

**BANDWIDTH ALLOCATION FOR MULTIPLE- USER AND MULTIPLE-
RELAY COOPERATIVE SYSTEMS USING STACKELBERG GAME**

A Thesis Submitted in Fulfillment of the Requirement for the Award of the Degree of

MASTER OF ENGINEERING

in

Wireless Communication

Submitted By

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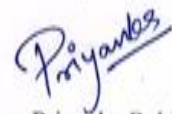
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JULY, 2017

DECLARATION

I, Priyanka Rahi hereby declare that the work presented in this thesis entitled BANDWIDTH ALLOCATION FOR MULTIPLE- USER AND MULTIPLE- RELAY COOPERATIVE SYSTEMS USING STACKELBERG GAME in fulfillment of the requirement for the award of degree of Master of Engineering submitted at Electronics and Communication Department, Thapar University, Patiala is an authentic record of work carried out under supervision of Dr. Sanjay Sharma (Professor, Electronics and Communication Department, Thapar University) from 2015 to 2017. The matter presented in this report has not been submitted either in part or full to any other university or institute for the award of any other degree.

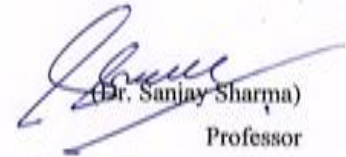
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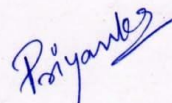
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ABSTRACT

While dealing with wireless communication systems (whether infrastructure based systems that have one controlling entity known as access point, or ad-hoc systems), the nodes present can be fixed at a location or can be moving from one coverage area to another. With this randomness, the channel conditions between the users always changes due to different paths followed by signals to reach from one user to another. Due to multiple paths, several mechanisms can occur in between the source and the destination due to the surroundings like reflection, scattering, diffraction, or Doppler Effect. These mechanisms lead to multiple copies of a single information signal, and due to mainly destructive interference at the receiver fading occurs which degrades the quality of signal. To combat this fading effect, several diversity techniques are employed namely time diversity, frequency diversity, spatial diversity, etc. Out of the above mentioned diversity techniques spatial diversity technique is the most suitable form as it doesn't require any extra frequency bands or time intervals, but it comes with a disadvantage too of more complex hardware requirement which is not handy.

To avoid these problems, a new diversity technique has been introduced in literature which is known as cooperative diversity technique. This technique provides the advantage of spatial diversity without actually introducing new antennas. The users which are already present in the system helps each other to forward the information hence relaying each other's information. This technique hence gives the benefit of Multiple Input Multiple Output (MIMO) technique virtually. The users however may be willing to help without need of a profit or may be selfish in nature.

This work focuses on allocating the most important as well as the limited resource required essentially for the communication purpose i.e. Bandwidth. So, a two-level Stackelberg Game is introduced in the work according to which the nodes which are helping in relaying are termed as leaders or vendors that sell their bandwidth to the users which are in need of transmission of information and the users hence become followers or purchasers who pay charges for buying bandwidth slots. The Stackelberg Equilibrium hence solves the problem of which relays should be selected, what charges they should demand from the users and which users should be given the bandwidth by allocating the optimal bandwidth and optimal prices. Further, the difference is found out between the resource allocation done in distributive and in a centralized way in which it is proved that the distributed method is actually better in allocating the resources than the centralized one.

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LIST OF ABBREVIATIONS

ISI	Inter Symbol Interference
ICI	Inter Channel Interference
LOS	Line Of Sight
MIMO	Multiple Input Multiple Output
AF	Amplify and Forward
DF	Decode and Forward
CF	Compress and Forward
MRC	Maximum Ratio Combining
EGC	Equal Gain Combining
FRC	Fixed Ratio Combining
CSI	Channel State Information
QAM	Quadrature Amplitude Modulation
SNR	Signal to Noise Ratio
SER	Symbol Error Rate
QOS	Quality Of Service
OFDMA	Orthogonal Frequency Division Multiple Access
CDMA	Code Division Multiple Access
MCMC	Markov Chain Monte Carlo
CEO	Cross Entropy Optimisation
DS/ CDMA	Direct Sequence- Code Division Multiple Access
UE	User Equipment
BE	Bandwidth Exchange
AWGN	Additive White Gaussian Noise

CHAPTER 1

INTRODUCTION

While dealing with the communication systems, the two very crucial but limited resources are bandwidth that should be allotted to the systems to communicate, and the transmitting power [1]. Hence various techniques have been implemented in the literature to optimally allocate these two resources so that factors like dearth of resources, overlapping of bands, Inter Symbol Interference (ISI), Inter Channel Interference (ICI), etc. can be avoided. One of the techniques which are emerging in the recent research areas is the cooperative communication [2]. Cooperative communication is a technique which is employed nowadays to increase the capacity and reliability of the systems, and spatial diversity due to the broadcasting nature it follows. This is achieved by taking the help of nodes in between the transmitters and the receivers to forward the information so that the channel loss can be reduced. The helping nodes are called relaying nodes which help to pass on the transmitted data signal from the transmitting node to the receiving node through several relaying techniques. This can be seen as a way in which the relay nodes together with the source node(s) form a virtual transmitter-antenna array which helps in achieving the transmit diversity [3]-[5].

1.1 FADING

Fading is an effect on the received signal which degrades its quality due to multipath propagation.

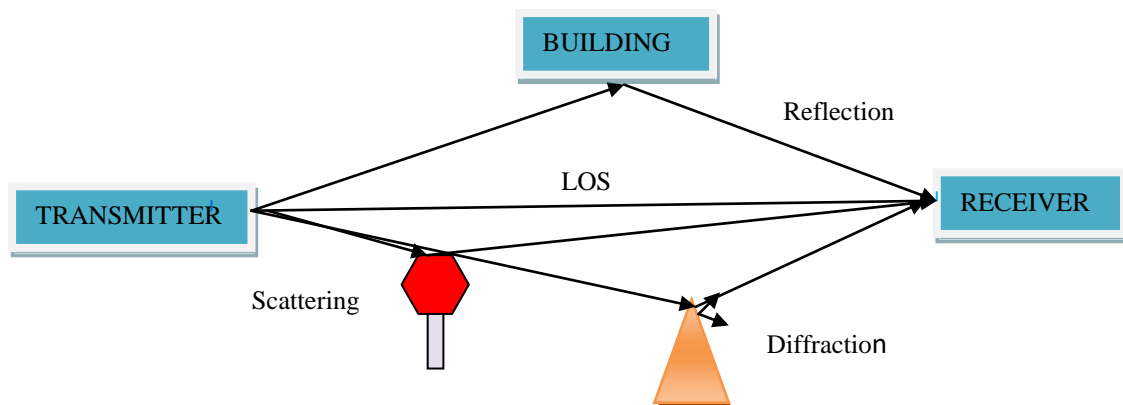


Figure 1.1: Multipath propagation.

It is caused due to the multipath propagation in which a signal transmitted from the transmitter takes different paths and undergoes different phenomenon before reaching at the receiver node, hence causing mainly destructive interference at the receiver [6]. There are basically two sorts of fading viz. small scale fading and large scale fading.

1.1.1 Large scale fading:

Large Scale Fading is caused due to attenuation in the mean level of the received signal when the transmitted signal follows multipath before reaching the receiver and undergoing through several phenomenon like reflection, diffraction and scattering. The large scale fading is considered for larger distances over larger durations. Some of the examples of Large Scale fading are Path loss and shadowing. These fading effects are independent of frequency and change gradually over time. To combat the effects of large scale fading in cellular and ad-hoc networks, cell planning and routing algorithm are used respectively [6].

1.1.2 Small scale fading:

Small scale fading is the another type of fading which is caused due to multipath propagation of the signals which results in a destructive interference of the incoming signal components at the receiver. The destructive interference occurs due to the slight changes in the phase and frequency of the different incoming signals at receiver since they have taken different paths. It is considered over small distances for short duration of time. It depends on frequency and changes rapidly. As it cannot be alleviated using cell planning and routing algorithm, it is the main limiting factor of wireless communication. Small scale fading causes time variations in the channel which is depicted by the coherence bandwidth and time spreading of the signal which is depicted by coherence time parameter [6]. Main causes of small scale fading are source motion, obstacle motion in the environment, and propagation of signal through multipath in wireless environment. Small scale fading is further illustrated as Rician fading, if LOS (Line of Sight) exists and Rayleigh fading if it does not exists [6].

The data rate of received signal is directly related to strength of the signal received. Due to fading, received signal strength can drop due to destructive combining at the receiver node and therefore the data rate is affected. This fading effect has led to intensive research work in developing new wireless technology which can reduce fading effects. Diversity is a technique used to combat fading [6].

1.2 DIVERSITY

Diversity in wireless communication is a technique in which multiple versions of the signal are transmitted to the receiver node through different uncorrelated channels such that the various copies of same signal travelling through different channels possess different fading coefficients and hence get affected in different manner [6].

At the receiver node all the versions of the incoming signal are clubbed to have average of all the signals received from various paths. If the signal travelling through one channel suffers deep fading then the signal travelling through another channel may not have such severe fading effects as the probability that the two signals travelling through different channels will be affected by same fading is quite low. Thus combined signal at receiver node will never face a deep fade and there will surely be a signal at the receiver which improves the efficiency of the system [6]. Some common diversity techniques are:

1.2.1 Time diversity:

Time diversity is an approach to achieve diversity in which same symbol is sent at different time instances such that difference between these time instances is more than the coherence time of the channel and the copies of the symbol sent are uncorrelated and experience independent fading. The channel conditions in these time gaps are different from each other [6].

1.2.2 Space diversity:

Space diversity is an approach to achieve diversity in which same signal is sent from different antennas placed at a distance (ideally one half or more of the wavelength) in space such the channels through which signal travels are uncorrelated and hence the signal's copies undergo independent fading. The optimum distance between the antennas depends on environmental conditions around the antenna. In mobiles multiple antenna are used to exploit spatial diversity should have minimum distance half the wavelength of carrier frequency whereas the base station antenna should have distance more than wavelength of carrier frequency as they are less surrounded by obstacles [6].

1.2.3 Frequency diversity:

Frequency diversity is an approach to achieve diversity in which same signal is send using different carrier frequencies which have difference more than the coherence bandwidth of the channel [6].

1.2.4 Polarization diversity:

In this diversity, same signal is transmitted from different antennas with different polarizations which are orthogonal in nature. Mostly vertical and horizontal polarisations are utilised. The signal with different polarization reacts differently when strike to an obstacle. Thus every signal travelling different path will have different fading effects on itself [6].

Among all the techniques described above, spatial diversity is most widely used in the wireless communication since there is limited bandwidth to achieve frequency diversity and time diversity causes decrement in the data rate.

