

**Relay Positioning for Energy Efficiency and Improved Performance of
Cooperative Wireless Networks**

by

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Abstract

Cooperative communications in wireless networks have gained much interest due to their ability to mitigate the effect of fading in wireless networks by achieving spatial diversity. One of the techniques used in cooperative communication systems, is by relaying data through relay nodes. The number of base stations (BS) in a network is small, so many users who are far from them require more power to transmit data. One issue is to find where to position a limited number of available relay nodes (RN) to reduce energy consumption of user nodes.

Two ideas are proposed in this thesis as solutions to the above problem. First, we use a greedy algorithm to determine the position of the relay nodes. In this method, relays are placed at half way distance between the farthest user and the base station. Second, we use an approximation algorithm for positioning the relay nodes. In this method, relays are positioned at near optimal locations in an iterative manner. The algorithm tries to position the relay nodes at the periphery of the base station's coverage area. We compare both the algorithms in terms of average energy consumption, average number of hops for a packet to reach the base station and average r-cover which is the coverage radius of RN. The approximation algorithm is shown to outperform the greedy algorithm in all the above mentioned metrics.

We then investigate the application of two capacity enhancement techniques - Receiver Diversity (RD) and Transmitter zero forcing (TZF) - in cooperative wireless networks. The objective is to provide an analysis for the comparison of TZF and different RD strategies such as Maximal Ratio Combining (MRC), Equal Gain Combining (EGC) and Selective Combining (SC). We find that there is no case of dominance for the two techniques. TZF can be used when interference is weak while RD can be adopted when the interference is high. There always exists a trade-off between RD and TZF in network performance.

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List of Abbreviations

Auburn Auburn University

LoA List of Abbreviations

Chapter 1

Introduction

Cooperative communications allow communication terminals in a network to listen and help the information transmission of each other, by taking advantage of the broadcast nature of wireless communication. It can be used in improving network connectivity, enhancing power and spectral efficiency and improving communication reliability.

The basic ideas behind cooperative communication can be traced back to the groundbreaking work of Cover and El Gamal on the information theoretic properties of the relay channel [1]. This work analyzed the capacity of a three node network consisting of a source, a destination, and a relay and determined the upper and lower bounds on its channel capacity. In cooperative communication, a number of relay nodes are assigned to help in forwarding a users transmission to its destination. Various cooperative schemes such as decode and forward, amplify-and-forward, selective relaying and incremental relaying have been designed for enhancing the performance of wireless communication networks [2] - [3].

Most recently, cooperative communication has been adopted in Long Term Evolution (LTE) Advanced network. LTE is the globally embraced wireless communication standard adopted by smart phones and tablets manufacturers [40].

1.1 Cooperative Relay Networks

In a cooperative relay system, sources first transmit their data to the relay nodes (RN). Each RN then processes and forwards its received data to the destination nodes following some cooperation protocols. With the received signal from the RNs, the destinations decode the data from their corresponding sources.

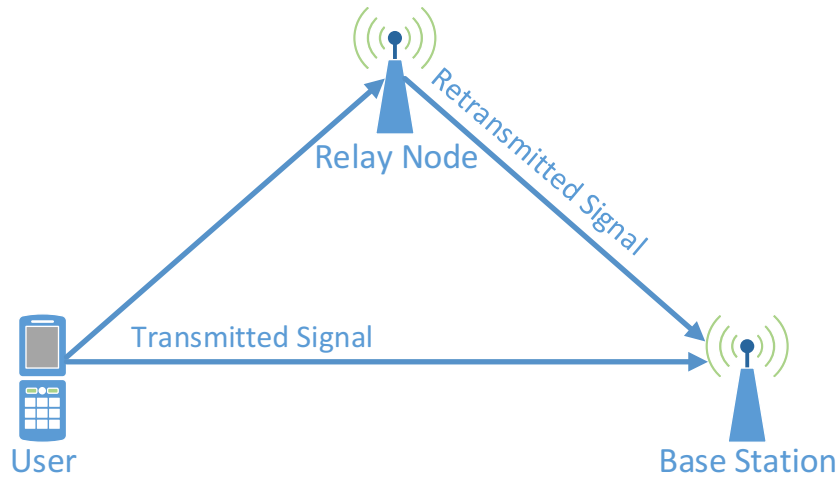


Figure 1.1: Simple Cooperative System

A simple cooperative system consisting of a source, a relay and a destination is shown in Figure 1.1. The RN is connected to the base station (BS) and functions like a BS, but is less expensive. Users can connect directly to the BS or indirectly via a RN. By relaying the packet from user to BS via RN, the long distance communication is broken to short distance links. Since the energy consumption is proportional to the distance, shorter distance communication (RN based) requires less energy than direct communication. RNs, however, have small coverage area compared to the BS. With large number of RNs being deployed in the network the delay for a packet to reach BS increases. As a result good placement strategy of the RNs is required to achieve spatial diversity and to reduce energy consumption of the terminal users.

1.2 Transmitter Zero Forcing and Receiver Diversity

Interference in traditional wireless networks has been considered harmful. Multiple concurrent transmission techniques (e.g., zero forcing, interference alignment and distributed MIMO) [17] - [18], are proposed in which multiple senders jointly encode signals to multiple receivers so that interference is aligned or canceled and each receiver is able to decode its desired information.

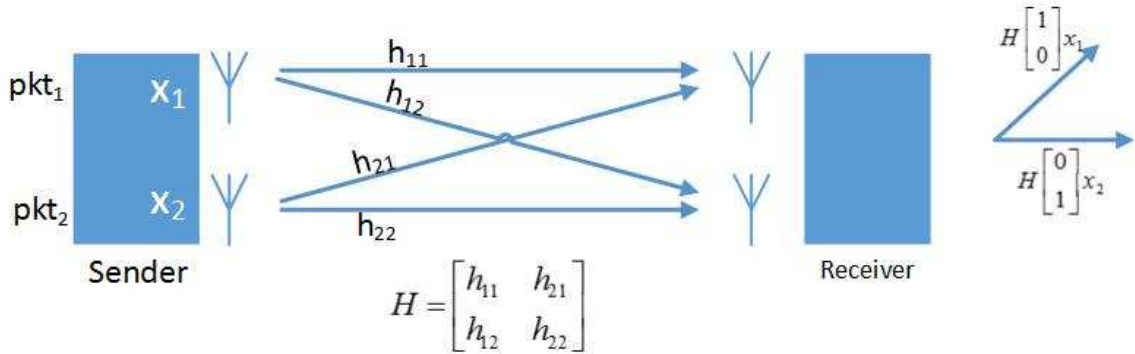


Figure 1.2: Transmitter Zero Forcing

In [31] - [32], when the number of antennas in sender and receiver are 2 as shown in Figure 1.2. If we represent the signals corresponding to packets 1 and 2 as x_1, x_2 respectively, ignoring noise, we have that the received signals at receiver antennas 1 and 2 are $y_1 = h_{11}x_1 + h_{21}x_2$, and $y_2 = h_{12}x_1 + h_{22}x_2$, respectively. Here h_{ij} is a complex number whose magnitude and phase represent signal attenuation and delay from sender antenna i to receiver antenna j . The receiver estimates the channel H as shown in Figure 1.2. It can recover x_1 and x_2 by multiplying H^{-1} , the inverse of H , with the received signal vector Y ($Y = [y_1 y_2]^T$ where $[\cdot]^T$ represents vector transpose). By rewriting the received signal as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = H \begin{bmatrix} 1 \\ 0 \end{bmatrix} x_1 + H \begin{bmatrix} 0 \\ 1 \end{bmatrix} x_2 \quad (1.1)$$

we can view the received signal as the sum of two scaled vectors. The decoding of each packet, say x_1 , can be viewed as projecting $H \begin{bmatrix} 1 \\ 0 \end{bmatrix}^T x_1$ onto a vector that is orthogonal to the vector $H \begin{bmatrix} 0 \\ 1 \end{bmatrix}^T$ carrying the interfering signal x_2 .

If the sender knows the channel H , the sender can multiply H^{-1} with X and send the resulting signal X' . Again, ignoring noise, we can verify that the receiver antenna 1 will receive only x_1 , no mixing of x_2 ; similarly, receiver antenna 2 will receive only x_2 . This technique is often called *zero forcing*.

The basic concept of receiver diversity [33], is that the receiver has more than one version of the transmitted signal available, and each version of transmitted signal is received through a distinct channel. When several versions of the signal, carrying the same information, are received over multiple channels that exhibit independent fading with comparable strengths, the chances that all the independently faded signal components experience the same fading simultaneously are greatly reduced. There are three common technique to diversity combining, viz Selective Combining (SC), Maximum Ratio Combining (MRC) and Equal Gain Combining (EGC).

Further explanation of RD and TZF can be found in chapter 3.

1.3 Objective of this Thesis

Here our objective is to reduce the energy consumption at the user node assuming the number of relays in the system is known. First, we use a greedy algorithm to deploy the relay nodes in the system. In this method the relays are placed at half way distance between the farthest user and the base station. The other method proposed in this thesis - the approximation algorithm, is a 2-approximation [15], for the center selection problem. This algorithm tries to position the relay at the periphery of the base stations coverage area.

Next, we investigate the performance of TZF and RD in cooperative relay networks. We formulate the problem of cellular network with multiple relay nodes and two users. Then we derive system capacity for TZF and RD and evaluate the capacity of the system by varying the distance between the user and relay, and also by varying the transmit power at the relays.

The main contributions of this work consist of:

- Comparison between the greedy and approximation algorithms and determine the best algorithm for positioning the relay nodes to reduce energy consumption,
- Comparison between RD and Transmitter Zero Forcing in cooperative relay networks,

- Deriving a closed-form expression for influence of RD and Transmitter Zero Forcing on network throughput
- The implementation of the proposed relay node placement algorithms and capacity enhancement techniques using Matlab.

1.4 Organization

This work is divided into two parts. The first part discusses the relay node placement strategies to reduce energy consumption for the users and the second part discusses the comparative study of the capacity enhancement techniques applied in a cooperative relay network. The related work and the introduction required for the respective topics are discussed before the idea is presented. As a result, a separate literature review section is necessitated. A conclusion section summarizes the finding in the study of cooperative wireless networks.

Chapter 2

Relay Node Placement for Energy Saving in Cooperative Networks

In cooperative communication, wireless nodes assist each other in information delivery, with the objective of gaining greater reliability and efficiency than they could obtain individually. Cooperative communication represents another new paradigm for wireless communications [16].

A number of relay nodes is integrated in the single hop cellular network [4] and [40], to improve the performance, fairness, energy, throughput etc. These benefits make relay node an asset to the network. The location for installing the relay node must satisfy conditions like quality of the link to the base station, power supply, Signal to Interference plus Noise Ratio (SINR). Finding the best relay node location in a network is an important task. It should be noted that with increase in the number of relays the delay for the packets to arrive at its destination in the network increases i.e, the number of hops for a packet to reach the destination increases which increases the delay. Deploying relay nodes at the optimal position minimizes the number of relay nodes required to effectively cover the network, improve the performance and reduce the energy consumption for the users.

The goal is to find a set of relay node (RN) positions, so that the maximum distance from a user to its nearest RN is minimized.

2.1 Literature Review

The relay node placement problem can be found in different applications like wireless sensor networks [5], heterogeneous networks [6], wireless local area networks [7] and 802.16j networks [8].

The cost optimal deployment of the RN and access points (AP) for wireless local area network (WLAN) are discussed in [9]. The methodology proposed can determine and compare the most cost efficient deployment mixes of APs and RNs. A comparison between deployment of micro APs and RNs along with macro APs is studied. The result shows that deploying RN is more cost efficient. In [10], location of the RNs depends on the demanded telegraphic distribution. In the proposed method, the mobile station (MS) constructs a database from the location pattern and teletraffic pattern. This scheme provides teletraffic demand with higher spatial resolution which is used for RN location planning. In [11], the relays are positioned to achieve full diversity gain and minimize error probability. The scheme proposed in [11] places the relays based on the SINR between the source and destination. In [6], RN placement is based on the physical distance between the nodes and BS. The algorithm arranges the RNs to optimize connectivity at disadvantaged location and uses both cellular and ad hoc medium resource. In [12], RN placement is dependent on link quality and power allocation.

