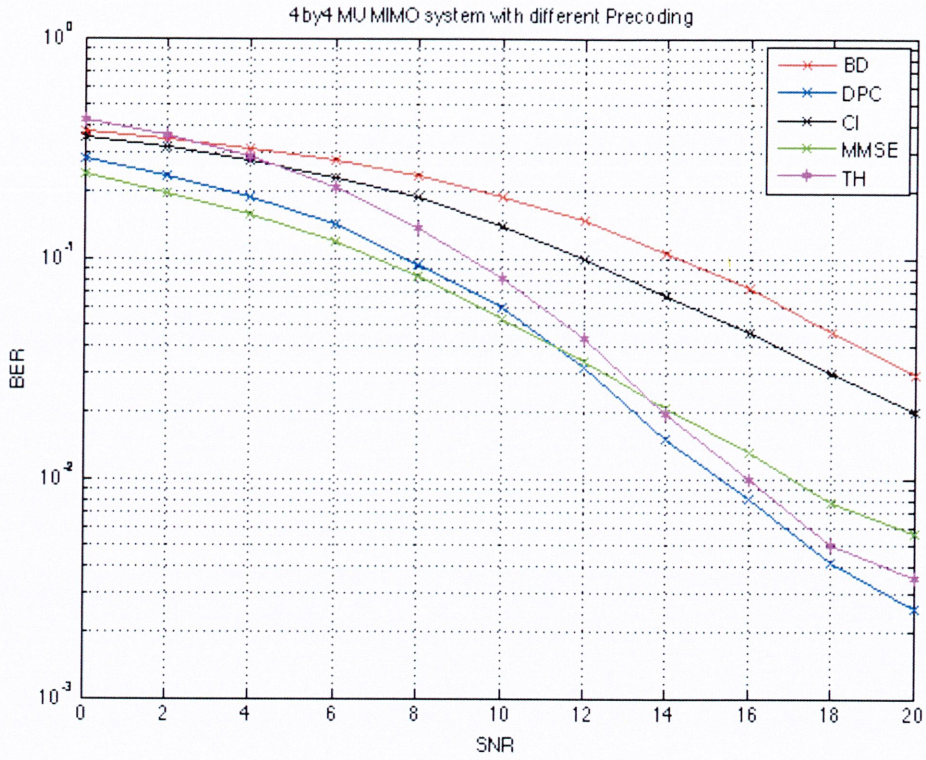


Figure 5.17, BER versus SNR, different Precoding methods

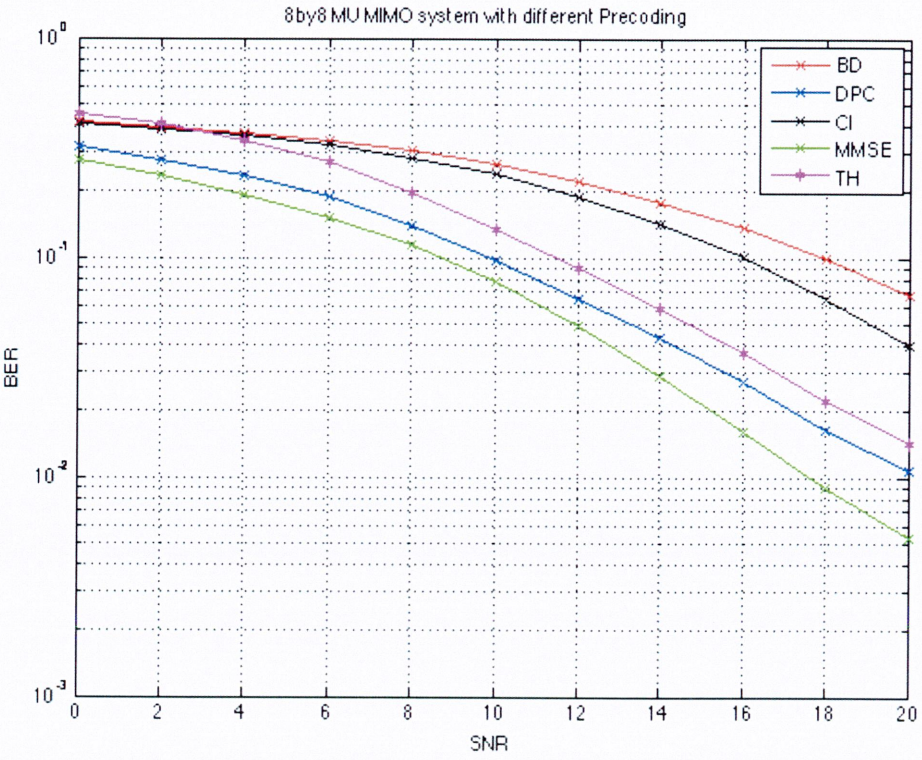


Figure 5.18, BER versus SNR, different Precoding techniques

5.5 Sum Rate Capacity investigations of MU-MIMO Relay downlink with linear precoding

Because of the complexity of DPC, other suboptimal methods are of interest to help reduce the interference between users. Linear beamforming methods are particularly desirable due to their comparatively low complexity.

5.5.1 MU-MIMO Relay System Model

We consider a MU-MIMO system with K multiple antenna users MS1 , . . . , MSK at the receive side which are respectively equipped with N1, . . . , NK antennas. At the transmit side, a multiple antenna base station with N antennas transmits data signals $x_1, \ldots, x_K$ to users $MS_1, \ldots, MS_K$. The signal for each user can be precoded separately by multiplying the data ($S_k \in C^{N_k \times 1}$) for the user (k)by a beamforming matrix (W_k). Then, the transmitted signal $X = \sum_k W_k S_k$ the received signal vector for user k is given by:

$$y_k = H_k W_k S_k + \sum_{j \neq k} H_k W_j S_j + n_k \quad \text{for} \quad k=1,\ldots..,K \qquad (5.14)$$

where:

- $H_k(N_k \times N_r)$ is the complex channel matric between receiver MS_k and the relay station
- $n_k(N_k \times 1)$ is additive noise signal vector
- $W_k(N_r \times 1)$ is the relay transmitted vector of index k. The Transmit Beamforming Matrix is

$$W = [W_1 W_2 \ldots . W_K],\ k = 1,2,3 \ldots K \tag{5.15}$$