For implementing spatial diversity more number of antennas is needed to be located in space which is a limiting factor for small radio devices such as mobile. The main disadvantage of multiple antennas is the increment in the cost of deployment, more hardware requirement and device size limitation as these impractical for small size, low cost mobile devices.

1.3 COOPERATIVE DIVERSITY

Thus a new form of diversity called cooperative diversity is introduced in the literature. Cooperative diversity addresses the above discussed limitation by using antennas of other surrounding devices to build a virtual multiple input multiple output (MIMO) structure. Cooperative diversity is a technique by which a virtual MIMO system is created by using antennas of nearby nodes. Thus, in this way spatial diversity is achieved with the benefit of increased range, increased capacity and reliability of the system, proper bandwidth utilisation, proper transmitting power distribution, and increased data rates [7].

The network performance can be improved by taking advantage of wireless propagation environment. Hence a new class of spatial diversity called cooperative diversity is introduced in which mobile terminals interact with one another to transmit information to the destination. Cooperative diversity when implemented in wireless systems is called cooperative communication. The main motive behind cooperative communication is to improve outage probability, symbol or bit error rate. Besides this reliability improvement, cooperative diversity also improves transmission rate [7].

1.4 BASIC MODEL FOR COOPERATIVE COMMUNICATION

In wireless networks signal is broadcasted in every direction such that all the nearby nodes can overhear the signal transmitted by a source. This property of broadcasting in wireless

network is used in cooperative diversity. The signal sent by the transmitter can be heard by a relay which can further forward the signal to receiver [7].

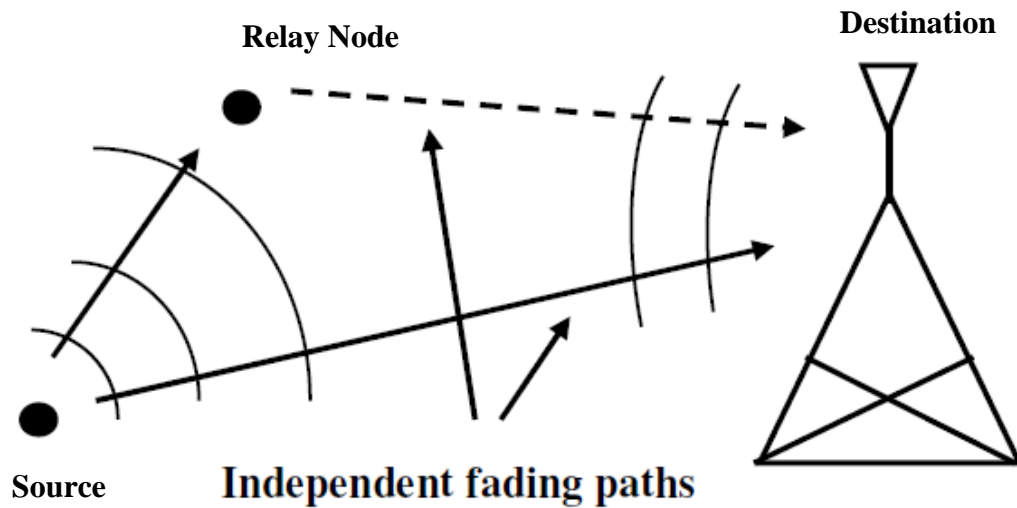


Figure 1.2: Cooperative System working.

Suppose we have a transmitting node S, a receiving node D and a helping node R. When signal is transmitted from transmitting node it follows two paths from S to D. One is direct path; another is from S to D through R. The helping node R overhears the signal from source and retransmits it to D. It can be observed that the transmission is carried out in two stages. The two stages in cooperative diversity are:

1.4.1 Direct transmission Stage:

The stage in which the information is transmitted directly to the receiving node is the direct transmission stage. During this transmission relaying node overhears the signal transmitted by the transmitting node [7]. The relaying node then follows certain protocol or the relaying technique for the received signal which are described later in the report.

1.4.2 Cooperative transmission Stage:

The stage in which the information sent by the transmitting node which is overheard by the relaying node in previous time slot is then retransmitted by it to the receiving node in next stage i.e. cooperative transmission stage [7].

Thus same signal reaches the receiving node by travelling two different uncorrelated independent paths. The signals received are uncorrelated, which when gets combined, results in a signal which will never undergo a deep fade. As signal travels two paths and is transmitted in two different time slots both spatial and time diversity is exploited in cooperative diversity.

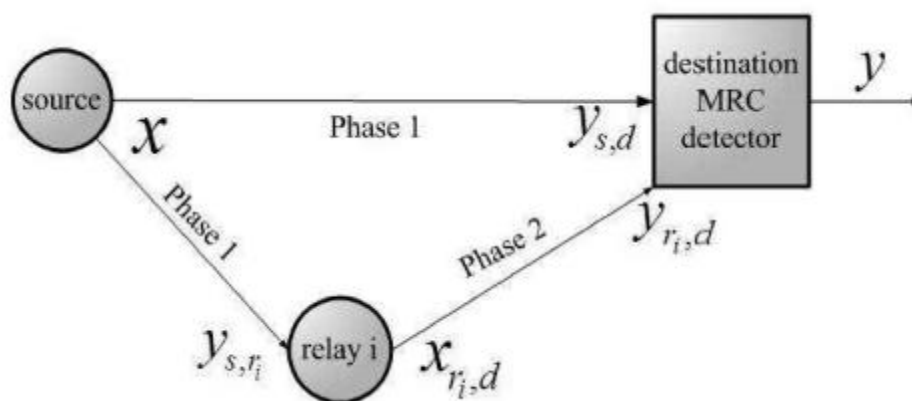


Figure 1.3: The two phases/ stages of cooperative communication.

1.5 RUDIMENTS OF COOPERATIVE DIVERSITY

The three basic rudiments of cooperative communication are transmitting node, helping node and receiving node. All the elements follow certain characteristics which vary from the non-cooperative model elements.

1.5.1 Transmitting Node:

The work of the transmitting node is to transmit the information to the receiving node with an optimal transmitting power and bandwidth as per required, with the awareness of the presence of relaying node and its location. It will hence select the suitable relaying nodes out of the lot according to the channel conditions, revenue charges, distance from itself and the receiving node, etc. The signal transmitted from this node reaches the relaying node and the receiving node in the first time slot, after which the relaying node forwards it to the receiving node in second time slot after following a certain relaying technique. Thus the receiving node should be sentient of the fact that after receiving signal from transmitting node it has to stay for signal from relay [7].

1.5.2 Relaying/ Helping Node:

This node over-hears the signal in first time slot and retransmits it to the receiving node after following certain relaying protocol. The protocol followed by the relaying node depends on the system characteristics. The basic protocols followed by relaying nodes are Amplify- and- forward (AF) mode protocol, decode- and- forward (DF) mode protocol, compress- and- forward (CF) mode protocol. In Amplify and forward relaying node acts as a repeater because it only regenerates the signal by just amplifying it. As it amplifies the received signal it also amplifies the noise, which is its disadvantage. In decode and forward relaying the received signal is first decoded and then forwarded to the receiving node. The compress and forward relaying compresses the signal at relaying node and then forward it to the receiving node [7].

1.5.3 Receiving Node:

This node receives signal from both the transmitting node and the relaying node. If the signal from transmitter is good enough it can inform the relaying node not to forward the signal and can implement non cooperative mode also. The signal received is combined using various combining techniques. Some of them are maximal ratio combining (MRC), equal gain combining (EGC) and fixed ratio combining (FRC) [7].

1.6 TYPES OF RELAYING PROTOCOLS

In Cooperative Communication systems, a node can work both as a source or transmitter as well as a relay. In other words it can be said that in these types of systems, a transmitting node not just only broadcasts its own information but they also help to relay each other's information because here they are cooperating with each other. These nodes may be selfish in the fact that they want their own profit by cooperating or they can willingly help to relay other's information. The strategy which is followed by these helping nodes to relay the information is named as relaying protocol [7], [8], [9]. Following are a few types of relaying protocols:

1.6.1 Amplify- and- Forward (AF) relaying protocol:

This protocol is the simplest of all. In this, the received information signal at the relaying node (sent by the transmitting node) is just scaled to a different level or in other words, it is just amplified and then retransmitted to the receiving node. Here, the relaying node can be said to act as a repeater to reduce the effect of noise in the channel link [7] - [9].

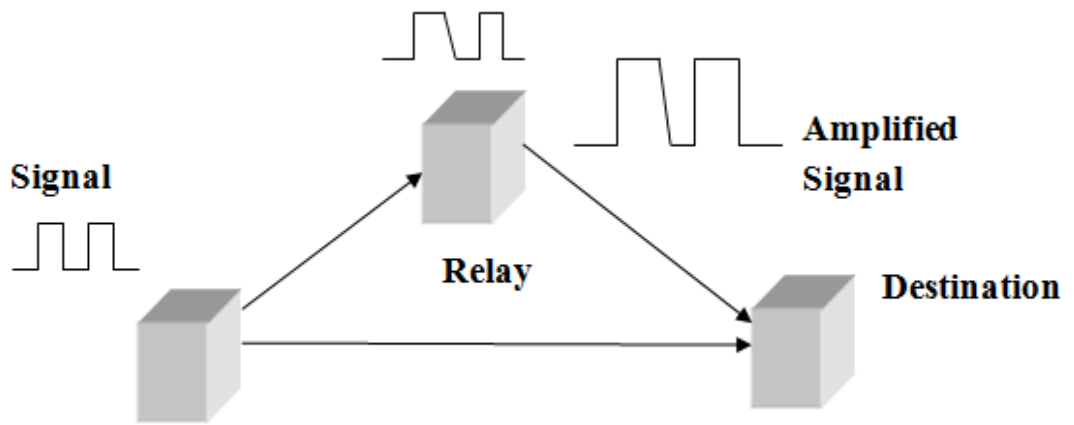


Figure 1.4: Amplify- and- Forward Protocol explained through a system.

1.6.2 Decode- and- Forward (DF) relaying protocol:

In this protocol, the received information signal at the relaying node (sent by the transmitting node), is first decoded, then after re- encoding it is retransmitted to the receiving node [7] - [9].