The algorithms proposed in this thesis are also distance based in selecting the RN position. When the number of RNs that can be deployed in the network is predetermined, the algorithm gives the best possible location for positioning the RNs, so that the users energy consumption is less while minimizing the number of hops required for the packets to reach a BS.

2.2 System Model

We consider a network with M base stations (BS) (indexed from 1 to M) and N end users (indexed from 1 to N) randomly deployed within a huge area. Due to the deployment cost of BSs, the number of BSs is very small and many devices far away from BSs require a large amount of power to transmit data. In order to address this problem, we would place K relay nodes to help users to deliver their data to the destination and reduce their power consumption.

2.2.1 Path Loss Model

The complexity of signal propagation makes it difficult to obtain a single model that characterizes path loss accurately across a range of different environments. In order to capture the essence of signal propagation and seek a trade off between complexity and approximation accuracy, we adopt the following simplified model for path loss [13], as a function of distance:

$$P_r \text{dBm} = P_t \text{dBm} + \kappa \text{dB} - 10\gamma \log_{10}\left(\frac{d}{d_0}\right) \quad (2.1)$$

where P_r , P_t , and d are received power, transmit power, and distance, respectively. κ is a unit less constant that depends on the antenna characteristics and average channel attenuation, d_0 is a reference distance, and γ is the path loss exponent. κ is given by

$$\kappa \text{dB} = 20 \log_{10}\left(\frac{\Lambda}{4\pi d_0}\right) \quad (2.2)$$

where Λ is wavelength of radio wave. Path loss exponent γ , is a function of carrier frequency, environment, obstruction etc. Typically ranges from 2 to 8. For a free space propagation model γ is 2 and for two ray propagation model γ is 4. To meet the Quality of Service (QoS) requirements, we assume that the received power P_r should be greater than certain threshold.

Then, the transmit power P_t becomes a function of distance d . Therefore, reducing power consumption is equivalent to reducing transmission distance.

2.2.2 Routing Model

Since our objective is to reduce transmitted power, we assume that each relay node is connected to its nearest BS and each user is connected to its nearest BS or relay node (RN). Denote \mathcal{A} , \mathcal{R} and \mathcal{U} as the set of BSs, RNs and user nodes, respectively. Then, the BS m^* that relay node k is connected to is given by:

$$m^* = \arg d(k, \mathcal{A}) = \arg \min_{m \in \mathcal{A}} d(k, m) \quad (2.3)$$

where $d(k, m)$ is the distance between BS m and user k . We assume the distance is symmetric: i.e. $d(k, m) = d(m, k)$. Similarly, the BS or RN that user n is connected to is given by:

$$i^* = \arg d(n, \mathcal{A} \cup \mathcal{R}) = \arg \min_{i \in \mathcal{A} \cup \mathcal{R}} d(n, i) \quad (2.4)$$

2.2.3 Objective

We say that BS's and RN's form an r -cover if each user is within distance at most r from one of BS or RN which implies $d(n, \mathcal{A} \cup \mathcal{R}) \leq r$ for all users $n \in \mathcal{U}$. The minimum r is called the r -cover of the union \mathcal{A} and \mathcal{R} and is denoted as $r(\mathcal{A} \cup \mathcal{R})$. Since the locations of BS's are fixed, we can simplify $r(\mathcal{A} \cup \mathcal{R})$ as $r(\mathcal{R})$. Our objective is to select a set \mathcal{R} of K RN's for which $r(\mathcal{R})$ is as small as possible.

2.3 Solutions for Relay Node Placement in Cooperative Networks

2.3.1 A Simple Greedy Algorithm

Simple greedy algorithm works as follows. It places the first relay node (RN) at halfway between the base station (BS) and its furthest user, and then keeps on adding RN's so as

to reduce the r - *cover* (coverage radius of RN) each time. The algorithm is presented in table 2.1.

Table 2.1: A Simple Greedy Algorithm

1:	Initialize \mathcal{A} and \mathcal{U}
2:	Let $\mathcal{R} = \phi$
3:	While $ \mathcal{R} \leq K$
4:	Find the BS-user or RN-user pair with minimum distance: $\{i^*\} = \arg \min_{i \in \mathcal{A} \cup \mathcal{R}, j \in \mathcal{U}} d(i, j)$
5:	Find i^* -user pair with maximum distance: $\{j^*\} = \arg \max_{i \in i^*, j \in \mathcal{U}} d(i, j)$
6:	Place RN c at the halfway point between i^* and j^* and add c to \mathcal{R}
7:	End while

It turns out that this algorithm is too simplistic to be effective. The RNs are selected based only on the longest distance. In some cases, it can lead to very poor performance.

2.3.2 An Approximation Algorithm with Known Optimal Radius

k-center problem - Given n cities with specified distances, one wants to build k warehouses in different cities and minimize the maximum distance of a city to a warehouse. In graph theory this means finding a set of k vertices for which the largest distance of any point to its closest vertex in the k -set is minimum.

Although the *k-center problem* is NP complete, there is a simple 2-approximation algorithm [14] - [15], that provides a *near optimal solution for the k-center problem*. Suppose we know that there is a set of K optimally deployed RN's, \mathcal{R}^* , with radius $r(\mathcal{R}^*)$. We need to find some set of K RN's whose radius is not much larger than $r(\mathcal{R}^*)$. It turns out that finding a set \mathcal{R} of K RN's with covering radius at most $2r(\mathcal{R}^*)$ can be achieved by our approximation algorithm in table 2.2.

Table 2.2: An Approximation Algorithm with Known Optimal Radius

1:	Initialize \mathcal{A} and $\mathcal{U}_0 = \mathcal{U}$
2:	Let $\mathcal{R} = \phi$ and $\mathcal{U}_1 = \phi$
3:	Move users whose $d(n, \mathcal{A}) \leq 2r(\mathcal{R}^*)$ from \mathcal{U}_0 to \mathcal{U}_1
4:	While $ \mathcal{R} < K$ and $\mathcal{U}_0 \neq \phi$
5:	$\mathcal{D}_j = \min_{i \in \mathcal{U}_1, j \in \mathcal{U}_0} d(i, j)$
6:	$\{j^*\} = \arg \max_{j \in \mathcal{U}_0} \mathcal{D}_j$
7:	$\{i^*\} = \arg \min_{i \in \mathcal{U}_1} d(i, j^*)$
8:	Add i^* to \mathcal{R}
9:	Move users whose $d(n, i^*) \leq 2r(\mathcal{R}^*)$ from \mathcal{U}_0 to \mathcal{U}_1
10:	End while
11:	If $\mathcal{U}_0 \neq \phi$ and $ \mathcal{R} = K$
12:	There is no set of K RN's with covering radius $r(\mathcal{R}^*)$
13:	End if

Lemma 1. *Any set of RN's, denoted by \mathcal{R} , returned by the algorithm in table 2.2 has covering radius $r(\mathcal{R}) \leq 2r(\mathcal{R}^*)$*

Proof. Figure 2.1 gives us an idea of the approximation algorithm. We must show that $r(\mathcal{R}) \leq 2r(\mathcal{R}^*)$.

Let us assume, for the sake of contradiction, that $r(\mathcal{R}) > 2r(\mathcal{R}^*)$.

Let U be any site in $\{u_0, u_1, \dots, u_n\}$. Let $r^* \in \mathcal{R}^*$ be the center closest to U . Similarly, let $r \in \mathcal{R}$ be the center closest to r^* .

Then, by the triangle inequality, we must have $dist(U; \mathcal{R}) \leq dist(s; r^*) + dist(r^*; r)$.

We know that, $dist(U; r^*) \leq r(\mathcal{R}^*)$ and $dist(r^*; r) \leq r(\mathcal{R}^*)$.

Therefore, we must have

$dist(U; \mathcal{R}) \leq 2r(\mathcal{R}^*)$, which implies that $r(\mathcal{R}) \leq 2r(\mathcal{R}^*)$.

This is a contradiction, and, therefore, our assumption must be incorrect.

Hence $r(\mathcal{R}) \leq 2r(\mathcal{R}^*)$.

□

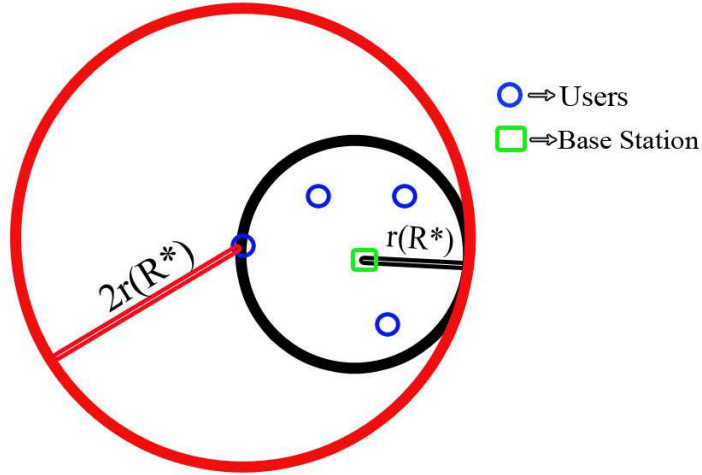


Figure 2.1: Approximation Algorithm

2.3.3 An Approximation Algorithm with Unknown Optimal Radius

We can start with some guesses about the optimal radius. According to the design of the algorithm in table 2.2, one of two things will happen. Either we find a set of RN's or we conclude that there is no solution. In the first case, we can lower our guess on the radius. In the second case, we can raise it. This makes us to perform a binary search on the radius. This algorithm is described in table 2.3

Table 2.3: An Improved Algorithm with Unknown Optimal Radius

1:	Initialize $r_0 = 0$ and $r_1 = \max_{i \in \mathcal{A}, j \in \mathcal{U}} d(i, j)$
2:	While $ r_1 - r_0 > \delta$
3:	Set $r = (r_1 + r_0)/2$ and run the algorithm in table 2.2
4:	If there is no solution
5:	$r_0 = r$
6:	Else
7:	$r_1 = r$
8:	End if
9:	End while

The algorithm stops when two estimates, r_0 and r_1 , are close to each other. The solution $2r_1$ is a 2-approximation to the optimal radius.

2.4 Simulation Results

We performed simulations using MATLAB to study the performance of the proposed algorithms. The following system model is used. We created a network area of 100x100, the number of base stations (BS) in the network is 3 and the number of Users in the network are 100. Both Users and BSs in the network are uniform randomly distributed. The simulations are done multiple times and the average r - cover, number of hops and energy consumption are determined to evaluate the performance of the proposed algorithms.