The goal of linear precoding is to design $\{W_k\}$ based on the channel $\{H_k\}$ knowledge, so a given performance metric is maximized for each stream.

5.5.2 Sum Rate of ZF Precoding (Channel Inversion)

One linear method is channel inversion, sometimes called zero-forcing beamforming (ZFB) or zero forcing precoding or channel inversion (CI), which is designed for users with a single receive antenna1. Channel inversion creates a set of orthogonal, non-interfering channels. Let $H = [H_1^T, H_2^T, \ldots, H_K^T]^T$ be the vertical concatenation of K users' channels (where K $\leq$Nr). Then, the signal transmitted by the base station is $X = H^{\ddagger}S$, where s is the vector of data symbols for the K users; the k^{th} entry of s is the data symbol s_k for user k. $H^{\ddagger}$ is the Moore-Penrose pseudo inverse of H, given by. $H^{\ddagger} = H^H(HH^H)^{-1}$ The beamforming matrix Wk for user k is the k^{th} column of $H^{\ddagger}$. An alternative method is to use regularized channel inversion, also called minimum mean squared error precoding or MMSE Beamforming. In this case, s is processed by the matrix $H^H\left(HH^H + \frac{K}{P}I\right)^{-1}$, where ρ is the SNR. Both methods are somewhat sensitive to errors in the channel estimate, and can require a great deal of power to perform the channel inversion with badly conditioned channels, which can lead to noise enhancement at the receivers. Assuming equal power allocation over the users with none correlated. The achievable sum rate is given by

$$R_{ZF} = \sum_k log_2(1 + \frac{P}{K\sigma^2}|h_k w_k|^2)\ k = 1,2,3 \ldots K \qquad (5.16)$$