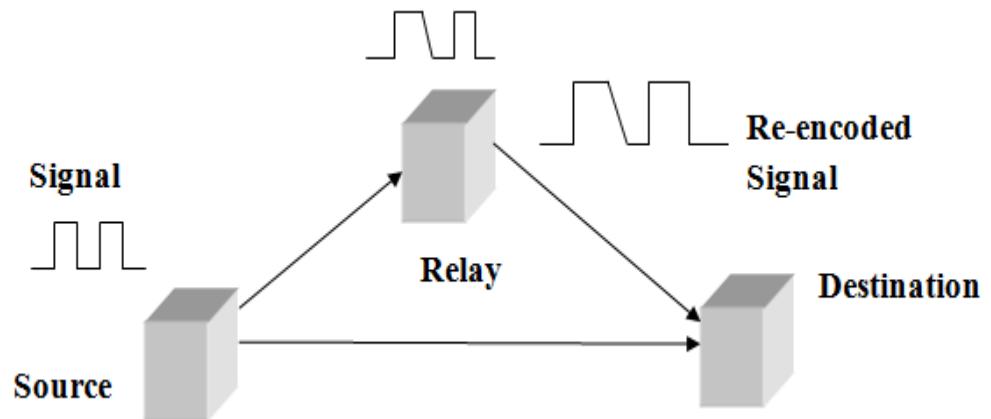


Figure 1.5: Decode- and- Forward protocol explained through a system.

1.6.3 Compress- and- Forward (CF) relaying protocol:

In this protocol, the received information signal at the relaying node (sent by the transmitting node), is first decoded and then its compressed version is retransmitted to the receiving node [7] - [9].

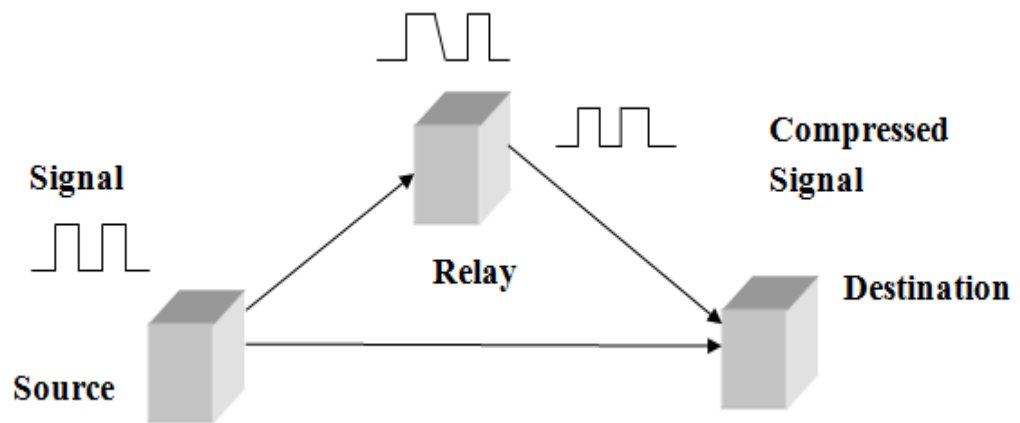


Figure 1.6: Compress- and- Forward protocol explained through a system.

1.7 FEATURES OF COOPERATIVE COMMUNICATION

- Due to the presence of multiple relay nodes in the surroundings, it can be said that it takes the benefit of multiple antennas and form a virtual MIMO, hence exploiting the spatial diversity.
- Spectral Efficiency is increased when wireless systems work in cooperation because bandwidth or the carrier frequencies are allocated to the system in an optimal manner as it is a limited resource.
- Co- channel interference reduces in cooperative communication systems because of proper channel allocation.
- Overall network resources are saved because of less hardware requirement as compared to other MIMO systems.
- Optimal transmit power sharing is achieved.
- Range or coverage is also increased in these systems because of the hops or the nodes present acting as relays.

1.8 GAME THEORY

Game theory is a hypothesis which grants us the means by which we can design an interaction between decision makers which here in cooperative systems are referred to as users. These decision makers or users are the players in the game which have a mutual impact on each other [10].

The wireless network consists of nodes that compete with one another for resources such as time slots, spectrum etc. They all want to make preferences that will prove to be beneficial

for themselves or which will help them in making profit by increasing their utilities. These types of nodes are selfish in nature [10].

The relaying aspirants are considered as the players which contend with each other for getting selected as the best relay so that the users can buy more of their resources and they could make more money. The players or the relaying aspirants compete with one another in distributed manner [10], [11]. The relay selection will depend on the payoff they accomplish while contending with other relays. The payoff is difference between the benefit a relay accomplish on acting as the best relay and cost of the same. The relays in order to accomplish high payoff act rationally and follow certain predefined policies. They act selfishly and try to achieve high payoffs even if their policies have adverse impact on other relays' payoffs [10], [11].

In game theory it is assumed that the players know about other players' policies in present and the strategies followed by them in previous time slot.

1.9 ELEMENTS OF GAME THEORY

Game theory [10] - [14] consists of three major elements explained below:

1.9.1 A set of players:

These are the decision makers that will interact with one another in the designed system model. The players in wireless communication networks are the nodes or the users present in the networks.

1.9.2 A set of policies:

In wireless communication the policies can be varied from type of modulation to coding rate to bandwidth or power etc. The actions or the policies that the players adopt decide the outcomes.

1.9.3 A set of benefits:

The set of benefits are the all possible outcomes when a player follows different policies. The benefits are represented by the utility function which assigns a value to every outcome. The upper the value the more the strategy followed is preferred. In wireless communication one can go for strategies which provide higher signal to noise ratio, low power consumption, low symbol or bit error rate.

1.10 TYPES OF GAMES:

Types of games depend upon the model of the system in observation and number of players included in the model. This division of games into different types helps in following a type for a particular wireless system condition [10] – [14]. There are following 5 possible types of games which are also shown in the Fig. 1.10:

1. Cooperative and Non- Cooperative Games
2. Normal form and Extensive form Games
3. Simultaneous move and Sequential move Games
4. Constant sum, zero sum and non- zero sum Games
5. Symmetric and non- symmetric Games

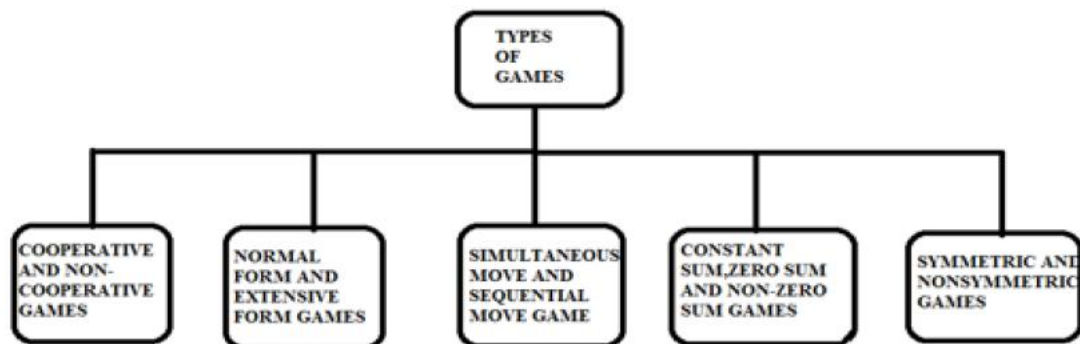


Figure 1.7: Types of Games in Game Theory.

1.10.1 Cooperative and Non- Cooperative Games:

The cooperative games are the ones in which the players bargain with each other and then are encouraged to adopt a particular strategy. The bargaining is carried out among the players in order to have common benefits. The non cooperative games are the ones in which the players work selfishly and without interacting with each other decides for their own profit [15].

1.10.2 Normal Form and Extensive Form Games:

Normal Form games are those in which the matrix- form or the tabular- form is used to describe a game which depicts the payoff and the strategy. This tabular form depicts the outcomes of the particular player by following a policy. Extensive Form games are the ones

in which tree- form is used to depict the result of the player by following a certain strategy [15].

1.10.3 Simultaneous Move and Sequential Move Games:

Simultaneous Move Games are those in which players make their decisions simultaneously without knowing what other players will do. Sequential move games are those in which a player decides its policy according to the other players' policies. In Sequential move games, players know each others' present policies only [15].

1.10.4 Constant Sum, Zero Sum and Non- Zero Sum Games:

Constant Sum games are the ones in which the sum of results of all the players remain constant even if they individually obtain differing result every time. Zero sum games are the one in which sum of the results of all the players is zero and they eventually don't affect the resources. For the non-zero sum games the sum is non zero. The non-zero sum games can be made zero sum games by introducing a dummy player to the model [15].

1.10.5 Symmetric and Non- Symmetric Games:

In Symmetric games all the players implement same policy. The choices in Non- Symmetric games are players independent. In these games the players adopt varying policies and always look for their own benefits [15].

1.11 RESOURCE ALLOCATION IN COOPERATIVE COMMUNICATION THROUGH GAME THEORY:

In cooperative systems, the nodes not only have to relay the information for each other but they also share each other's resources and this comes with some price too. Cooperative communication works efficiently when it is known whether to cooperate or not and how the resources of a relaying node are to be shared among the fellow nodes. Also it is important to know that which relay nodes should a user rely on among the pool of surrounding nodes. Generally for this purpose, an extensive game called Stackelberg Game is implemented in which the resource sharing among the relay nodes is analysed by modelling a buyer seller system, where the transmitter who act as a buyer wish to buy resource from the relay which is acting as a seller. The transmitters/ users compete with one another for the resource of the relay. The resource allocation is analysed using game theory [16] – [25].

Most of the researchers have worked on centralised model. In this work, the model is considered to be distributed in nature and game theory concept is used to analyse the bandwidth allocation among multiple users and multiple relays present.

1.12 DISTRIBUTED AND CENTRALIZED RESOURCE SHARING APPROACH:

A Centralized resource sharing approach is the one in which a central controlling unit is considered which has assigned the work of collecting the information from all the fixed as well as autonomous nodes present in a cooperative diversity system, then calculates the available spectrum and the total transmit power constraint and broadcast this information again to all the users or it can be said that the central controlling unit directly controls the user traffic. In this approach it is assumed that all the nodes present in a system whether fixed or autonomous will help each other in forwarding the information. This approach hence requires partial or a complete knowledge of channel statistics and the channel state information (CSI) i.e. gain of each link present, at each node. This approach hence increases the overheads and signalling because of this pre- required information and is hence neither robust nor scalable to channel estimation errors. On the other hand, a Distributed approach is the one the users present in a cooperative diversity system share information about each other's resources and needs through local communications, hence doesn't require a central controlling unit. They make their own decisions as to which part of the spectrum can be utilized and how the transmit power can be distributed under the total power constraint. This approach is hence robust to network changes as it doesn't pre require any channel statistics or channel state information (CSI). This approach has to decide that among the distributed nodes present which nodes will help to relay the information and improving the quality of the transmitting node's link, and after that how much resource such as power or the bandwidth they can share.

In this work, the comparison between these two approaches is shown which proves that on using distributed approach, a comparable performance is seen between the two which is beneficial as it increases the robustness and efficiency.