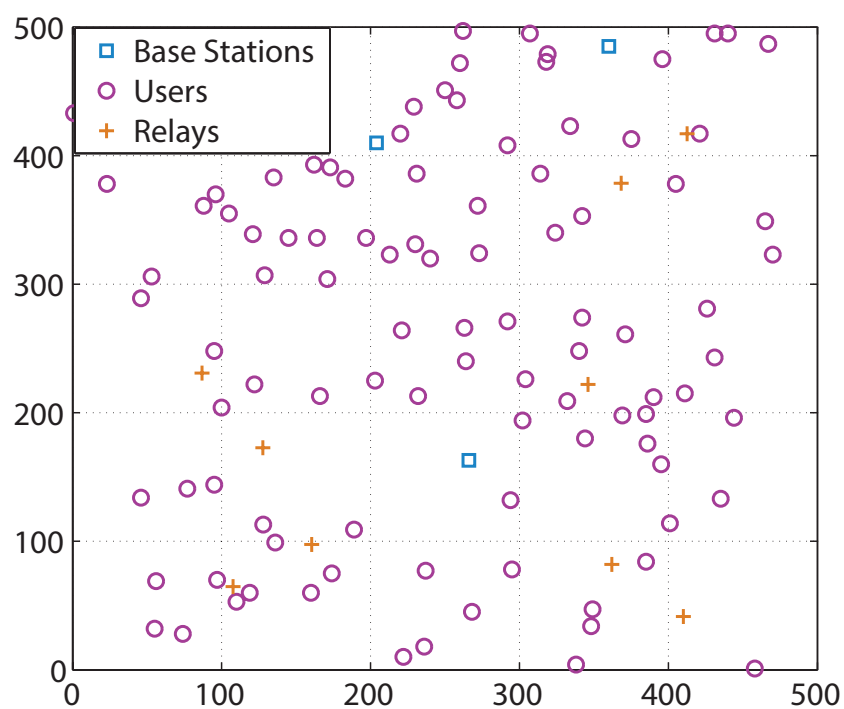


Figure 2.2: Placement of Relay Nodes using Greedy Algorithm

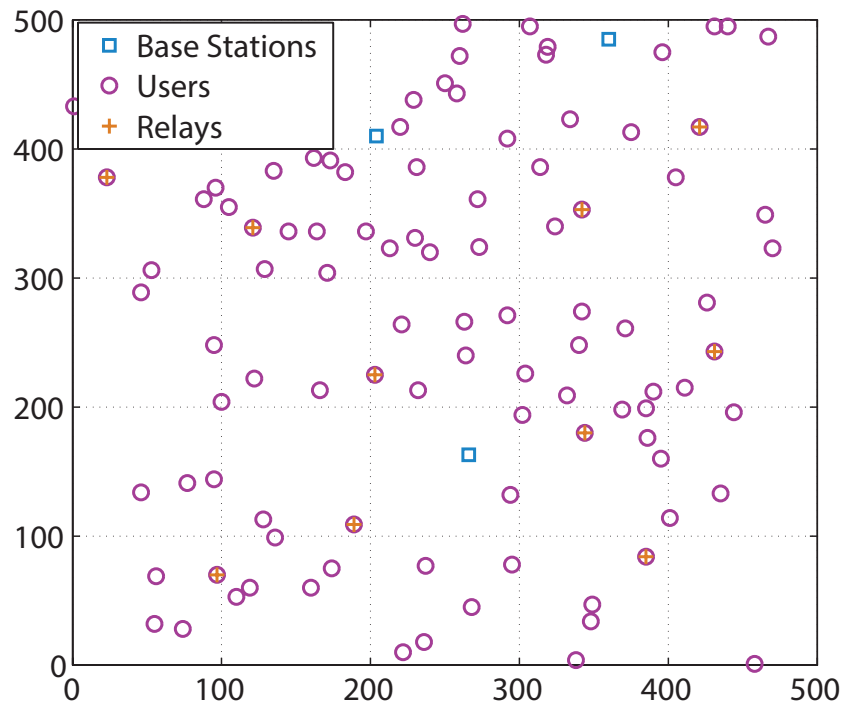


Figure 2.3: Placement of Relay Nodes using Approximation Algorithm

Figure 2.2 and Figure 2.3, show the placement of the $K(\text{Number of relays}) = 10$ relay nodes when greedy algorithm and approximation algorithm are used, respectively.

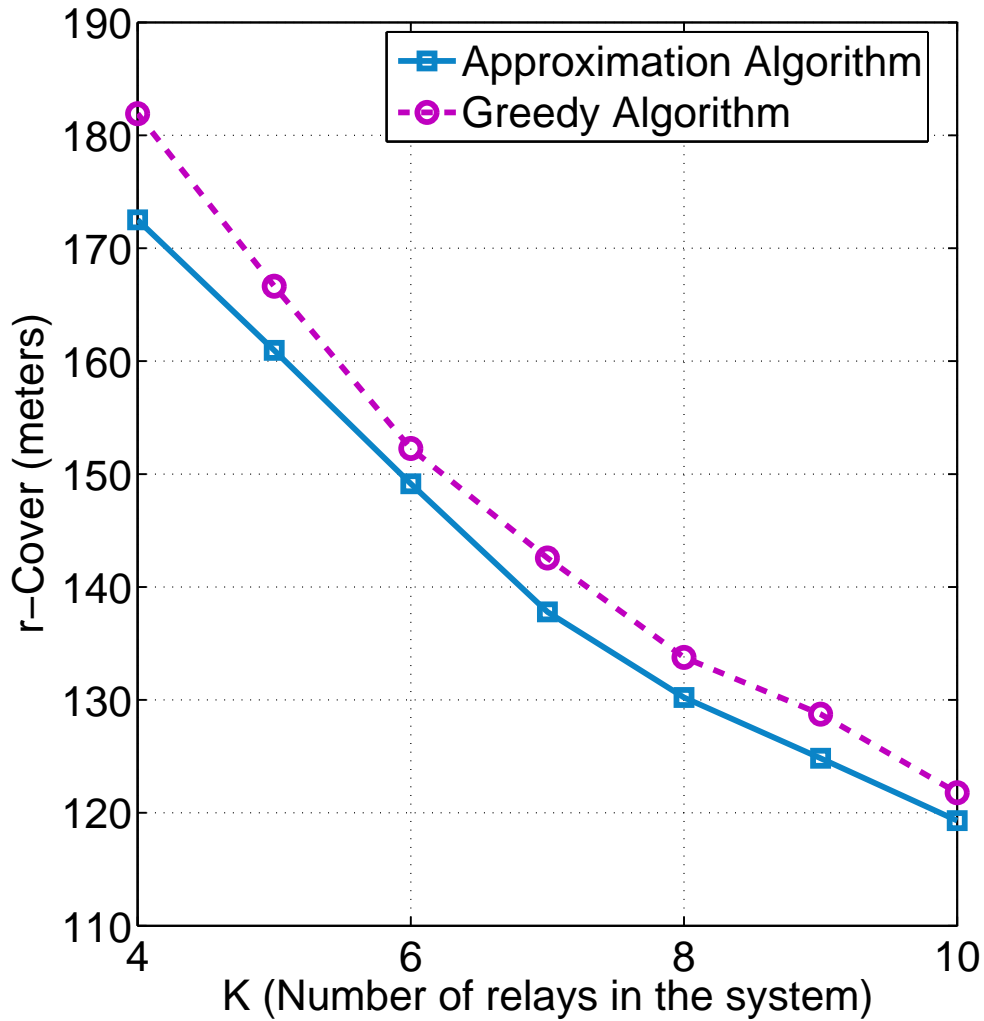


Figure 2.4: Number of Relays vs. Average r-cover

In Figure 2.4, we examine the $r - cover$ value for the two algorithms. It can be seen that the approximation algorithm has smaller $r - cover$ value compared to the greedy algorithm. This is due to the near optimal positioning of the relay nodes. Smaller $r - cover$ value means the users need to spend less energy to send their packet to the relays. K (the number of relays) in the system is varied from 4 to 10. It can be seen that, as the number of relays allowed in the system increases the difference $r - cover$ value between the two algorithm decreases.

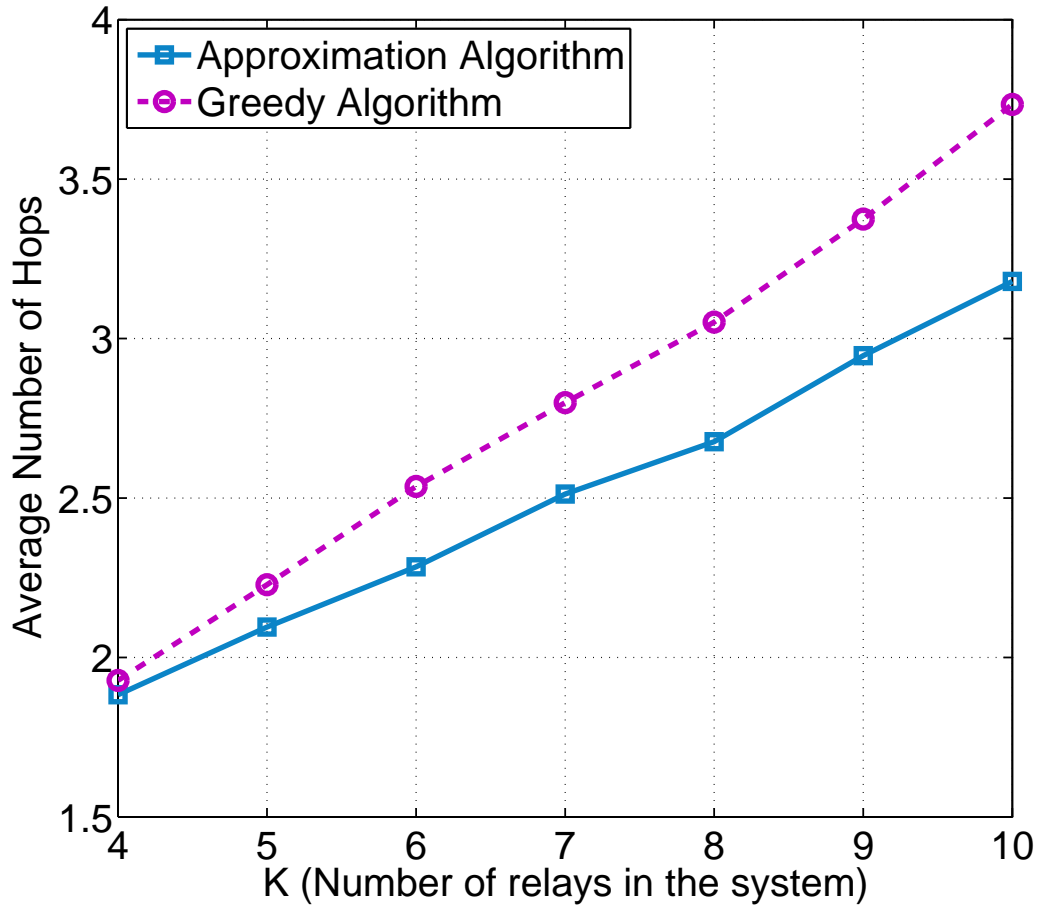


Figure 2.5: Number of Relays vs. Average Number of Hops

In Figure 2.5, we examine the average number of hops for the two algorithms for transmitting a packet from a user node to a BS. It can be seen that, when approximation algorithm is used, it takes less number of hops compared to the greedy algorithm. Less number of hops means less time delay for a packet to reach the destination from the users. For different K relays ($K = 4$ to 10) in the system, the average number of hops for the user is calculated and it is evident that, for different number of relays in the system the approximation algorithm has better performance.

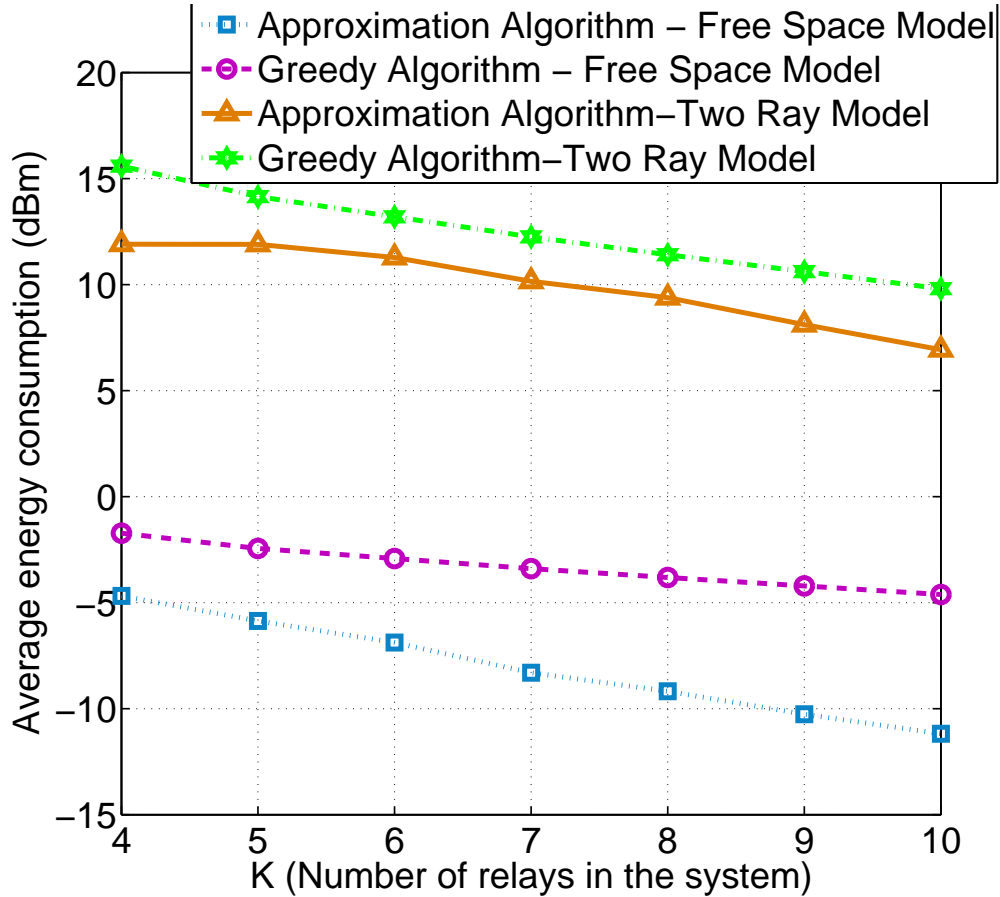


Figure 2.6: Number of Relays vs. Average Energy Consumption

In Figure 2.6, we examine the average energy consumption for the users in the system. It can be seen that the approximation algorithm saves more energy compared to the greedy algorithm. As the K ($K = 4$ to 10) value increases, the average energy consumption of the user decreases. In all cases, the approximation algorithm consumes less energy. This is because in the approximation algorithm the relays are placed at the periphery of the coverage distance of the BS, energy consumption for the users to reach the relays is less. Whereas in the greedy algorithm the relays are placed at half way points from the farthest user, which may not be an optimum distance for positioning the relays. The average energy consumption for both free space model and two ray model [13] are shown in Figure 2.6. In both the cases the approximation algorithm performs better than the greedy algorithm.