5.5.3 Sum Rate of Block Diagonalization

Block diagonalization (BD) is a generalization of channel inversion techniques when there are multiple antennas at each receiver. When BD is employed, the precoding matrices Wj,Hj are chosen such that Hk*Wj = 0, $H_K \neq$ j, thus eliminating the multi-user interference so that $K = H_K W_K S_K + n_K$. This requires determining an orthonormal basis for the left null space of the matrix formed by stacking all Hj , □j≠k matrices together. The transmitter requires that the number of transmit antennas is at least the sum of all users' receive antennas to satisfy the dimensionality constraint required to cancel interference for each user [*]. The sum rate of BD with equal power allocation is given by

$$R_{ZF} = \sum_k log_2 \left| I + \frac{P}{K} H_k W_k W_k^H H_k^H \right|, k = 1,2,3 \ldots K \qquad (5.17)$$

5.5.4 Numerical Results

In Fig 5.19, we compare the performance of a ZF precoder, with BD based on the empirical cumulative density function (CDF) of the sum rate. As shown, the CDF of the sum rate of the two UEs with one receive antenna each. We show results for i.i.d. frequency-flat Rayleigh fading channel as well as the measured channel. The average SNR is fixed to 10dB for each user. BD gains over 2 bits/sec/Hz compared to CI when the users are equipped with multiple antennas with different relay transmitted powers of 0, 10 and 20 dB.

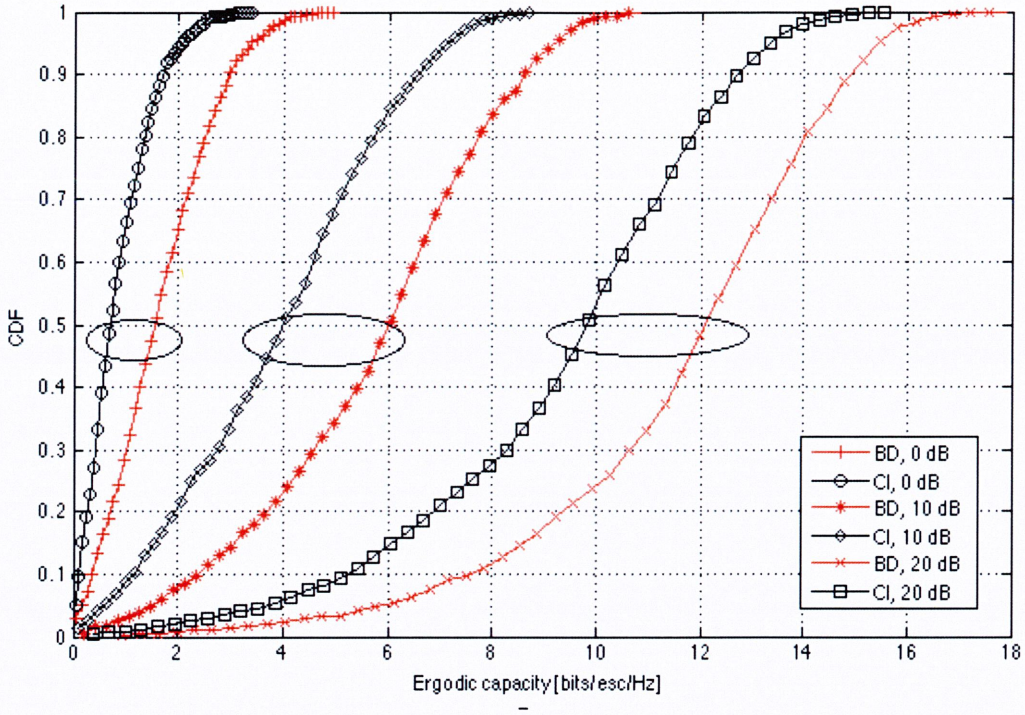


Figure 5.19, CDF versus Ergodic capacity of Relay MU-MIMO

5.6. Conclusion

Having introduced the Amplify and Forward MIMO Relay system earlier, this part discussed increasing the system capacity by implementing Filter Matrix Design techniques. The introduction of the relay node in the MIMO system will not result in increasing the system capacity as proven earlier. However the relay node serves as range extension to better serve the edge customers of the MIMO network. So increasing the system capacity can be done physically by adding more antennas to the system as seen when multiplying the number of antennas and its effect on the system capacity. Alternatively, a more intelligent design of the gain matrix would result in an increase in the system capacity. This however comes on the expense of an added cost and design complexity. Three Filter Matrix Design techniques were discussed. The Blind Amplify, the Singular Value Decomposition and the Matched Filter Design were discussed. The SVD being the most complex in

implementation as it involves SVD calculations and multiple matrix inversions had a performance succeeded by the MF, which is relatively simpler. The blind amplify is the simples of them all and provides no advantage over the normal AF MIMO Relay implementation. So it could act as the reference ground when comparing all the other designs.