1.13 OBJECTIVE OF THE THESIS:

1. The aim of the thesis is to allocate the optimal bandwidth which is a very limited resource to a cooperative diversity system consisting of multiple relays and multiple users.

2. It has to be decided how the various users compete with one another to attract more relays so that they can acquire more spectrum(s) or more of relaying nodes' bandwidth for their own transmission to increase their utilities.
3. It is also to be shown as to how the various relaying nodes compete with each other to attract more buying of their resources by either decreasing their charges to an optimal price when they possess good channel conditions or by asking for more price(s) when they are away from source nodes and possess poor channel conditions.
4. A Stackelberg game approach of dividing the system into two levels of purchasers and vendors for fulfilling the above two requirements stated in 2 and 3 is need to be applied.
5. Another aim of this thesis is to prove that applying a distributed approach for resource allocation gives comparable result to a centralized approach, hence improving the robustness and reducing the overheads.

1.14 ORGANISATION OF THE THESIS:

- In chapter 2, the research papers are discussed which helps in building a general understanding about the cooperative communication model and basics of game theory. It gives a brief knowledge about the work done by the researchers till date and scope of improvements.
- In chapter 3, the power allocation is performed on a simple cooperative communication model possessing single relay and multiple relays to show the basic understanding as to how the Stackelberg game works to allocate the resources.
- In Chapter 4, the main work of bandwidth allocation on the multi- user and multi-relay system model following Amplify- and- Forward relaying protocol is shown using distributed Stackelberg approach with proper equations.
- In chapter 5, all the results for single relay, multiple relay systems and comparison between the two approaches is shown.
- Finally, chapter 6 shows the conclusion of the work performed and the future scope.

CHAPTER 2

LITERATURE SURVEY

Sendonaris (2003) et al. [3] in “User Cooperation Diversity—Part I: System Description” proposed a diversity technique which helps in combating the attenuation in the signal when a call is in process which results in different data rate and quality of service for the mobile users. This new diversity technique is a kind of spatial diversity which is achieved by the cooperation of the mobile users. This work describes the strategy for the user cooperation for a traditional Code- Division Multiple Access (CDMA) system. The resulting parameters are increase in capacity for every user and more robustness with less susceptibility of data rates of the user to variations in the channel. The cooperation was achieved on the users which are active in nature i.e. users who have to send their own data too and not merely be a relay for another user.

Sendonaris (2003) et al. [4] in “User Cooperation Diversity—Part II: Implementation Aspects and Performance Analysis” considered the practical issues related to the implementation of the cooperation concept. Two receiver designs were considered, Optimal and Sub- Optimal and their performance analysis are done for a traditional Code- Division Multiple Access (CDMA) system. Secondly, a high- rate CDMA implementation is discussed when there is no Channel State Information (CSI) is present at transmitters and how the cooperation can be achieved in this scenario.

Laneman (2004) et al. [5] in “Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behaviour” proposed the protocols which are helpful in mitigating the effects of fading resulted by multipath propagation of information signals in wireless systems. These protocols are cooperative- diversity protocols which have low complexity. The relaying strategies are also considered such as Fixed relaying: Amplify- and- Forward (AF) scheme and Decode- and- Forward (DF) scheme, as well as Selection relaying which adapts based upon the channel measurements between the cooperating nodes. Performance is analysed based upon the outage events and resulting outage probabilities. Except Decode- and- Forward scheme, all the other ones are proved to be efficient since they achieve full diversity. It is shown that space diversity can be achieved by distributed antennas too and not requiring physical arrays but at a cost of extra receiver hardware and decreased spectral efficiency.

Yu (2007) et al. [8] in “Joint Optimization of Relay Strategies and Resource Allocations in Cooperative Cellular Networks” considered a cellular network in which there is a base station and the subscribers are cooperating with each other to relay each other’s information. The network is considered to be working as a frequency- selective slow fading channel for which a Centralized framework is designed for maximising the utility which not only allocates the power and bandwidth optimally to every user but also selects the relay nodes and the better relay strategy between the Amplify- and- Forward (AF) and Decode- and- Forward (DF) techniques. The Lagrangian duality theorem is applied in this work.

Laneman (2004) et al. [9] in “Network Coding Gain of Cooperative Diversity” compares the network coding gains for two types of cooperative diversity protocols having low complexities which are Amplify- and- Forward (AF) and repetitive Decode- and- Forward (DF). Although both types of schemes provide full diversity advantage, the results indicate that amplify-and-forward (AF) provides several dB of additional coding gain from any network geometries, and performs for those geometries in which the relays are much closer to the source than to the destination. Maximum Ratio Combining (MRC) is employed with the proposed protocol.

MacKenzie (2001) et al. [10] in “Game Theory and the Design of Self -Configuring, Adaptive Wireless Networks” provided a brief introduction of the Game Theory which is a tool to design and operate the communication systems. It is also shown to be applicable in the problems of random access and power control. The behaviour of selfish users is examined in the case of random access ALOHA protocol where it was seen that these selfish nodes do not transmit the information continuously and always. In the case of power control, it was observed that game theoretic techniques can yield an optimal operating point without an external need of a controller.

Niyato (2008) et al. [11] in “Competitive Spectrum Sharing in Cognitive Radio Networks: A Dynamic Game Approach” proposed a non cooperative game to solve the problem of sharing of the spectrum among a primary user and multiple secondary users. The problem is formulated as an oligopoly market competition. The solution to spectrum sharing is done using two strategies: one is the static game in which the secondary users are assumed to have the knowledge of the strategies which are adopted by each user and also their payoffs, second being the case where secondary users gradually adjust their own strategies based upon the previous observations.

Huang (2007) et al. [12] in “Auction-Based Distributed Resource Allocation for Cooperation Transmission in Wireless Networks” proposed two share auction mechanisms, one being the SNR auction, another being the Power auction. These two mechanisms help in coordinating the resource allocation among the users in a distributive way. The uniqueness, existence and the effectiveness of the auction results are also proved. The SNR auction results in a fairer resource allocation than the Power auction among users. The Power auction leads to a solution which is close to the efficient allocation means that the efficiency of Power auction is more than the SNR auction.

Bacci (2010) et al. [13] in “Game Theory in Wireless Communications with an Application to Signal Synchronization” solved the problem of optimizing the function of initial code acquisition in a CDMA network based upon game theory. The problem was restated as a non cooperative (distributed) game in which the transmitter-receiver pairs jointly set their transmit powers at the transmitter side and detection thresholds at the receiver side to maximize the ratio between the probability of detection and the transmitted energy per acquisition.

Alpcan (2002) et al. [14] in “CDMA Uplink Power Control as a Non cooperative Game” proposed a game theoretic approach for the control of the power in a distributive way in code division multiple access (CDMA) wireless systems. The pricing problem among the users is also considered. For showing the difference between the pricing and the utility functions, a cost function is introduced. Parallel update and Random Update algorithms are also shown to be stable globally. The proposed solution gives satisfactory decentralized and market- based solutions. Convergence properties of each algorithm are also studied through various simulations.

Hasna (2004) et al. [15] in “Optimal Power Allocation for Relayed Transmissions Over Rayleigh-Fading Channels” analysed the effect on power distribution when the number of hops that are relay nodes are increased in a system between the source and destination. Due to multi- hopping, the coverage area increases, battery life increases and the overall interference reduces. In this work, the optimal power to be allocated is analysed over multiple hops when there is an overall fixed power supply. The channel hops are assumed to be experiencing Rayleigh Fading. The criterion for optimization used in this work is the Outage probability which represents the probability of the link quality between source and destination falling below a particular threshold value. It showed that when no power optimisation is performed

on regenerative systems, then their performance is weak as compared to non- regenerative system with optimal power allocation.

Bletsas (2005) et al. [16] in “A Simple Distributed Method for Relay Selection in Cooperative Diversity Wireless Networks, based on Reciprocity and Channel Measurements” analysed and derived the best relay among a pool of M relays which has the best link quality from source to relay as well as from relay to destination. The technique applied in this work does not require any prior knowledge of Channel State Information (CSI) nor does it require the topology of network to be known. Hence it best suits the distributed networks in which the topology changes regularly and randomly. Space- time coding in the system is simplified due to the presence of a single relay in observation.

Han (2005) et al. [17] in “Fair Multiuser Channel Allocation for OFDMA Networks Using Nash Bargaining Solutions and Coalitions” proposed a fair method to allot the number of subcarriers, rate, power for a multiple- user orthogonal frequency division multiple access (OFDMA) system. The power and overall system rate is to be maximized while keeping the minimal rate constraints. Nash bargaining solutions and coalitions are considered here. For bargaining between two users for the subcarriers, a different algorithm is designed and then a generalised multiuser algorithm is designed on the basis of optimal coalition pairs possible among the users. This proposed iterative implementation gives a lesser complexity.

Zhao (2007) et al. [18] in “Improving Amplify-and-Forward Relay Networks: Optimal Power Allocation versus Selection” considered a multiple- relays model in which the power is optimally allocated based on two levels, one being the Channel State Information (CSI), another being the statistics of the channel. The relaying technique considered here is the Amplify- and- Forward (AF) technique. These methods give the sub- optimal results for power allocation and they tend to reduce the Symbol- Error- Rates (SER) and the outage probability of the system. This work selects the best relay to cooperate which results in less interference and doesn't require partitioning the resources among the orthogonal channels of various transmitting and receiving nodes. This technique is named as Selection- AF technique and it provides better throughput and full diversity order as compared to the traditional cooperative schemes in which every relay participates.

Ibrahim (2008) et al. [19] in “Cooperative Communications with Relay-Selection: When to Cooperate and Whom to Cooperate With?” discussed two main things for a multi- relay

single- user cooperative communication system model which applies Decode- and- Forward (DF) as the relaying technique. Those two being the time when the source needs to cooperate with a single relay and the decision of nodes which will help in relaying when dealing with the case of cooperation. The protocol proposed in this work used to achieve higher bandwidth efficiency while keeping the diversity order to be same as the traditional cooperation techniques. It derives the optimal relay which has the highest instantaneous scaled mean function of its source to relay and relay to destination channel gains, which is harmonic in nature. The trade- off between the resulted bandwidth efficiency and the Symbol- Error- Rate (SER) is shown to be achieved properly.

Zheng (2009) et al. [20] in “Optimizing Relay Selection and Power Allocation for Orthogonal Multiuser Downlink Systems” proposed the allocation of power and selection of helping relays for the orthogonal multi- user networks in which Amplify- and- Forward (AF) relaying scheme is used in the downlink. This work deals with maximizing the total data rate of the users, subject to individual and total power constraints on the relay nodes and a relay assignment constraint. The problem of power allocation is convex for the fixed relaying scheme while the joint optimization of selection of the relay nodes and power allocation is non- convex which can be solved by Markov chain Monte- Carlo (MCMC) algorithm combined with Cross Entropy Optimization (CEO).