2.5 Summary of the Chapter

In this chapter, we studied the positioning of relay nodes (RN) to reduce energy consumption. We modeled the two relay node placement strategy i.e. greedy algorithm and approximation algorithm. In greedy algorithm the RNs are placed at halfway distance between the farthest user and base station (BS) whereas, in approximation algorithm the RNs are placed at the periphery of the coverage distance of the BS. We compared both the algorithms against various metrics such as average $r - cover$, average number of hops for a packet to reach the BS and average energy consumption at the user node. We found that the approximation algorithm performs better than greedy algorithm in all aspects.

Performance Evaluation of Transmitter Zero Forcing and Receiver Diversity in Cooperative Wireless Networks

3.1 Transmitter Zero Forcing

In the communications community, novel techniques such as zero forcing [17] and interference alignment [18] are proposed for simultaneous transmission and reception. If the sender knows the channel state information, the sender can precode the message and send the resulting signal to the receiver. Ignoring noise, the receiver receives only the intended message and there is no interference from other transmitters. This technique is called Transmitter zero forcing (TZF) [17].

Description of transmitter zero forcing is as follows [25]. Consider two transmitters (denoted as X_1 and X_2) and two receivers (denoted as R_1 and R_2). Let S_1 and S_2 be the signal corresponding to the packet to be sent to R_1 and R_2 , respectively. With transmitter zero forcing, the transmitter X_1 and X_2 send the compound signal $C_{1,1}S_1 + C_{1,2}S_2$ and $C_{2,1}S_1 + C_{2,2}S_2$, respectively, to the two receivers R_1 and R_2 simultaneously. Where $C_{i,j}$ is the precoding matrix. If the channel noise is ignored, the received signals Y_1 and Y_2 can be written as:

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} H_{1,1} & H_{1,2} \\ H_{2,1} & H_{2,2} \end{bmatrix}^T \begin{bmatrix} C_{1,1} & C_{1,2} \\ C_{2,1} & C_{2,2} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = H^T \times C \times S \quad (3.1)$$

Where $H_{i,j}$ is the channel gain from transmitter X_i to receiver T_j , for all i and j .

From (3.1), it can be seen that both the receiver can perfectly decode their signal if the precoding matrix C is chosen to be $[H^T]^{-1}$, i.e., the inverse of the channel gain matrix. With this technique, the transmitters are able to send packets simultaneously and the interference between the two concurrent transmission can be effectively canceled at both the receiver.

3.2 Receiver Diversity

Diversity combining [33], devotes the entire resources of the array to service a single user. Specifically, diversity schemes enhance reliability by minimizing the channel fluctuations due to fading. The central idea in Receiver Diversity (RD) is that different antennas receive different versions of the same signal. The chances of all these copies being in a deep fade are small.

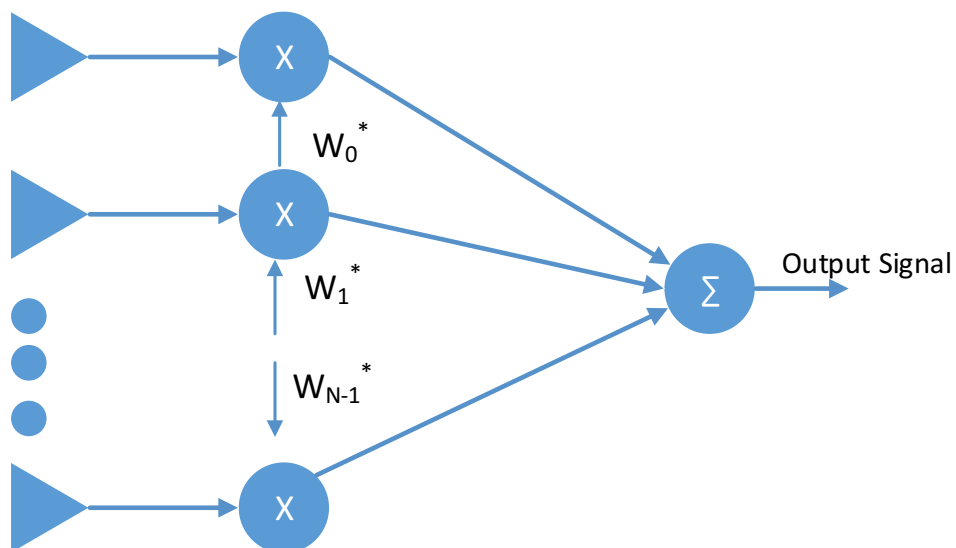


Figure 3.1: The Receiver in a diversity combining system

Figure 3.1 shows the working of a receiver in a diversity combining system. Within Receiver Diversity (RD) are three common techniques: Selective Combining(SC), Maximal Ratio Combining (MRC) and Equal Gain Combining (EGC). For all three schemes, the goal is to find a set of weights w , as shown in Figure 3.1. The weights are chosen to minimize the impact of fading for a single user. The three techniques differ in how this weight vector is chosen.

3.2.1 Selective Combining

Selective Combining (SC), is one of the simplest diversity techniques. The signals are not weighted and the receiver simply picks the signal with the largest SNR. The overall SNR is presented by:

$$\gamma^{SC} = \max_{i=1, \dots, M} \gamma_i \quad (3.2)$$

where γ_i is SNR at the i -th branch.

3.2.2 Maximal Ratio Combining

In Maximal Ratio Combining (MRC), all the branches are co-phased and individually weighed to provide the optimal SNR at the output. The signals are *co-phased* prior to summing in order to ensure all the branches are added in phase for maximum diversity gain. The weights assigned to each branch are optimized to maximize the overall SNR, denoted by γ^{MRC} , which can be expressed as:

$$\gamma^{MRC} = \sum_{i=1}^M \gamma_i \quad (3.3)$$

where γ_i is SNR at the i -th branch.

3.2.3 Equal Gain Combining

The signals are co-phased on each branch and then combined with equal weights. The overall SNR is given by:

$$\gamma^{EGC} = \frac{1}{M} \left(\sum_{i=1}^M \sqrt{\gamma_i} \right)^2 \quad (3.4)$$

where γ_i is SNR at the i -th branch.

3.3 Literature Review

In [19], the design of the zero forcing precoder in a Multiple Input Multiple Output (MIMO) system for maximizing performance under high signal-to-noise ratio (SNR) and low SNR regime has been studied. The computation cost of finding the optimal precoder is high. [20], focuses on the design of coordinated beam forming for zero forcing (ZF) in static channel and [21] focuses on design of coordinated beam forming for ZF in time varying channel for a MIMO system. In [22], the performance of Transmitter/Receive ZF in a MIMO system is studied by deriving the upper and lower bounds of the overall outage probability, their high signal-to-noise ratio approximations and diversity order. In [23], a modified ZF decoder for ill conditioned MIMO channels has been proposed. The proposed decoder overcomes the inherent noise enhancement in the zero forcing decoder by only considering the well conditioned elements of the channel. In [24], source nodes and the relays cooperate in choosing their precoding matrices and the filter coefficients, respectively, to perform a cooperative zero forcing.

Receive Diversity is a well known combining scheme that has been studied extensively. In [26], the impact of receive diversity on the error rate performance of a relay assisted cooperative scheme has been studied. It is shown that for a destination with N antennas, the maximum achievable diversity order under average power scaling and instantaneous power

scaling constraints are $N+1$ and $2N$ respectively. In [27] receive-diversity combining technique for Single Carrier - Frequency Division Multiple Access scheme (SC-FDMA), based cooperative relay systems is proposed which was shown to provide diversity gain in multipath channel environment without suffering from error propagation phenomena. In [28], the effects of phase noise on the performance of Maximum ratio combining-Orthogonal Frequency Division Multiplexing (MRC-OFDM), wireless system in Rayleigh fading channel are investigated. [29] describes the application of receive diversity in wireless sensor network for improving field estimation while ensuring energy and spectrum efficiency. In [30], RD for OFDM based broadband communication system is investigated. TZF and RD are two well-known physical layer technologies. To our knowledge, research on the comparison of TZF and RD has not been conducted yet.

3.4 System Model

In this section, we present the system models for both transmitter zero forcing and signal combining technologies. We consider two users, denoted as user 1 and 2, are located in a cellular network. The two users are so far away from the Base Station (BS) that they cannot successfully receive the signals from the BS directly. We further assume M ($M \geq 2$) relays are deployed to help the BS deliver data to the two users. The transmission between the BS and all relay nodes (RN) is assumed to be reliable. The channel is modeled as a time-slotted, block-fading channel [36]. In the following section, we analyze the network performance for two cases: receiver diversity and transmitter zero forcing.

3.4.1 Receiver Diversity

In receiver diversity, the signals from independent paths associated with multiple relays are combined to obtain a compound signal which is a weighted sum of the co-phased fading signals from different paths.

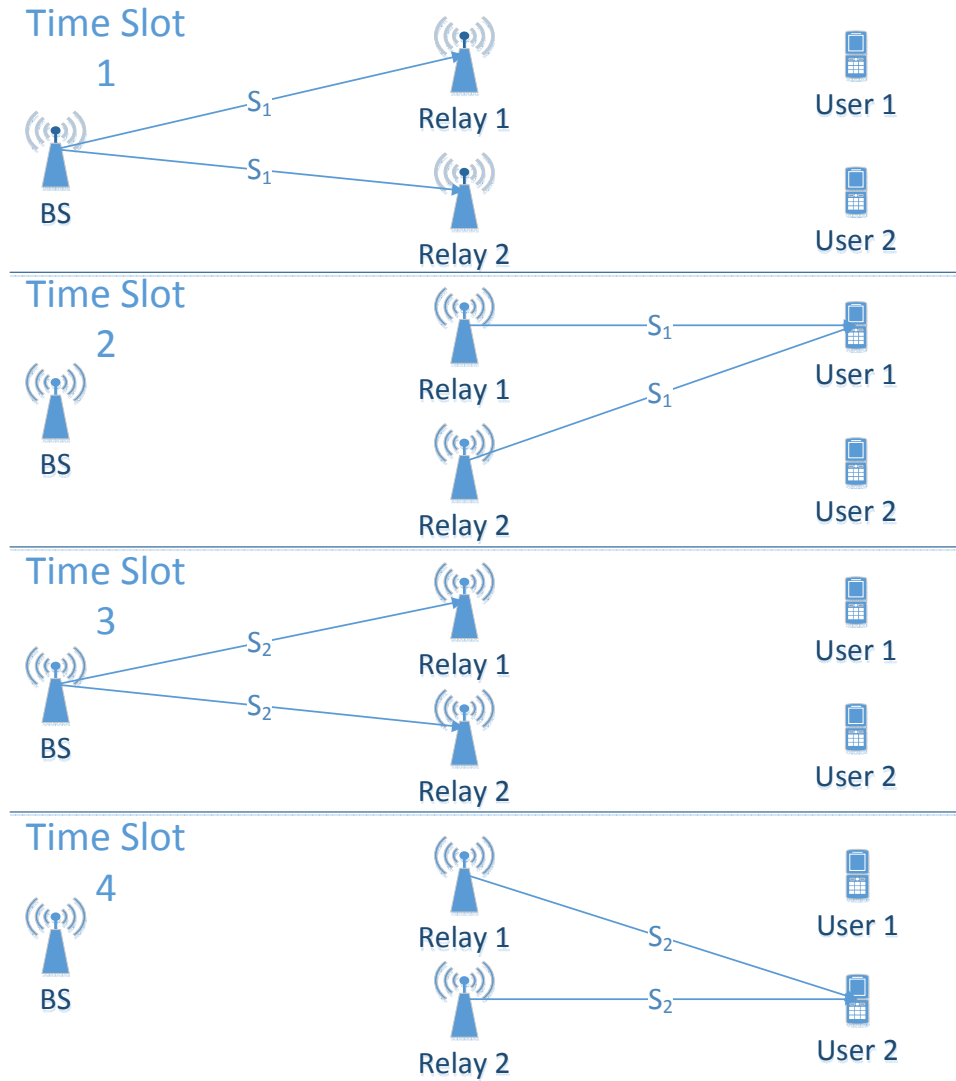


Figure 3.2: Receiver diversity

For receiver diversity, we need to use four time slots to send two packets to two users. In Figure 3.2, the BS sends packet 1 to all relays in the first time slot, and then, user 1 receives all signals from all relays in the second time slot. Packet 2 is sent to relays and user 2 in the third and fourth time slot, respectively. The total network throughput (C_{RD}) using Shannon capacity [37] - [38], is given by:

$$C_{RD} = \frac{B}{4} [\log_2(1 + \gamma_{RD}^1) + \log_2(1 + \gamma_{RD}^2)] \quad (3.5)$$

where B is channel bandwidth, γ_{RD}^1 and γ_{RD}^2 are received signal-to-noise ratio (SNR) for user 1 and 2 using receiver diversity, respectively.

3.4.2 Transmitter Zero Forcing

In Figure 3.3, the BS sends signal 1 and 2 to all relays in the first and second time slot, respectively. Let S_j ($j = 1, 2$) denote the signal to be transmitted to user j . In the third time slot, relays transmit compound signals to the two users simultaneously using transmitter zero forcing. In this way, the undesired signals are canceled at the receivers and

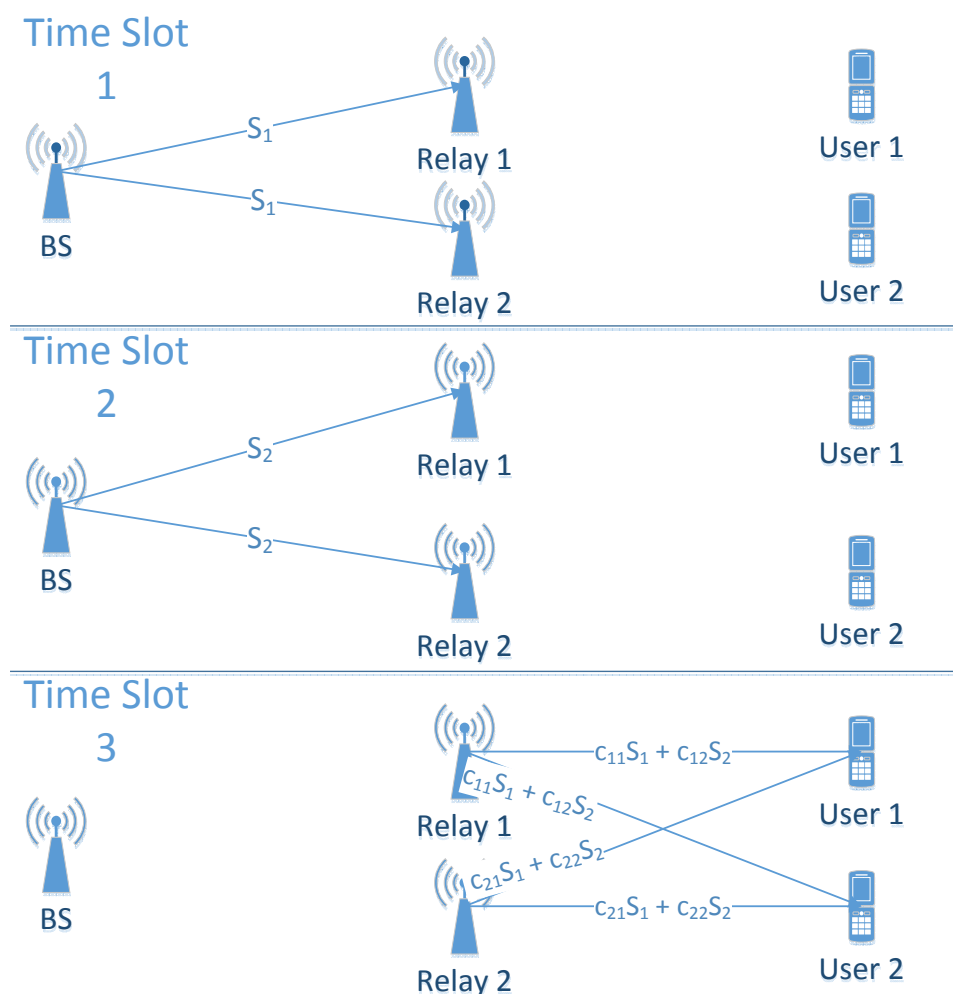


Figure 3.3: Transmitter Zero Forcing

it takes three time slot to complete the transmission. Thus, the total network throughput

(C_{TZF}) , is expressed as:

$$C_{TZF} = \frac{B}{3} [\log_2(1 + \gamma_{TZF}^1) + \log_2(1 + \gamma_{TZF}^2)]. \quad (3.6)$$

where γ_1^{TZF} and γ_2^{TZF} are received SNR for users 1 and 2 using transmitter zero forcing, respectively.

As mentioned before, in the third time slot, relay i sends a compound signal $c_{i,1}S_1 + c_{i,2}S_2$ to the two users, where $c_{i,1}$ and $c_{i,2}$ are the weights to be determined. Ignoring channel noise, we can obtain the received signal Y_j at a user j as, [25]:

$$\begin{aligned} Y_j &= \sum_{i=1}^M H_{i,j} \sum_{n=1}^2 c_{i,n} S_n \\ &= \sum_{n=1}^2 S_n \sum_{i=1}^M c_{i,n} H_{i,j} \end{aligned} \quad (3.7)$$

where $H_{i,j}$ is the channel gain from the i -th relay to user j . For user j , only signal S_j should be decoded and the other signals should be forced to zero. The zeros-forcing constraints [17], can be written as:

$$\sum_{i=1}^M c_{i,2} H_{i,1} = 0 \text{ and } \sum_{i=1}^M c_{i,1} H_{i,2} = 0 \quad (3.8)$$

Usually, the transmit power of the relay is limited by a peak power P_{max} . Since S_j has unit power, the power of each transmitted signal is the sum squared of the coefficients. The peak power constraint is given by:

$$c_{i,1}^2 + c_{i,2}^2 \leq P_{max}, i = 1, \dots, M \quad (3.9)$$

Since S_j has unit power, the received SNR at user j is written as:

$$\gamma_j^{TZF} = \frac{(\sum_{i=1}^M c_{i,j} H_{i,j})^2}{N_0}, j = 1, 2 \quad (3.10)$$

To determine the weights, we maximize the network throughput in equation (3.6) with constraints (3.8), and (3.9). To solve the problem, we define non-negative dual variables $\vec{\lambda} = [\lambda_1, \dots, \lambda_M]^T$ for the inequality constraints (3.9) and arbitrary dual variable $\vec{\beta} = [\beta_1, \beta_2]^T$. The non-negative dual variables and arbitrary dual variables are the Lagrangian multipliers. Lagrangian multiplier is a strategy to find the local maxima and minima of a function subject to equality constraints. The Lagrangian function is [25]

$$\begin{aligned}
\mathcal{L}(\vec{c}, \vec{\lambda}, \vec{\beta}) &= \sum_{j=1}^2 \log_2 \left(1 + \frac{(\sum_{i=1}^M c_{i,j} H_{i,j})^2}{N_0} \right) + \\
&\quad \sum_{i=1}^M \lambda_i (P_{max} - c_{i,1}^2 - c_{i,2}^2) + \\
&\quad \beta_1 \sum_{i=1}^M c_{i,2} H_{i,1} + \beta_2 \sum_{i=1}^M c_{i,1} H_{i,2} \\
&= \sum_{j=1}^2 \mathcal{L}_j(\vec{c}, \vec{\lambda}, \beta_j) + \sum_{i=1}^M \lambda_i P_{max}
\end{aligned} \tag{3.11}$$

where \vec{c} is a vector consisting of all weights $c_{i,j}$'s and

$$\begin{aligned}
\mathcal{L}_j(\vec{c}, \vec{\lambda}, \beta_j) &= \log_2 \left(1 + \frac{(\sum_{i=1}^M c_{i,j} H_{i,j})^2}{N_0} \right) - \\
&\quad \sum_{i=1}^M (\lambda_i c_{i,j}^2 - \beta_j c_{i,3-j} H_{i,j})
\end{aligned} \tag{3.12}$$

The primal dual algorithm is a method for solving a linear programming problem by working with the dual and a related primal problem. Optimization problems may be viewed from either of two perspectives, the primal problem or the dual problem. The solution to the dual problem provides a lower bound to the solution of the primal problem. However, in general, the optimal values of the primal and dual problems need not be equal. Their difference is called the duality gap. The standard primal problem is generally defined as the maximization problem [25] and [39].

The above problem can be solved iteratively. In Step $\tau \geq 1$, for given vector $\vec{\lambda}(\tau)$ and $\vec{\beta}(\tau)$, we adopt the gradient method to maximize the primal problem [25].

$$\vec{c}(\tau + 1) = \vec{c}(\tau) + \phi_p \sum_{j=1}^2 \nabla_{\vec{c}} \mathcal{L}_j(\vec{c}(\tau), \vec{\lambda}(\tau), \beta_j(\tau)) \quad (3.13)$$

where $\nabla_{\vec{c}} \mathcal{L}_j(\vec{c}(\tau), \vec{\lambda}(\tau), \beta_j(\tau))$ is the gradient of the primal problem and ϕ_p is a small positive step size.

The master dual problem for a given $\vec{c}(\tau + 1)$ is:

$$\min_{\vec{\lambda}, \vec{\beta}} \mathcal{L}(\vec{c}(\tau + 1), \vec{\lambda}, \vec{\beta}) \quad (3.14)$$

Since the Lagrangian function is differentiable, we adopt the sub-gradient method to update $\vec{\lambda}$

$$\vec{\lambda}(\tau + 1) = [\vec{\lambda}(\tau) - \phi_d \nabla_{\vec{\lambda}} \mathcal{L}(\vec{c}(\tau + 1), \vec{\lambda}(\tau), \vec{\beta}(\tau))]^+ \quad (3.15)$$

where ϕ_d is a positive step size, and $[\cdot]^+$ denotes the projection onto the non-negative axis. Since $\vec{\beta}$ is a vector with two arbitrary numbers, we update it using the gradient method

$$\vec{\beta}(\tau + 1) = \vec{\beta}(\tau) - \phi_d \nabla_{\vec{\beta}} \mathcal{L}(\vec{c}(\tau + 1), \vec{\lambda}(\tau), \vec{\beta}(\tau)) \quad (3.16)$$

The duality gap between the primal and dual problem will be zero. The Primal-Dual algorithm is presented in Table 3.1 [25], where ϵ is a sufficiently small threshold for convergence.