Chapter 6

Conclusions

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Chapter 6

Conclusions

6.1 Summary

This thesis examined the channel capacity, system performance, and coverage analysis and relay design issues of MIMO Relay systems under different channel conditions including the effects of multipath and fading correlation. The aim was to apply a spatial temporal channel models that can be used in the simulation of different Relay MIMO configurations in particular for cellular communication systems. In this chapter, Conclusions driven from the numerical results of this thesis are presented in Section 6.1. Some suggestions for future work are recommended in Section 6.2.

6.2 Conclusion

One of the main objectives of this thesis was to apply a realistic channel model in the simulations of MIMO Relay systems that can fully characterize the fading correlation properties of a cellular communications environment. An outdoor stochastic spatial clustered (OSSC) channel model (Mangoud, 2009) is adopted, as it is a correlation-based analytical model, which describes different spatial conditions about scatterers and includes in the propagation environment and antenna geometry.

In this model, the groups of scatterers are modeled as multi-clusters located around the antenna arrays. Three different Power Azimuth Spectrum (PAS) were assumed with uniform, truncated Gaussian and truncated Laplacian distributions can be used. This model was presented in chapter 3for both Uniform Linear Array(ULA) and Uniform Circular Array (UCA) geometries Path Loss model that is compatible with SCM model suits the cellular system is included in the channel model to be used for relay coverage analysis. This model is an extension to the simple correlation model for the relay configurations in MIMO Relay outdoor cellular systems.

Secondly, The effect of the relay position, AS variation and transmitted power ratio between relay and destination directions on the AF MIMO relay system capacity has been investigated in this thesis. The system capacity will be highest when the relay is positioned at an equal distance from the source and destination. Moving the relay closer to the destination has a slightly better capacity rather than locating the relay closer to the source.

AS variation affects the system capacity to a certain level. The system capacity is then limited by other system parameters. Also, the effect of varying the AoA at the Relay and Destination on the system capacity was presented. From the numerical results it is concluded that if the destination is far enough away from the source to make their central area NLOS to both of them, it is better to place the relay in the region close to source. The results are compared with the published work in for validation and it is found in good agreement. Results, for a single relay node, showed placing the relay at an equal distance from the source and destination results in the highest system capacity. However, placing the relay closer to the destination with more power directed towards relay

than the direct link results in higher system capacity. The variation of the AS on the system capacity revealed if the signal arrives with higher AS exceeding a certain value, this any effect on the system capacity.

It is concluded that MIMO Relay AF systems are more immune to system parameters changes on their source to relay and relay to destination links. Their most vulnerable link is the source to destination. Also, The antenna spacing affects the system capacity significantly when the spacing is less than a certain threshold. After this threshold, the antenna spacing does not affect the system capacity. For a ULA antenna structure with two antennas the threshold antenna spacing is 0.4λ. A four antennas array has a higher threshold, 1.5λ. UCA antenna array has a different threshold for the same antennas count. Moreover, The Relay Node location significantly affects the system capacity for MIMO Relay AF systems. In general, the antenna should be place halfway through closer to the destination to maintain high system capacity. Introducing the source to destination link enhances the system coverage over the two hop AF system, i.e. P4.