Wang (2009) et al. [21] in “Distributed relay selection and power control for multiuser cooperative communication networks using Stackelberg game,” proposed a single- user, multiple- relays cooperative communication model which employs Amplify- and- Forward (AF) as its relaying technique in which the relay nodes simply amplify the received signal from the source node which is scaled down due to channel conditions in between, and then forward it to the destination node. The Stackelberg game theory which is applied divides the model into two parts: one being the sellers (relay nodes), another being the buyers (source nodes). The buyer buys optimum power from the sellers to increase its utility by selecting the sellers from which it has to buy depending on the distance and the channel conditions. The sellers on the other hand, ask optimal price from the seller to increase their utility, also keeping in mind one another’s prices. The Stackelberg equilibrium is shown to achieve the desired results. The proposed distributed scheme is shown to achieve the comparable results to the centralized scheme. The convergence speed according to the number of iterations is also observed in this work.

Zappone (2010) et al. [22] in “Resource Allocation in Relay-assisted DS/CDMA Interference Channels: a Stackelberg game Approach” addressed the problem of resource allocation for MSE minimisation in a Direct Sequence/Code Division Multiple Access (DS/CDMA) relay- assisted interference channel. Stackelberg game is applied on two levels for the resource allocation in which the relay nodes are considered as the leaders and the multiple access users are considered as the followers. Amplify- and- Forward (AF) relaying technique is considered.

Zhang (2011) et al. [23] in “A Stackelberg game for resource allocation in multiuser cooperative transmission networks,” analysed a multiple- users, single- relay Amplify- and- Forward (AF) cooperative communication model using a non- cooperative Stackelberg game approach. The problem in this work is formulated as a seller’s market competition since the relay which acts as a seller is willing to share its resource which is bandwidth among multiple users. The relay node focuses on increasing its utility by asking the related prices from each user according to their demand, and the users tend to increase their utility by purchasing optimum bandwidth from the relay. Distributed Nash equilibrium is derived and compared with the centralized one. Homogenous network is considered in this work in which every user is supposed to have the same kind of utility function.

Al- Tous (2013) et al. [24] in “Joint Power and Bandwidth Allocation for Amplify and Forward Cooperative Communications Using Stackelberg Game,” proposed a non- cooperative Stackelberg Game strategy for allocating the optimum power and optimum bandwidth jointly to a multiple- users, single- relay cooperative communication model using an ‘Amplify- and- Forward’ (AF) relaying technique. Both the power and the bandwidth are considered to be variable in this work and as these two are the most important and at the same time scarce resources, their allocation is shown to be optimised among the multiple users. The solution to the proposed technique which is done using distributed approach is compared by the Nash Equilibrium which acts a Centralized Technique. Further, Jacobian matrix is used to study the convergence of the above stated algorithms. This work deals with allocating the resources to the users which are selfish in nature having no co- ordination among them.

Zhang (2015) et al. [25] in “A Distributed Algorithm for Bandwidth Resource Sharing in Relay-Aided Wireless Cellular Networks: From the Perspective of Economic Equilibrium Theory” performed the bandwidth sharing for cellular systems in which relay nodes are helping to forward the information. The data source is considered as a User Equipment (UE)

in this work which will forward its information as well as acts as a helping relay for other UEs. Also it is shown that a selfish UE will be willing to share its bandwidth if the cost can be recovered by the payment done by the source UE hence increasing the selfish UE's utility. The equilibrium point is achieved through the demand and supply theory.

CHAPTER 3

POWER ALLOCATION IN THE COOPERATIVE COMMUNICATION SYSTEM

3.1 POWER ALLOCATION PROCEDURE:

The model that we considered for allocating power in a cooperative communication environment is simply a single- user, multiple- relay model as shown in Fig. 3.1 below.

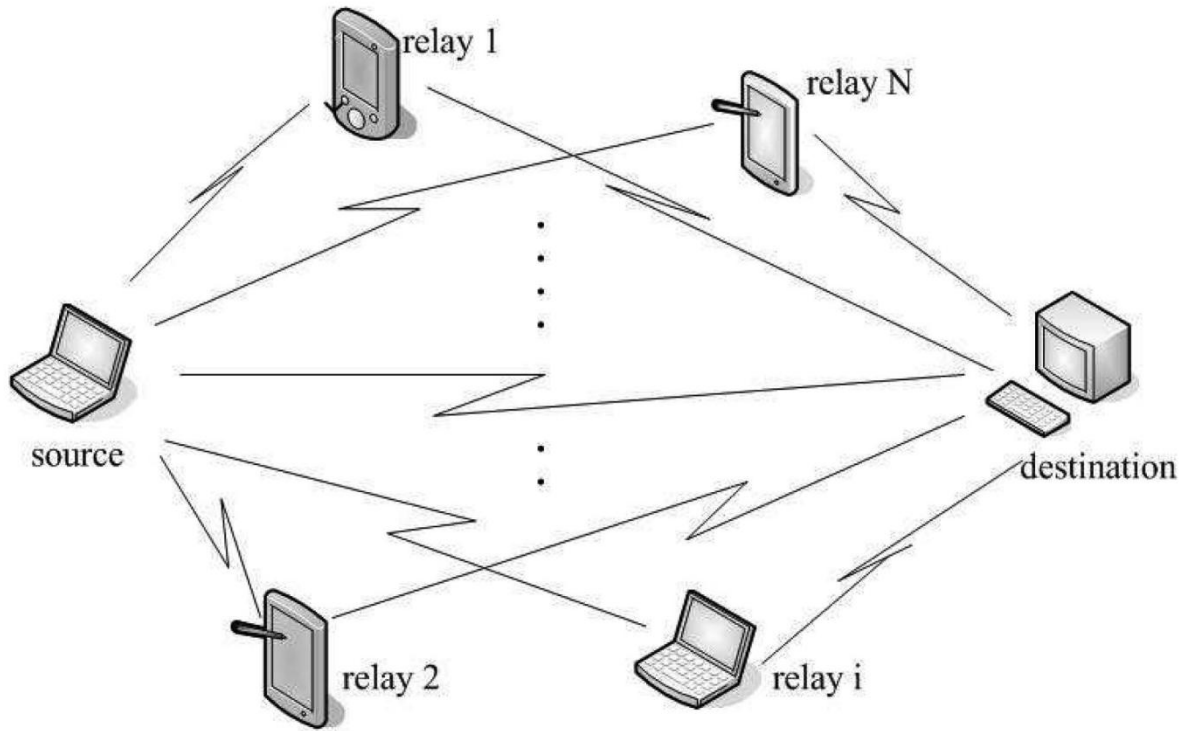


Fig. 3.1: System Model for Power Allocation.

Let number of relay nodes is given by $i = [1, 2, \dots, N]$, the received signals $l_{s,d}$ and l_{s,r_i} at nodes d and r_i respectively in the first phase are given as follows:

$$l_{s,d} = \sqrt{P_s H_{s,d}} t + n_{s,d}, \quad (1)$$

$$l_{s,r_i} = \sqrt{P_s H_{s,r_i} t} + n_{s,r_i}, \quad (2)$$

where, P_s denotes the transmitted power from source node s , t is the transmitted symbol of user with unit energy.

H_{s,r_i} and $H_{s,d}$ are the gains of the channeling paths from node s to node r_i and to node d respectively, $n_{s,d}$ and n_{s,r_i} are the additive white Gaussian noises (AWGNs). Noise power is assumed to be identical for all the channel links and denoted by σ^2 .

Given below is the signal to noise ratio (SNR) that results from direct broadcast of information from transmitting node s to receiving node d without the assistance of relaying node:

$$\Gamma_{s,d} = \frac{P_s H_{s,d}}{\sigma^2}, \quad (3)$$

and the rate of the direct broadcast is as given:

$$R_{s,d} = B \log_2 \left(1 + \frac{\Gamma_{s,d}}{\Gamma} \right), \quad (4)$$

where, B is the bandwidth for transmission and Γ is an unvarying factor which represents the capacity gap.

In second phase, the relaying node r_i performs amplification of the received signal l_{s,r_i} and passes it on to the receiving node d with P_s as the transmitted power. So, the signal at receiving node d is:

$$l_{r_i,d} = \sqrt{P_r H_{r_i,d}} t_{r_i,d} + n_{r_i,d}, \quad (5)$$

where,

$$t_{r_i,d} = \frac{l_{s,r_i}}{|l_{s,r_i}|}, \quad (6)$$

is the signal sent from node r_i to node d , $H_{r_i,d}$ is the gain of the channeling link from node r_i to node d , and $n_{r_i,d}$ is the received noise.

Replacing (2) into (6), equation (5) can be rewritten as:

$$l_{r_i,d} = \frac{\sqrt{P_r H_{r_i,d}} \left(\sqrt{P_s H_{s,r_i}} t + n_{s,r_i} \right)}{\sqrt{P_s H_{s,r_i} + \sigma^2}} + n_{r_i,d}, \quad (7)$$

Using equation (7), the relayed SNR from transmitting node s by relay node r_i is hence given by:

$$\Gamma_{s,r_i,d} = \frac{P_r P_s H_{r_i,d} H_{s,r_i}}{\sigma^2 (P_r H_{r_i,d} + P_s H_{s,r_i} + \sigma^2)}, \quad (8)$$

Now since maximum ratio combining (MRC) detector is used in this work, therefore by using equations (4) and (8), the rate at the output of the detector using single relaying node r_j becomes:

$$R_{s,r_i,d} = \frac{B}{2} \log_2 \left(1 + \frac{\Gamma_{s,d} + \Gamma_{s,r_i,d}}{\Gamma} \right), \quad (9)$$

where, factor $\frac{1}{2}$ in equation (9) is due to the fact that two time periods are used for the cooperative communication.

If the relaying nodes which are ready to assist the transmitting node s are ranging from $i = [1, 2, \dots, N]$, then the rate becomes:

$$R_{s,r,d} = \frac{B}{2} \log_2 \left(1 + \frac{\Gamma_{s,d} + \sum_{i=1}^N \Gamma_{s,r_i,d}}{\Gamma} \right), \quad (10)$$

So, the utility for the transmitting node s or the buyer will become:

$$U_s = z R_{s,r,d} - V, \quad (11)$$

where, z denotes the gain per unit rate at the output of the maximum ratio combiner (MRC) detector, and

$$V = \sum_{i=1}^N q_i P_{r_i} = q_1 P_{r_1} + q_2 P_{r_2} + \dots + q_N P_{r_N}, \quad (12)$$

represents the total payments paid by the transmitting node s to the relay nodes. Here, q_i denotes the charge per unit of power selling from the relaying node r_i to transmitting node s and P_{r_i} shows amount of power node s will buy from node r_i .