Table 3.1: Primal Dual Algorithm

1:	Set $\tau = 1; \vec{\lambda}(1)$ to positive values;
2:	Set $\vec{c}(1)$ and $\vec{\beta}(1)$ to arbitrary values;
3:	DO
4:	Compute $\vec{c}(\tau + 1)$ as in (3.13)
5:	Compute $\vec{\lambda}(\tau + 1)$ as in (3.15)
6:	Compute $\vec{\beta}(\tau + 1)$ as in (3.16)
7:	$\tau = \tau + 1$
8:	WHILE ($\ \vec{c}(\tau) - \vec{c}(\tau - 1)\ > \epsilon$)

3.5 Analysis of Transmitter Zero Forcing and Receiver Diversity on Network Throughput for a two relay case

To analyze receiver diversity (RD) and transmitter zero forcing (TZF), we consider a simple case where the number of relays and the number of users is two and the channel is considered to be symmetric. Figure 3.4, shows a simple case with two relays and two users.

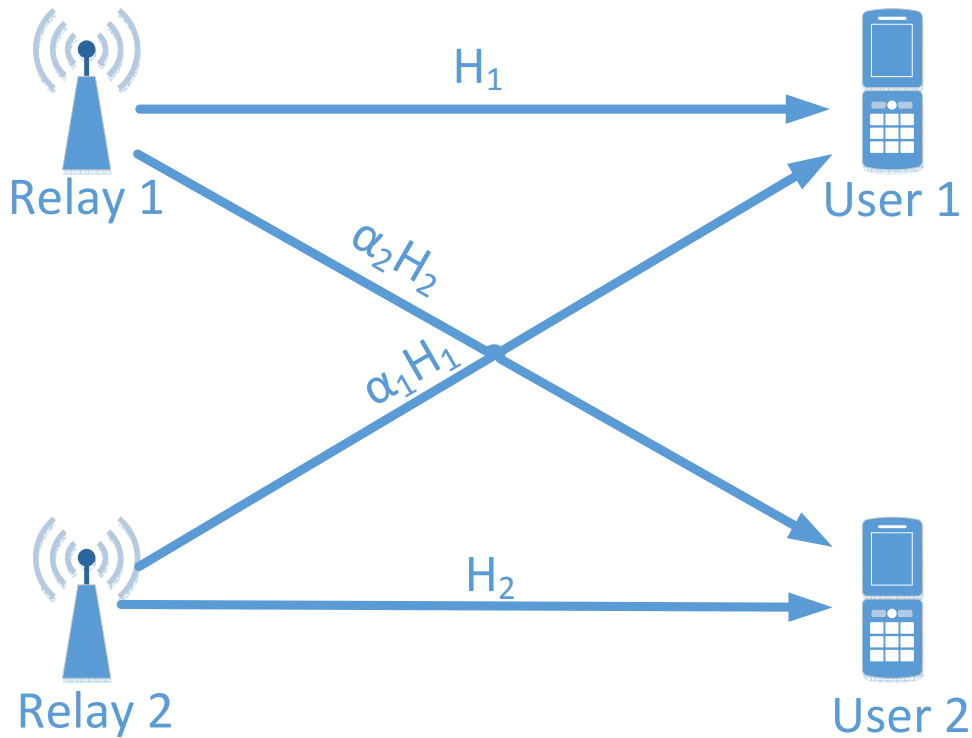


Figure 3.4: Channel Model

The channel gains from relay 1 to user 1 and from relay 2 to user 2 are denoted as H_1 and

H_2 , respectively. The cross channel gains are $\alpha_1 H_1$ and $\alpha_2 H_2$, where $0 < \alpha_1, \alpha_2 < 1$ are cross channel fading factors. Depending on the relation between signal parameters and the channel parameters different signals will undergo different types of fading. Here, the fading factor considered is *flat fading* [34].

3.5.1 Receiver Diversity

According to equations (3.3), (3.4) and (3.2), we can find the overall signal to noise ratio (SNR) for all three combining schemes, namely, maximum ratio combining (MRC) γ_j^{MRC} , equal gain combining (EGC) γ_j^{EGC} and selective combining (SC) γ_j^{SC} , which is given by:

$$\begin{aligned}\gamma_j^{MRC} &= \frac{H_j^2 P_{max}}{N_0} + \frac{\alpha_j^2 H_j^2 P_{max}}{N_0} \\ &= (1 + \alpha_j^2) \frac{H_j^2 P_{max}}{N_0}\end{aligned}\quad (3.17)$$

$$\begin{aligned}\gamma_j^{EGC} &= \frac{1}{2} \left(\sqrt{\frac{H_j^2 P_{max}}{N_0}} + \sqrt{\frac{\alpha_j^2 H_j^2 P_{max}}{N_0}} \right)^2 \\ &= \frac{(1 + \alpha_j)^2 H_j^2 P_{max}}{2 N_0}\end{aligned}\quad (3.18)$$

$$\gamma_j^{SC} = \frac{H_j^2 P_{max}}{N_0}\quad (3.19)$$

Where, j represents the user and H_j and α_j are channel gain and fading factor between the relay and corresponding users, respectively. The following definition is used to calculate SNR [35]. $\gamma(SNR) = \frac{H^2 P}{N}$, where P , N and H are transmitted power, noise and channel gain, respectively.

Then, the network throughput [37] - [38], for three combining schemes (MRC, EGC and SC) using (3.5) can be written as:

$$\begin{aligned}
C_{MRC} &= \frac{B}{4} \sum_{j=1}^2 \log_2 \left(1 + (1 + \alpha_j^2) \frac{H_j^2 P_{max}}{N_0} \right) \\
C_{EGC} &= \frac{B}{4} \sum_{j=1}^2 \log_2 \left(1 + \frac{(1 + \alpha_j)^2 H_j^2 P_{max}}{2 N_0} \right) \\
C_{SC} &= \frac{B}{4} \sum_{j=1}^2 \log_2 \left(1 + \frac{H_j^2 P_{max}}{N_0} \right)
\end{aligned} \tag{3.20}$$

3.5.2 Transmitter Zero Forcing

For transmitter zero forcing, the compound signals X_1 and X_2 transmitted by relay 1 and 2 using the precoding matrix as the inverse of the channel gain matrix, are:

$$\begin{aligned}
X_1 &= K_1 H_2 S_1 - \alpha_1 K_2 H_1 S_2 \\
X_2 &= K_2 H_1 S_2 - \alpha_2 K_1 H_2 S_1
\end{aligned} \tag{3.21}$$

where K_1 and K_2 are two arbitrary real numbers. S_1 and S_2 are the signals transmitted by the relays 1 and 2, respectively. Assuming relay 1 and 2 use maximum power to transmit these two signals, we have the following two equations

$$\begin{aligned}
K_1^2 H_2^2 + \alpha_1^2 K_2^2 H_1^2 &= P_{max} \\
K_2^2 H_1^2 + \alpha_2^2 K_1^2 H_2^2 &= P_{max}
\end{aligned} \tag{3.22}$$

Then, the received signals at user 1 and 2 using equation (3.1), denoted by Y_1 and Y_2 , are

$$\begin{aligned}
Y_1 &= (1 - \alpha_1 \alpha_2) K_1 H_1 H_2 S_1 \\
Y_2 &= (1 - \alpha_1 \alpha_2) K_2 H_1 H_2 S_2
\end{aligned} \tag{3.23}$$

from (3.22) and (3.23), we have the SNRs [35], for two users as follows

$$\begin{aligned}\gamma_j^{TZF} &= \frac{(1 - \alpha_1\alpha_2)^2 K_j^2 H_1^2 H_2^2}{N_0} \\ &= \frac{(1 - \alpha_1\alpha_2)(1 - \alpha_j^2) H_j^2 P_{max}}{1 + \alpha_1\alpha_2} \frac{1}{N_0}\end{aligned}\quad (3.24)$$

where γ_j^{TZF} is received SNR at user j . The corresponding network throughput using (3.10) is given by

$$C_{TZF} = \frac{B}{3} \sum_{j=1}^2 \log_2 \left(1 + \frac{(1 - \alpha_1\alpha_2)(1 - \alpha_j^2) H_j^2 P_{max}}{1 + \alpha_1\alpha_2} \frac{1}{N_0} \right) \quad (3.25)$$

Comparing (3.20) and (3.25), we can rewrite the network throughput as

$$C = g_B B \sum_{j=1}^2 \log_2 \left(1 + g_P^j \frac{H_j P_{max}}{N_0} \right) \quad (3.26)$$

where g_B and g_P^j are coefficients of bandwidth and power, respectively. The comparison of RD and Transmitter Zero Forcing is presented in table 3.2.

Table 3.2: Comparison of RD and Transmitter Zero Forcing

	Coefficient of bandwidth (g_B)	Coefficient of power (g_P^j)
MRC	1/4	$1 + \alpha_j^2$
EGC	1/4	$\frac{(1 + \alpha_j)^2}{2}$
SC	1/4	1
Transmitter Zero Forcing	1/3	$\frac{(1 - \alpha_1\alpha_2)(1 - \alpha_j^2)}{1 + \alpha_1\alpha_2}$

3.6 Simulation Results

We performed simulations using MATLAB to study the performance of Transmitter Zero Forcing (TZF) and the diversity combining schemes - Maximum Ratio Combining (MRC), Equal Gain Combining (EGC) and Selective Combining (SC). The simulations are performed to determine network throughput by varying the distance between the user and relay and by varying the transmitter power.