Thirdly, having introduced the Amplify and Forward MIMO Relay system earlier, this part discussed increasing the system capacity by implementing Filter Matrix Design techniques. The introduction of the relay node in the MIMO system will not result in increasing the system capacity as proven earlier. However the relay node serves as range extension to better serve the edge customers of the MIMO network. So increasing the system capacity can be done physically by adding more antennas to the system as seen when multiplying the number of antennas and its effect on the system capacity. Alternatively, a more intelligent design of the gain matrix would result in an increase in the system capacity. This however comes on the expense of an added cost and design

complexity. Three Filter Matrix Design techniques were discussed. The Blind Amplify, the Singular Value Decomposition and the Matched Filter Design were discussed. The SVD being the most complex in implementation as it involves SVD calculations and multiple matrix inversions had a performance matched by the MF, which is relatively simpler. The blind amplify is the simples of them all and provides no advantage over the normal AF MIMO Relay implementation. So it could act as the reference ground when comparing all the other designs.

At good Signal to Noise Ratio the SVD yields the highest system capacity them the blind at the optimum distance them the MF. At non-optimum relay locations the MF outperforms the blind amplify but not the SVD. Surprisingly, the MF outperforms both the SVD and the blind amplify at low SNR values. This hints that the MF better serves users at the edges of the network where the SNR is typically low.

6.2 Future Work

This section describes some possible extensions to the research presented in this thesis.

- In this thesis, it was shown that two-hop AF relay was considered, multihop Relay could be considered with different channel model for higher frequency especially in the range of millimeter waves which is a trend for the 5G networks.
- The work presented in this thesis only focused on the impact of fading correlation on the performance of a MIMO Relay system. Real measurement campaign could be performed and compared with the simulation model.

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الملخص

في هذه الأطروحة، تم دراسة أداء نظام الاتصالات اللاسلكية المستخدم للمحطات التقوية الناقلة للأشاراتو التي تستخدم الهوائيات ذات المدخلات والمخرجات المتعددة و عندما يكون انتشار الأشارات في قناة الاتصال مترابطة و مصحوبة بظاهرة الخفوت.

يقترح الباحث في هذة الأطروح نموذج قناة اتصال واقعية خارجية ذات الخصائص المكانية الإحصائية عنقودية وتم استخدام هذا النموذج في محاكاة نظام نظام الاتصالات اللاسلكية المستخدم للمحطات التقوية الناقلة للأشارات و التي تستخدم الهوائيات ذات المدخلات والمخرجات المتعددة و قد روعي ان يكون هذا النموذج لقناة الاتصال متوافق مع نموذج المكاني القياسي المستخدم لشبكات و تطبيقات الاتصالات الخلوية. . بعد تقديم النموذج المحاكي للنظام تمت دراسة تأثير تغيير عدد الهوائيات و مكونات محطات التقوية علي اداء و علي سرعة نقل البيانات في الشبكة.

أيضا، يتم تقديم تحليل و دراسة مفصلة عن المحتويات المختلفة لمحطات التقوية المستخدمة و تصميم المرشح المصفوفي المكون الاساسي بها. كما تتم مقارنة أداء و القدرة المتوسطة لنظام الاتصالات اللاسلكية المستخدم للمحطات التقوية الناقلة للأشارات و التي تستخدم الهوائيات ذات المدخلات والمخرجات المتعددة عند توظيف المرشحات الخطية سواء بالهوائيات الخطية اوالدائرية.تناول هذا الجزء من الاطروحة تصميم مرشح للوصلة الهابطة لنظام التتابع اما عن طريق تجزئ القيمة المفردة أو التصفية المتطابقة.

وعلاوة على ذلك، تمت دراسة طرق التتابع الخطية لتوجية الأشعاعات نظام الاتصالات اللاسلكية المستخدم للمحطات التقوية الناقلة للأشارات و التي تستخدم الهوائيات ذات المدخلات والمخرجات المتعددة و المتعدد المستخدمين. يستخدم تكوين الشعاع أساسا للقضاء على التدخل من المستخدمين الغير معنيين، مثل طريقة القناة المعكسة و الكتلة القطرية. و تختتم الأطروحة بعرض و مقارنه نتائج معدلات الخطأ ومعدل متوسطالقدرة لمختلف طرق التوجية للنظم النتعددة المستخدميين تحت قناة المترابطة.

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تحليل أداء نظم الإتصالات المستخدمة لتقنية محطات التقوية ذات المدخلات و المخرجات المتعددة

أطروحة مقدمة كجزء من متطلبات الحصول على درجة الماجستير
في الهندسة الكهربائية و الإلكترونية

إعـداد

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