The buyer- level game is hence given as:

$$\max_{\{P_{r_i}\}} U_s = zR_{s,r,d} - V, \quad s. t. P_{r_i} \geq 0, i = [1,2, \dots, N], \quad (13)$$

Similarly, the utility of the relaying node or the seller node will become:

$$U_{r_i} = q_i P_{r_i} - c_i P_{r_i}, \quad (14)$$

where, c_i is the cost of power for relaying information. So, the seller- level game hence becomes:

$$\max_{q_i > 0} U_{r_i} = (q_i - c_i) P_{r_i}, \quad \forall i, \quad (15)$$

By finding the optimal solutions to these utility functions, the Optimal Power comes out to be:

$$P_{r_i}^* = \sqrt{\frac{X_i Y_i}{q_i} \frac{A + \sqrt{A^2 + 4CB'}}{2C}} - Y_i, \quad (16)$$

where, $X_i = \frac{P_s H_{s,r_i}}{(\Gamma \sigma^2 + P_s H_{s,d})}$ and $Y_i = \frac{P_s H_{s,r_i} + \sigma^2}{H_{r_i,d}}$. Also, $A = \sum_{k=1}^N q_k X_k Y_k$, $B' = \frac{zB}{\ln 2}$ and

$$C = 1 + \sum_{k=1}^N X_k.$$

The Optimal Price comes out to be as follows:

$$q_i^* = q_i^*(\sigma^2, \{H_{s,r_i}\}, \{H_{r_i,d}\}), \quad i = [1,2, \dots, N], \quad (17)$$

3.2 SINGLE USER- SINGLE RELAY CASE:

In a single user, single relay case as shown in the Fig. 3.2 below, the Amplify- and- Forward (AF) relaying scheme is employed. The transmitting node sends the signal directly to the receiving node and to the relaying node in the first phase. The received signal at the relaying node is then amplified and passed on to the receiving node in the second phase.

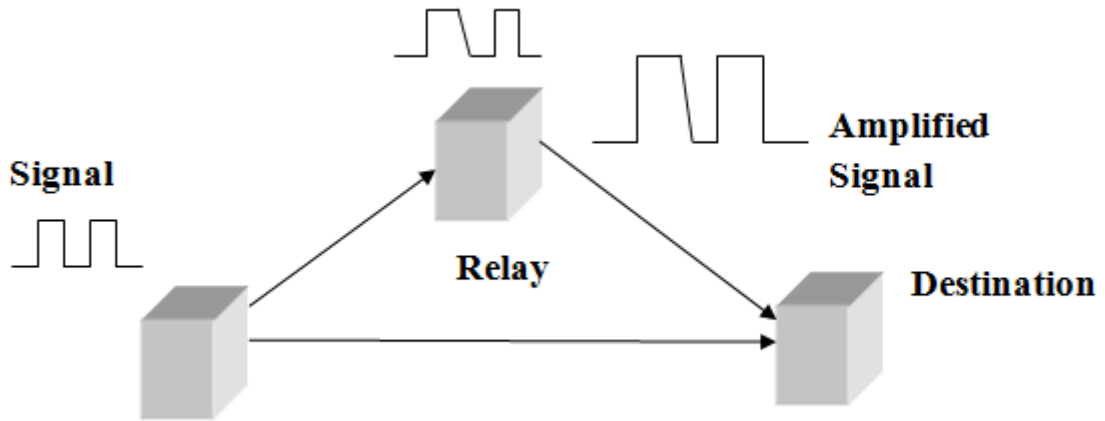


Fig. 3.2: Single user- single relay Amplify and Forward system model.

Let us consider that for our case, the transmitting node is fixed at $(100\text{m}, 0\text{m})$, the receiving node is fixed at $(0\text{m}, 0\text{m})$ and the relaying node's y co-ordinate is fixed at 25m while its x co-ordinate is varying from $[-250\text{m}, 300\text{m}]$ as shown in the Fig. 3.3 given below.

So, from the setup of single user, single relay cooperative communication model shown in Fig. 3.3 and all the equation above, the optimal power and price distribution is shown in Fig. 3.4.

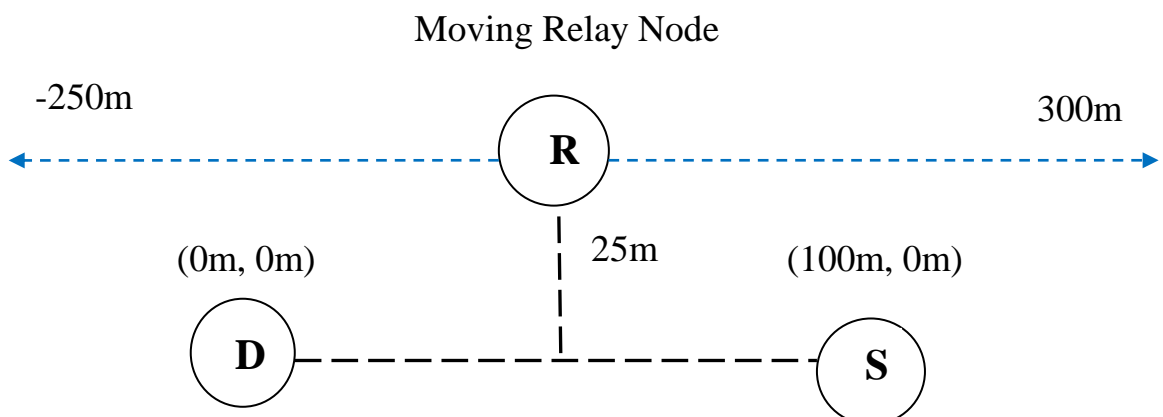


Fig. 3.3: Setup of the system.

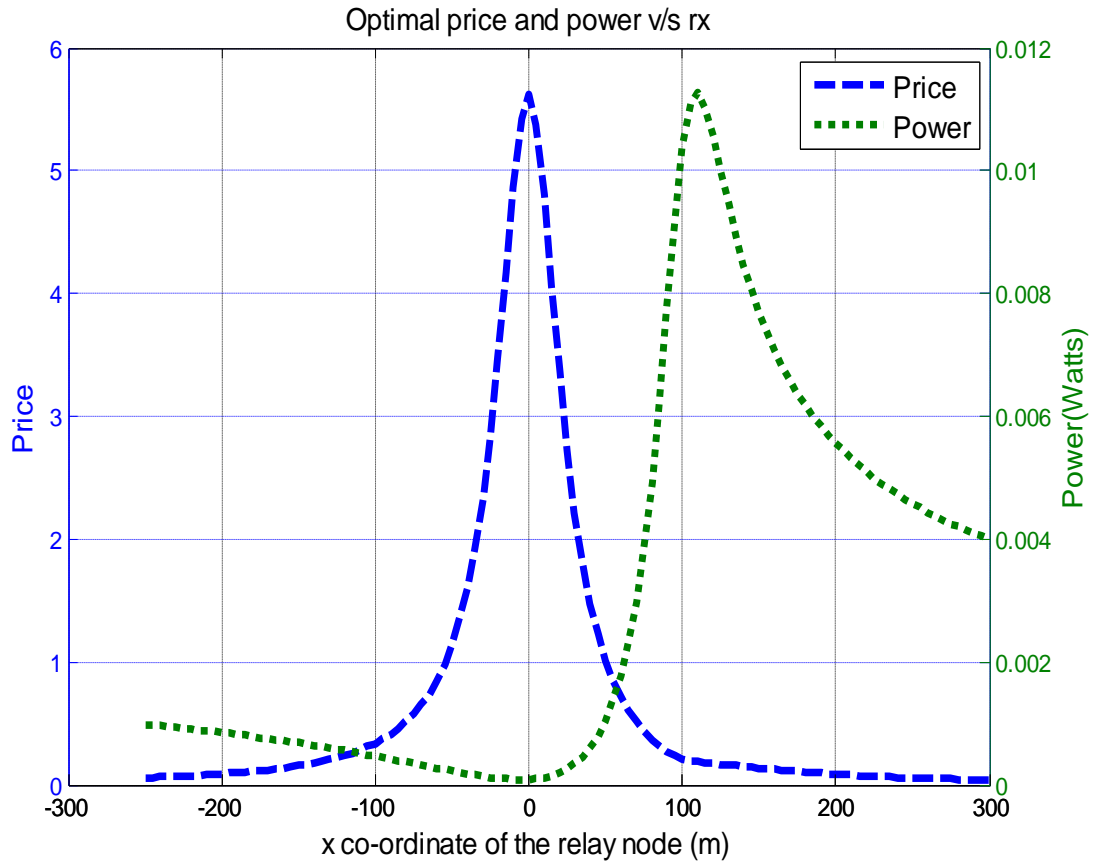


Fig. 3.4: Optimal Power and Price of the single relaying node at different locations.

From the graph shown in Fig. 3.4, it can be said that when the relaying node is close to the transmitting node s which is located at $(100\text{m}, 0\text{m})$, the power allocated to the user is maximum. Hence the transmitter utility is highest at this point. While to increase the utility of the relaying node it has to decrease its price optimally to attract more buying from the transmitting node.

When the relaying node moves close to the receiving node which is located at $(0\text{m}, 0\text{m})$, it can use a very small amount of power to relay the information of the transmitting node s since transmitter buys less power due to larger distance and poor channel condition that it provides at this point. However, the price here is higher than when the relaying node r was close to the receiving node d , still the power bought is less.

If the relaying node r keeps moving away from the receiving node d , transmitting node s stops to buy services from the relaying node since it is of no benefit now.

Similarly, when the relaying node r moves in the opposite direction from transmitting node s , its services would not be bought here either.