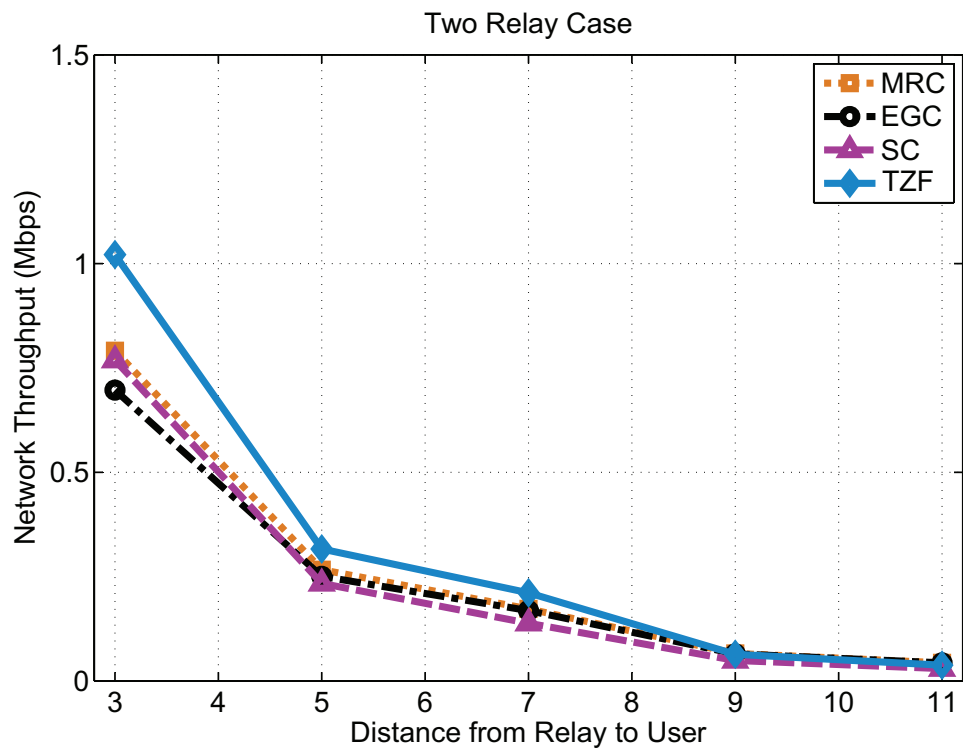


Figure 3.5: Network Throughput vs. Distance - Two Relay Case

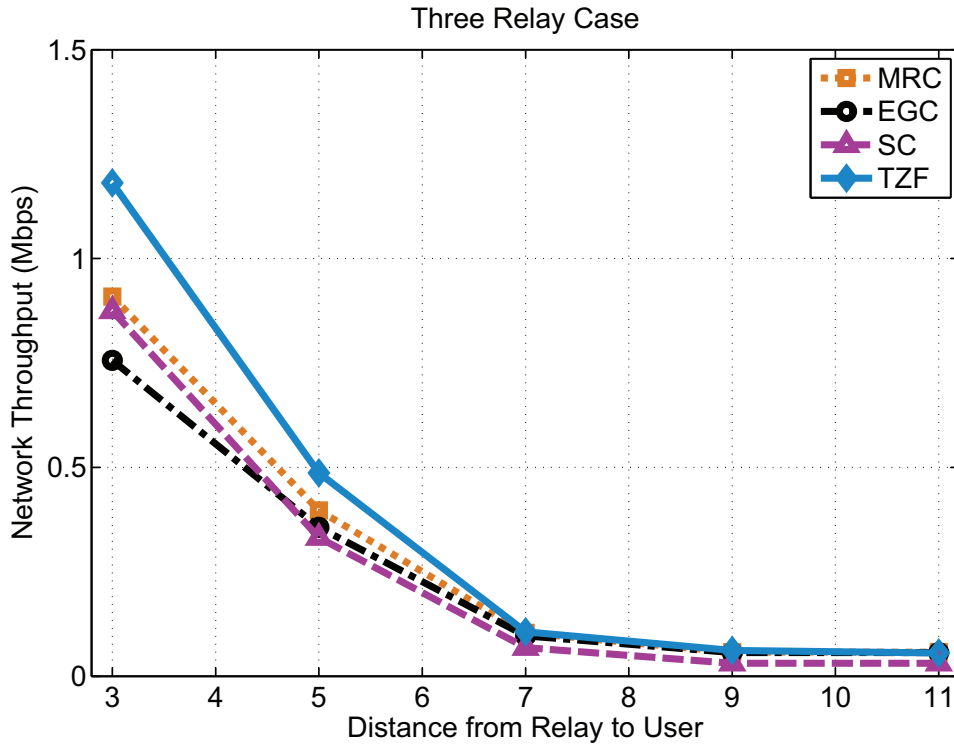


Figure 3.6: Network Throughput vs. Distance - Three Relay Case

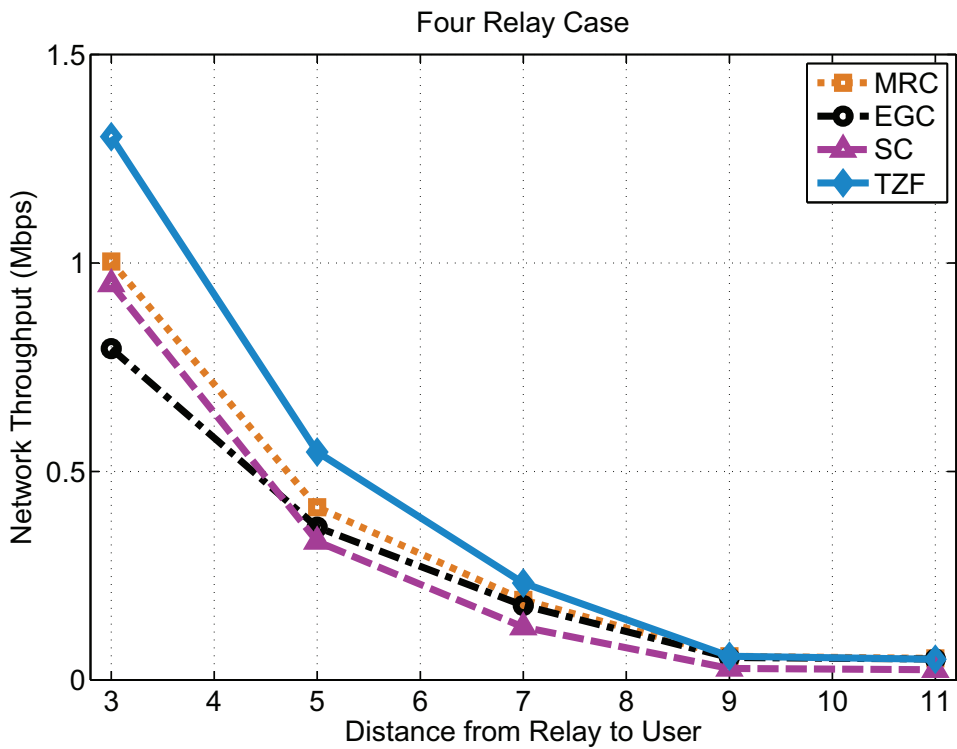


Figure 3.7: Network Throughput vs. Distance - Four Relay Case

Figure 3.5, 3.6 and 3.7 show the simulation results of a two relay, three relay and four relay cases in the system, respectively. The number of users considered for all cases are two and the channel gain between the users and relay depends on the distance and log normally distributed shadowing effect. The transmitter power is taken to be 1 watt. In Figure 3.5, 3.6 and 3.7, we demonstrate the impact of distance between user and relay on the throughput of the schemes. The distance between the user and relays are increased from 3 to 11 meters.

As the distance between user and relay increases all throughputs are degraded. TZF outperforms combining schemes when the distance between the user and relay are small but is inferior to combining schemes as the distance increases. There is a cross over point between TZF and diversity combining schemes curves when the distance between the user and relay is 9 meters. This is because as the distance increases, the interference increases in TZF and diversity combining schemes, but in diversity combining schemes, the receiver, receives different versions of the same signal there by mitigating the effects of fading.

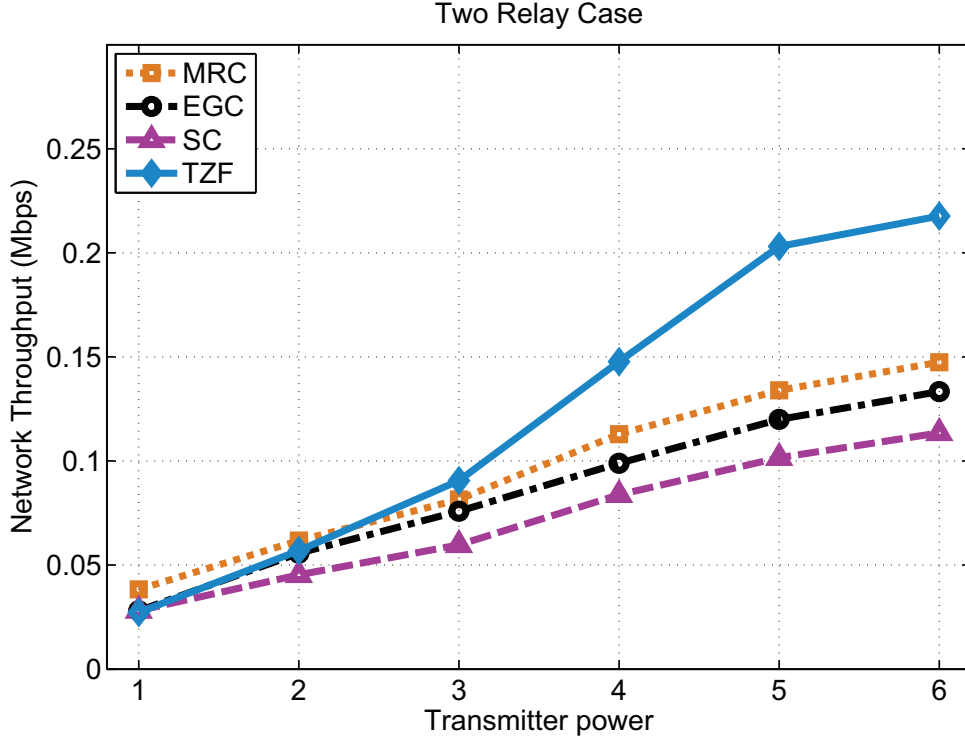


Figure 3.8: Network Throughput vs. Transmit Power - Two Relay Case

Figure 3.8, 3.9 and 3.10 show the simulation results of a two relay, three relay and four relay cases in the system, respectively. The number of users considered for all cases are two and the channel gain between the users and relay depends on the distance and log normally distributed shadowing effect. In Figure 3.8, 3.9 and 3.10, we demonstrate the impact of transmit power on the throughput of the schemes. The transmit power is varied from 1 to 6 watts.

As the transmitter power increases the throughput of both TZF and diversity combining schemes are increased. Diversity combining schemes outperform TZF when the transmitter power is small. However, as the transmitter power increases TZF outperforms all the combining schemes. This is because when the transmitter power is small, signal to interference plus noise ratio (SINR) is high in TZF and diversity combining schemes, but in diversity

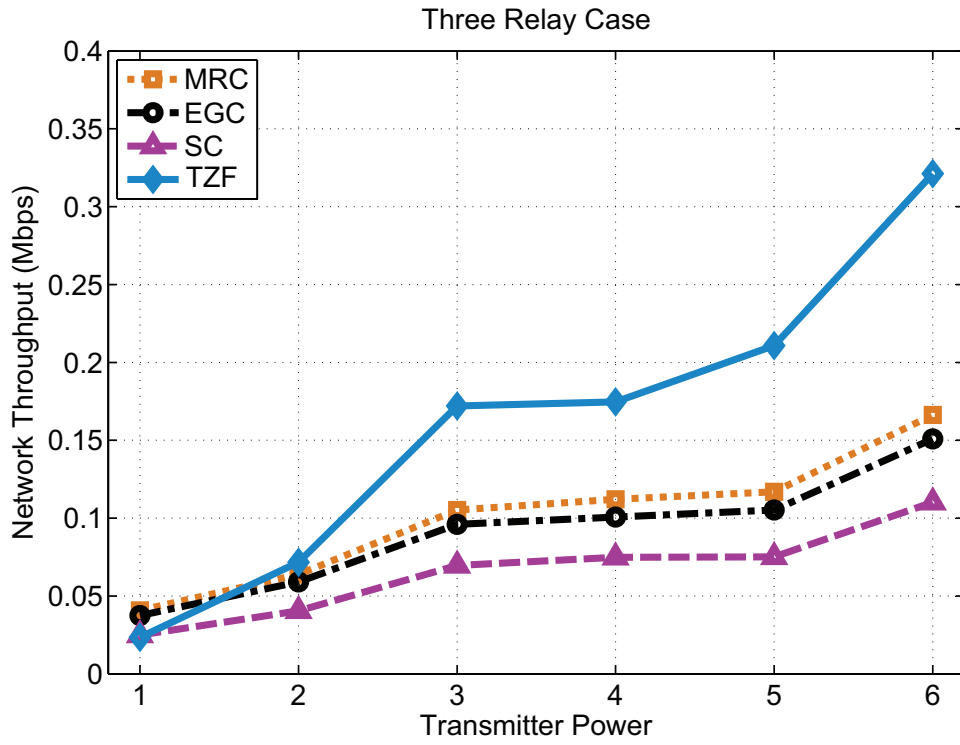


Figure 3.9: Network Throughput vs. Transmit Power - Three Relay Case

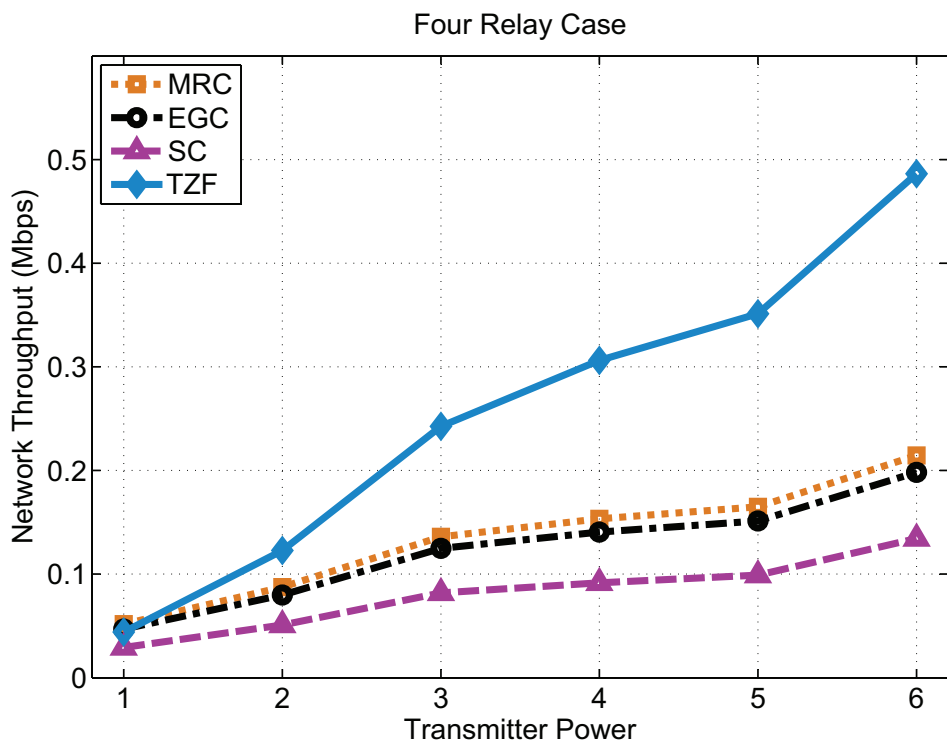


Figure 3.10: Network Throughput vs. Transmit Power - Four Relay Case

combining scheme, the receiver receives different versions of the same signal there by mitigating the fading. As the transmitter power increases, SINR in both TZF and diversity combining scheme reduces and TZF clearly outperforms diversity combining schemes.