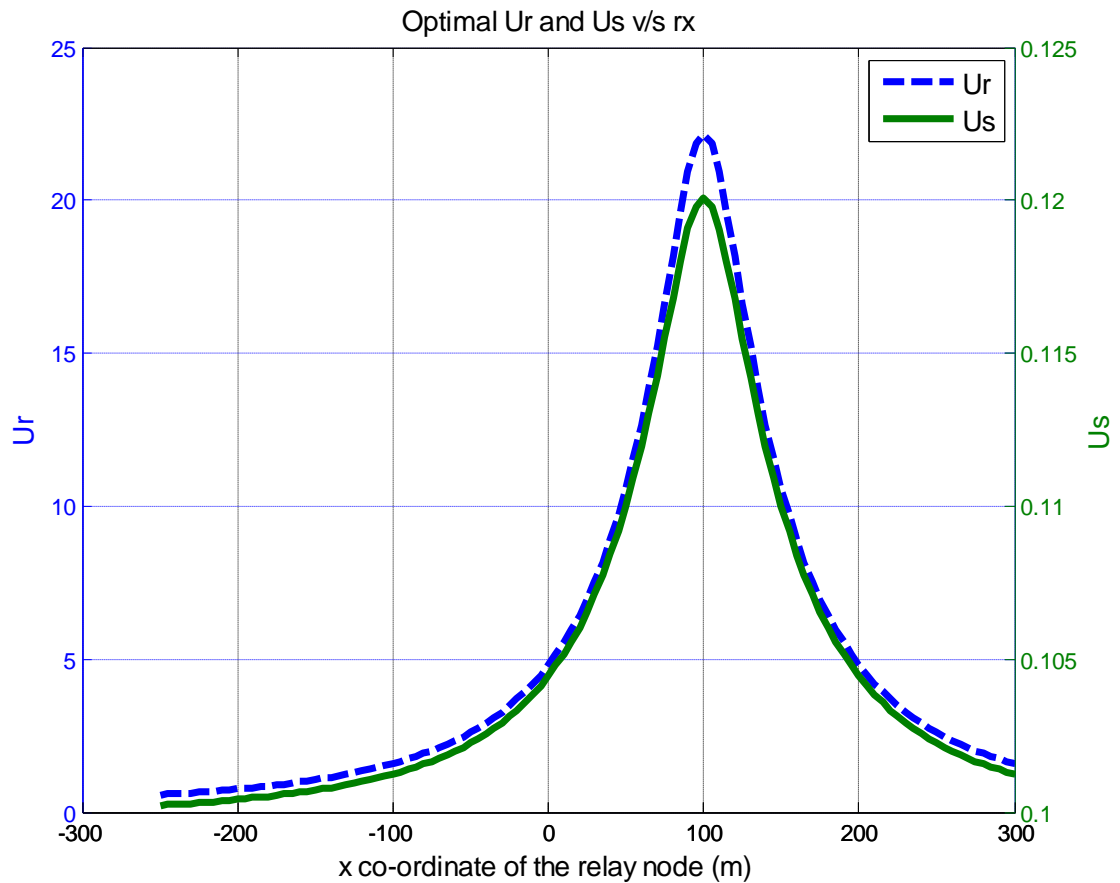


Fig. 3.5: Utilities of the source and relay nodes for single relay case.

From Fig. 3.5, it can be seen that both the utilities of the transmitting node s and the relaying node r are maximum when the relaying node is close to the transmitting node and are minimum when the relaying node is close to the destination node.

3.3 SINGLE USER- MULTIPLE (TWO) RELAY CASE:

In a single user, single relay case as shown in the Fig. 3.6 below, the Amplify- and- Forward (AF) relaying scheme is employed.

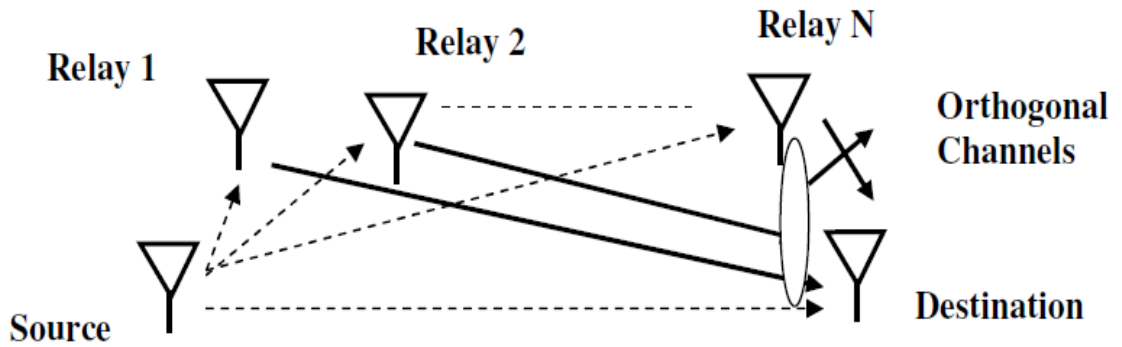


Fig. 3.6: Single user- multiple relay Amplify and Forward system Model.

For this case, let the transmitting node s is positioned at $(100\text{m}, 0\text{m})$, the receiving node d is positioned at $(0\text{m}, 0\text{m})$, relaying node r_1 be positioned at $(50\text{m}, 25\text{m})$ and the relaying node r_2 has y co-ordinate fixed at 25m while it is moving along the x axis from -250m to 300m as shown below in Fig. 3.7:

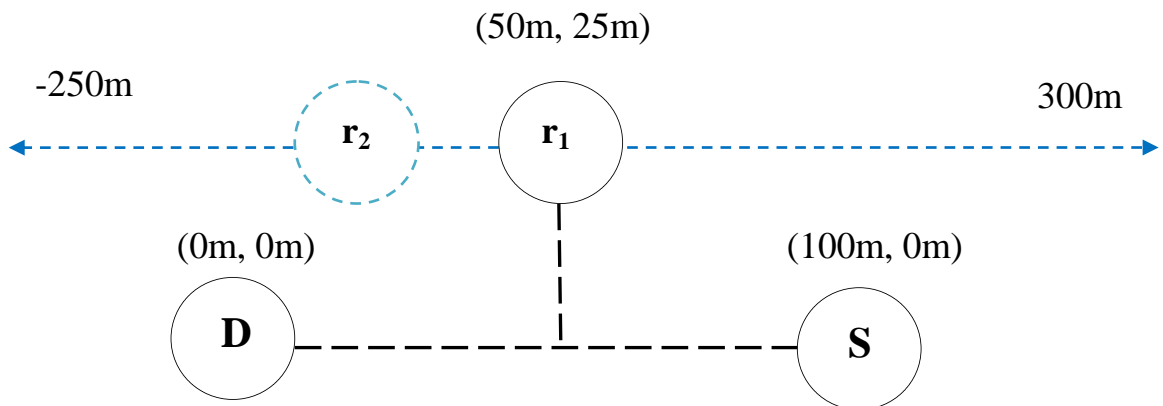


Fig. 3.7: Setup of the system.

Fig. 3.8 shows the optimal price distribution for the single user two relays case. It shows that even when only a single relaying node r_2 is moving, the prices of both the relaying nodes r_1 and r_2 change accordingly showing that they are dependent on each other.

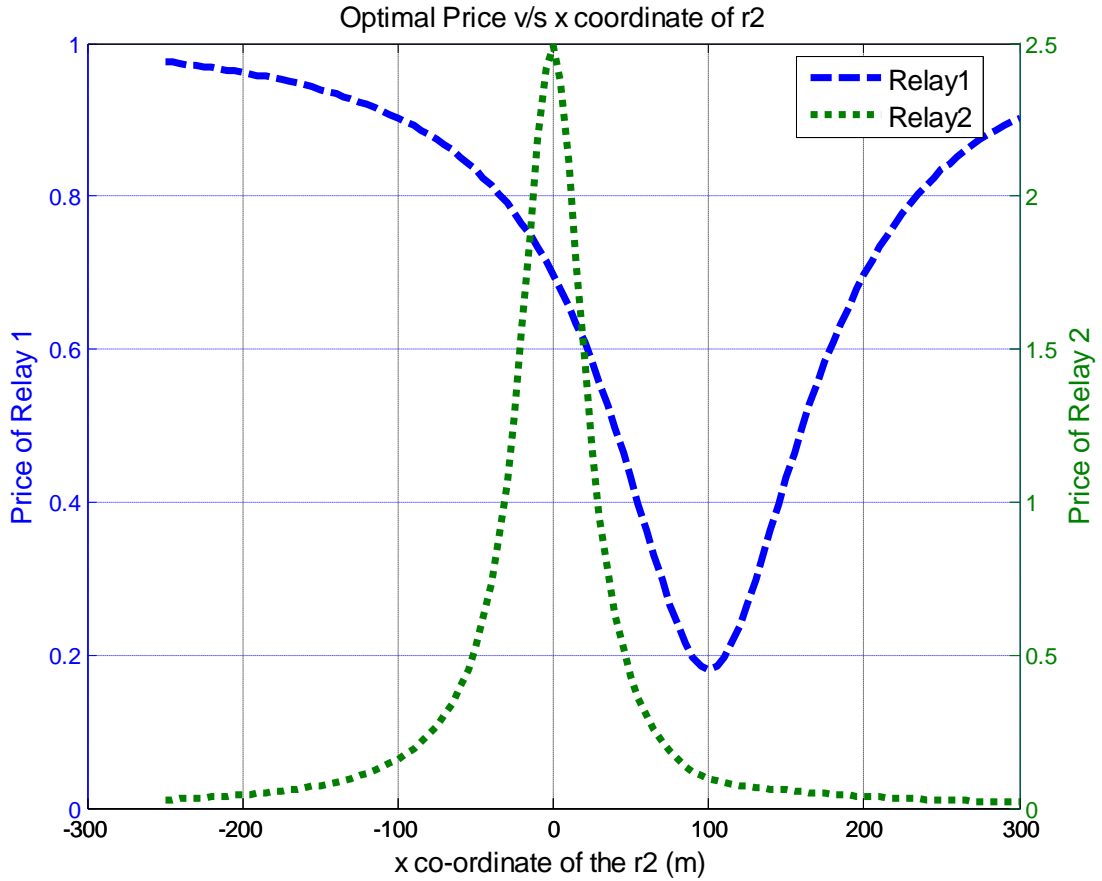


Fig. 3.8: Optimal Prices for the two relay nodes.

When relaying node r_2 is near to the receiving node d which is positioned at $(0m, 0m)$, it has to increase its price for increasing the utility since otherwise the source node s is not gone to buy the power from the relaying node at this point. Correspondingly, relaying node r_1 increases its price. When node r_2 moves to the transmitting node s which is positioned at $(100m, 0m)$, it becomes more suitable for s than relaying node r_1 . So, r_1 increases its price to improve its own utility.

As the relaying node r_2 goes away from either transmitting node s or receiving node d , its price drops because now it gives less competition to relaying node r_1 . Also if we compare the price distribution of this case with the one shown in Fig. 3.4, it can be seen that as the number of relaying nodes increases the overall amount of price distribution decreases.