3.7 Summary of chapter

In this chapter, we studied the application of Transmitter Zero Forcing (TZF) and Receiver Diversity (RD) techniques like, Maximum Ratio Combining (MRC), Equal Gain Combining (EGC) and Selective Combining (SC) in cooperative cellular networks. We formulated the problem of both RD and TZF in cooperative relay networks and addressed the problem using the primal-dual algorithm. We further analyzed a simple case with two relays and two users, and derived the closed-form formula for the influence of both RD and TZF on network throughput. There was excellent agreement between our analytical model and simulation results. We performed a simulation study and compared network throughput of both TZF and RD against transmitter power and distance between user and relay, and found that there is no case of dominance for the two strategies.

Chapter 4

Concluding remarks

In this thesis, initially, we studied the positioning of relay nodes (RN) to reduce energy consumption. We modeled the two relay node placement strategy - a greedy algorithm and an approximation algorithm. This positioning of the relay is dependent on the distance between the users and BS. In greedy algorithm, RNs are placed at halfway distance between the farthest user and base station (BS). In approximation algorithm the RNs are placed at the periphery of the coverage distance of the BS. We compare both the algorithms in terms of average energy consumption, average number of hops for a packet to reach the base station (BS) and average r-cover which is the coverage radius of RN. The approximation algorithm is shown to outperform the greedy algorithm in all the above mentioned metrics. The results provide us an insight into positioning of the relays in a cooperative wireless network to reduce energy consumption of the users.

Second, we studied the application of Transmitter Zero Forcing (TZF) and Receiver Diversity (RD) like, Maximum Ratio Combining (MRC), Equal Gain Combining (EGC) and Selective Combining (SC), to cooperative cellular networks. We analyzed a simple case with two relays and two users, and derived the closed-form formula for the influence of both RD and TZF on network throughput. There was excellent agreement between our analytical model and simulation results. We formulated the problem of both RD and TZF in cooperative relay networks and addressed the problem using the primal-dual algorithm. We compared network throughput of both TZF and RD against transmitter power and distance between user and relay. In the simulation study, cross points with TZF and RD were found, indicating that there was no case of dominance for the two strategies. We conclude that

TZF can be used when interference is weak while RD can be adopted when the interference is high.

Bibliography

- [1] T. Cover and A.E. Gamal, "Capacity theorems for the relay channel," *Information Theory, IEEE Transactions on*, vol.25, no.5, pp.572-584, Sep. 1979
- [2] J.N. Laneman, D.N.C. Tse and G.W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *Information Theory, IEEE Transactions on*, vol.50, no.12, pp.3062-3080, Dec. 2004
- [3] D. Hu and S. Mao, "Cooperative Relay in Cognitive Radio Networks: Decode-and-Forward or Amplify-and-Forward?," *Global Communications Conference (GLOBECOM 2010)*, 2010 IEEE, pp.1-5, Dec. 2010
- [4] Y.-D. Lin and Y.-C. Hsu, "Multihop cellular: a new architecture for wireless communications," *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol.3, pp.1273-1282, Mar. 2000
- [5] E.L. Lloyd and G. Xue, "Relay Node Placement in Wireless Sensor Networks," *Computers, IEEE Transactions on*, vol.56, no.1, pp.134-138, Jan. 2007
- [6] C. Shen and D. Pesch, "A Heuristic Relay Positioning Algorithm for Heterogeneous Wireless Networks," *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pp.1-5, Apr. 2009
- [7] A. So and B. Liang, "Enhancing WLAN Capacity by Strategic Placement of Tetherless Relay Points," *Mobile Computing, IEEE Transactions on*, vol.6, no.5, pp.522-535, May 2007

- [8] H.-C. Lu and W. Liao, "Joint Base Station and Relay Station Placement for IEEE 802.16j Networks," Global Communications Conference, 2009. GLOBECOM 2009. IEEE, pp.1-5, Dec. 2009
- [9] P. Moberg, P. Skillermark, N. Johansson and A. Furuskar, "Performance and Cost Evaluation of Fixed Relay Nodes in Future Wide Area Cellular Networks," Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposium on, pp.1-5, Sept. 2007
- [10] D. Yang, S. Mumtaz, J. Bastos, and J. Rodriguez, "A location-aided teletraffic measurement scheme for optimizing the locations of fixed relay nodes," Wireless Communications and Networking Conference Workshops (WCNCW), 2012 IEEE, pp.312-316, Apr. 2012
- [11] K. Kwak, S. Lee, M. Park and D. Hong, "Positioning the relay to achieve full diversity and minimize error probability in cooperative decode-and-forward relay systems," Wireless Conference, 2008. EW 2008. 14th European, pp.1-5, June 2008
- [12] L. Zuari, A. Conti and V. Tralli, "Effects of relay position and power allocation in space-time coded cooperative wireless systems," Wireless Communication Systems, 2009. ISWCS 2009. 6th International Symposium on, pp.700-704, Sept. 2009
- [13] Z. Ren, G. Wang, Q. Chen, and H. Li, Modelling and simulation of rayleigh fading, path loss, and shadowing fading for wireless mobile networks, Simulation Modeling Practice and Theory, vol. 19, no. 2, pp. 626637, 2011. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1569190X10002017>
- [14] L. Fleischer, K. Jain and D.P. Williamson, "An iterative rounding 2-approximation algorithm for the element connectivity problem," Foundations of Computer Science, 2001. Proceedings. 42nd IEEE Symposium on, pp.339-347, Oct. 2001

- [15] N. Fujimoto and K. Hagihara, "A 2-Approximation Algorithm for Scheduling Independent Tasks onto a Uniform Parallel Machine and its Extension to a Computational Grid," Cluster Computing, 2006 IEEE International Conference on, pp.1-7, Sept. 2006
- [16] A. Sendonaris, E. Erkip and B. Aazhang, "User cooperation diversity. Part I. System description," Communications, IEEE Transactions on , vol.51, no.11, pp.1927-1938, Nov. 2003
- [17] D. Tse and P. Viswanath, Fundamentals of Wireless Communication, New York, NY, USA: Cambridge University Press, 2005.
- [18] R.S. Ganesan, T. Weber and A. Klein, "Interference Alignment in Multi-User Two Way Relay Networks," Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd, pp.1-5, May 2011
- [19] F. Wang, S.-C. Liew and D. Guo, "Wireless MIMO switching with zero-forcing relaying," Communication, Control, and Computing (Allerton), 2011 49th Annual Allerton Conference on , pp.551-558, Sept. 2011
- [20] J. Zhang, R. Chen, J.G. Andrews, A. Ghosh and R.W. Heath, "Networked MIMO with clustered linear precoding," Wireless Communications, IEEE Transactions on , vol.8, no.4, pp.1910-1921, April 2009
- [21] H. Kim, H. Yu, Y. Sung; Y.H. Lee, "An Efficient Algorithm for Zero-Forcing Coordinated Beamforming," Communications Letters, IEEE , vol.16, no.7, pp.994-997, July 2012
- [22] G. Amarasuriya, C. Tellambura and M. Ardakani, "Performance Analysis of Zero-Forcing for Two-Way MIMO AF Relay Networks," Wireless Communications Letters, IEEE , vol.1, no.2, pp.53-56, April 2012

- [23] I. Al-Nahhal, M. Alghoniemy, A.B. Abd El-Rahman and Z. Kawasaki, "Modified zero forcing decoder for ill-conditioned channels," *Wireless Days (WD)*, 2013 IFIP , pp.1-3, Nov. 2013
- [24] R.S. Ganesan, H. Al-Shatri, T. Weber and A. Klein, "Cooperative zero forcing in multi-pair multi-relay networks," *Personal Indoor and Mobile Radio Communications (PIMRC)*, 2012 IEEE 23rd International Symposium on , pp.1740-1745, Sept. 2012
- [25] D. Hu and S. Mao, "Cooperative relay with interference alignment for video over cognitive radio networks," *INFOCOM*, 2012 Proceedings IEEE, pp.2014-2022, March 2012
- [26] H. Mheidat and M. Uysal, "Impact of receive diversity on the performance of amplify-and-forward relaying under APS and IPS power constraints," *Communications Letters, IEEE* , vol.10, no.6, pp.468-470, June 2006
- [27] K.-S. Woo, H. Yim, Y.-J. Kim, H.I. Yoo and Y.-S. Cho, "An Efficient Receive-Diversity-Combining Technique for SC-FDMA-Based Cooperative Relays," *Vehicular Technology, IEEE Transactions on* , vol.59, no.8, pp.4187-4191, Oct. 2010
- [28] M. Jalloh and P. Das, "On the Performance of Transmit and Receive Diversity OFDM Systems with Phase Noise and Imperfect Channel Estimation," *Vehicular Technology Conference*, 2009. VTC Spring 2009. IEEE 69th , pp.1-6, April 2009
- [29] S. Devarakonda and H. Radha, "The Impact of Receive Diversity in the Presence of Correlation in Wireless Sensor Networks," *Information Sciences and Systems*, 2007. CISS '07. 41st Annual Conference on , pp.621-626, March 2007
- [30] A.A. Hutter, J.S. Hammerschmidt, E. De Carvalho and J.M. Cioffi, "Receive diversity for mobile OFDM systems," *Wireless Communications and Networking Conference*, 2000. WCNC. 2000 IEEE , vol.2, pp.707-712, 2000

- [31] L.E. Li, R. Alimi, D. Shen, H. Viswanathan and Y.R. Yang, "A General Algorithm for Interference Alignment and Cancellation in Wireless Networks," INFOCOM, 2010 Proceedings IEEE , pp.1-9, March 2010
- [32] H. Zeng, Y. Shi, Y.T. Hou, W. Lou, S. Kompella and S.F. Midkiff, "On interference alignment for multi-hop MIMO networks," INFOCOM, 2013 Proceedings IEEE , pp.1330-1338, April 2013
- [33] V.K. Garg, , "Wireless communications and networking." Sam Francisco: Morgan Kaufmann 22 (2007)
- [34] T. S. Rappaport, "Wireless Communications: Principles and Practice (2nd Edition)" , Prentice Hall communications engineering and emerging technologies series, 10 January 2002
- [35] S. Hari and W. Yu, "Partial zero-forcing precoding for the interference channel with partially cooperating transmitters," Information Theory Proceedings (ISIT), 2010 IEEE International Symposium on, pp.2283-2287, June 2010
- [36] X. Xu and S.P. Radziszowski, "Bounds on Shannon Capacity and Ramsey Numbers From Product of Graphs," Information Theory, IEEE Transactions on , vol.59, no.8, pp.4767-4770, Aug. 2013
- [37] R.V. Sonalkar and D. Applegate, "Shannon capacity of frequency-overlapped digital subscriber loop channels," Communications, 2002. ICC 2002. IEEE International Conference on , vol.3, pp.1741-1745, 2002
- [38] A. Sharifkhani and N.C. Beaulieu, "Dynamic Power Allocation over Block-Fading Channels with Delay Constraint," Global Communications Conference, 2009. GLOBECOM 2009. IEEE , pp.1-7, Dec. 2009

- [39] M. Chiang; S.H. Low, A.R. Calderbank and J.C. Doyle, "Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures," Proceedings of the IEEE , vol.95, no.1, pp.255-312, Jan. 2007
- [40] A. Bleicher, "4G gets real," Spectrum, IEEE , vol.51, no.1, pp.38-62, Jan. 2014