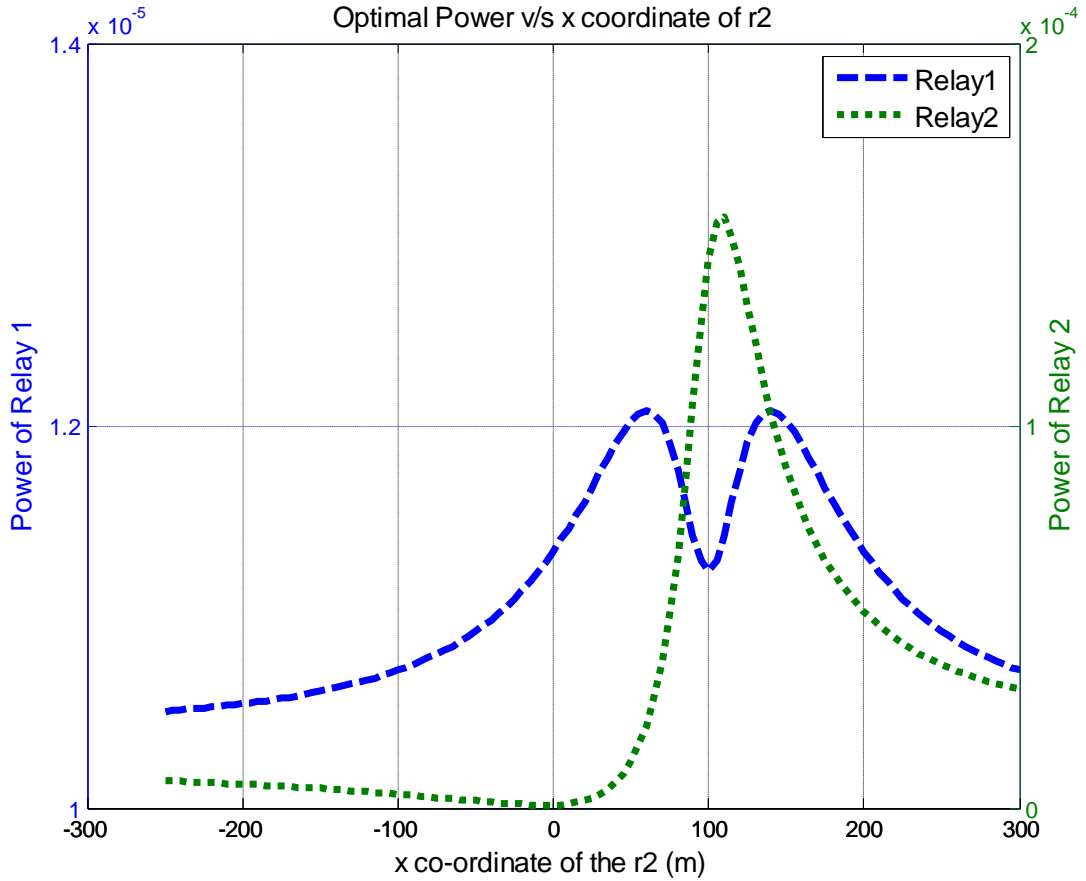


Fig. 3.9: Optimal Power Allocation for single user- two relay case.

Fig. 3.9 shows the Optimal Power allocation for the single user, two relay case. It can be seen that when the relaying node r_2 is near to the transmitting node s , it allocates maximum power to node s while relaying node r_1 allocates lesser power since r_2 is more competitive here because of the least distance and good channel conditions as compared to the node r_1 .

Finally Fig. 3.10 shows the utility functions of both the relaying nodes r_1 and r_2 . It shows that when the node r_2 is near to the receiving node d which is positioned at $(0m, 0m)$, its utility is minimum because at this point it has to increase its price to attract the transmitting node s but since r_1 is more near to s , r_1 's utility is more than r_2 at this point.

While if the node r_2 is near to the transmitting node s which is positioned at $(100m, 0m)$, its utility is maximum here because of least distance and good channel conditions as compared to node r_1 . So at this point r_2 's utility is more than r_1 .

At all the other positions when the relaying node r_2 goes away from either transmitting node s or receiving node d , its utility decreases while utility of node r_1 increases because r_2 becomes less competitive at all these points.

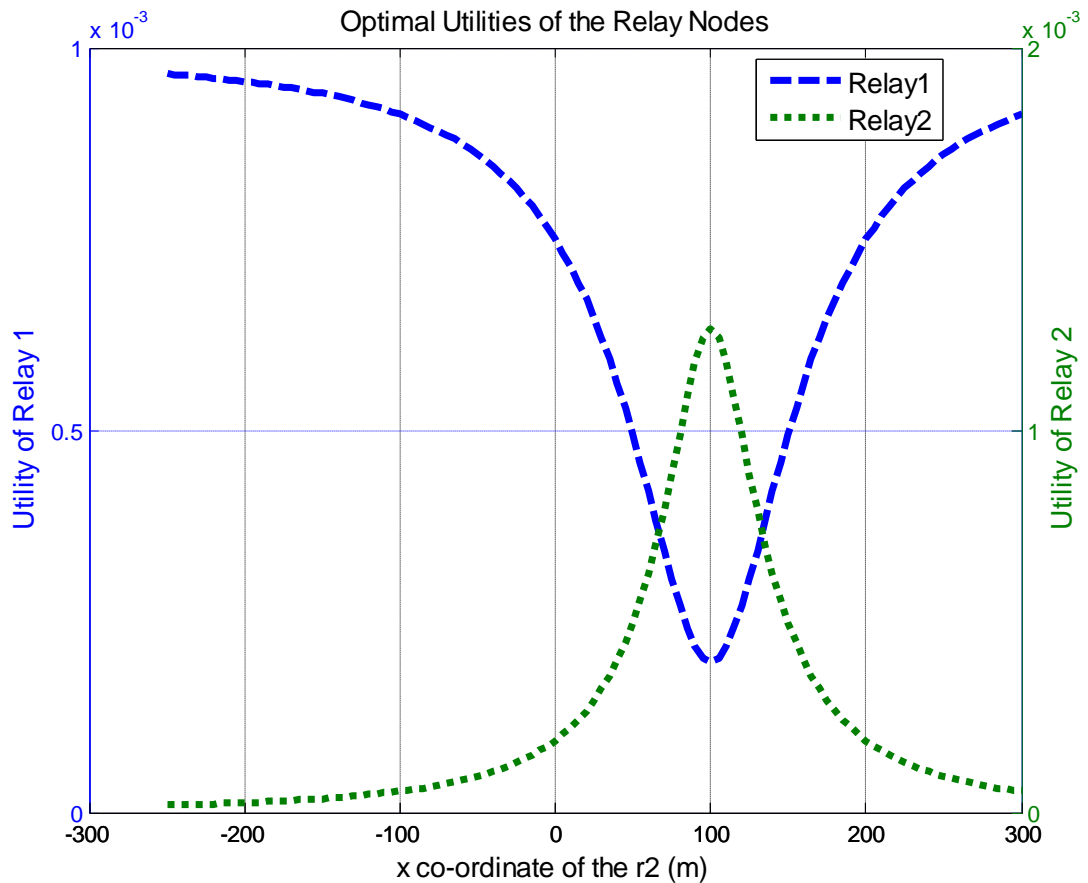


Fig. 3.10: Optimal relay nodes' utility for the single user- two relay case.

So, this is the conclusion of Chapter 3, in which the power allocation is being discussed for the basic single relay and multiple relays cooperative communication environment using Stackelberg Game. This portion is essential for understanding the behaviour of the Stackelberg Game and to understand how the resource allocation is done. For power allocation in this chapter, bandwidth is kept fixed, while in the next Chapter 4, the main work is done upon the bandwidth allocation for multi- user, multi- relay case, which is one step forward, where power is assumed to be fixed.

CHAPTER 4

BANDWIDTH ALLOCATION USING STACKELBERG GAME

The basic work that this research is based upon is to derive the optimal bandwidth that should and can be allocated to the users when they are multiple in number by the surrounding nodes so that they can forward their information, and also to decide the optimal charging prices by the multiple relays which are behaving as helping nodes to forward the transmit information. Thus, the model selected in this research is a Multi- user, Multi- relay model. The relaying technique applied here is the Amplify- and- Forward (AF) relaying technique.

For solving the above two requirements, the extensive or dynamic form game i.e., Stackelberg Game is applied. This game works on two levels. On one level, some nodes will be considered as the ‘leaders’ or ‘sellers’; in this case the helping relay nodes will be them. On another level, the remaining nodes will be considered as the ‘followers’ or the ‘buyers’; in this case the users (source- destination pairs) being them. The sellers are selling their bandwidth resources while the buyers are paying them charges for those resources.

In this chapter, firstly the expression of the maximal achievable rate of the source nodes in cooperative transmission with the relay nodes’ help is extracted. Then, the optimization problem of relay selection and bandwidth allocation using a Stackelberg game is solved.

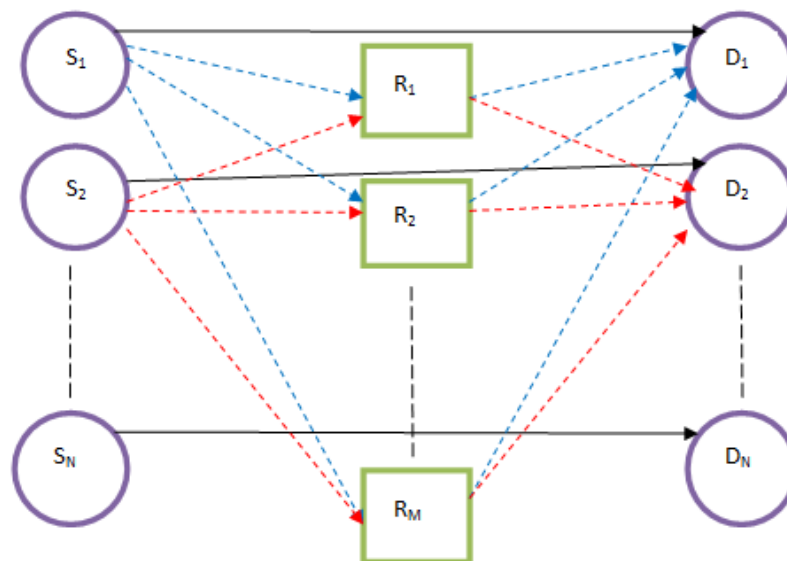


Fig.4.1: System Diagram.

4.1 SYSTEM MODEL

The Amplify- and- Forward (AF) cooperation procedure has been employed as the system model. According to this scheme, the surrounding nodes which are acting as helping nodes receives the information from the transmitting node(s) from one channel in the first phase and instead of any decoding they simply changes the amplitude of the signal i.e. perform amplification of this received signal and finally pass on the scaled information signal to the receiving node(s) in the second phase through another channel. The system diagram is shown in Fig. 4.2 below, which consists of M transmitter-receiver pairs (users) and N relaying nodes. Here, $M=2$ and $N=2$ are taken for the case study initially and then the generalisation is done for more than two users as well as more than two relay nodes.

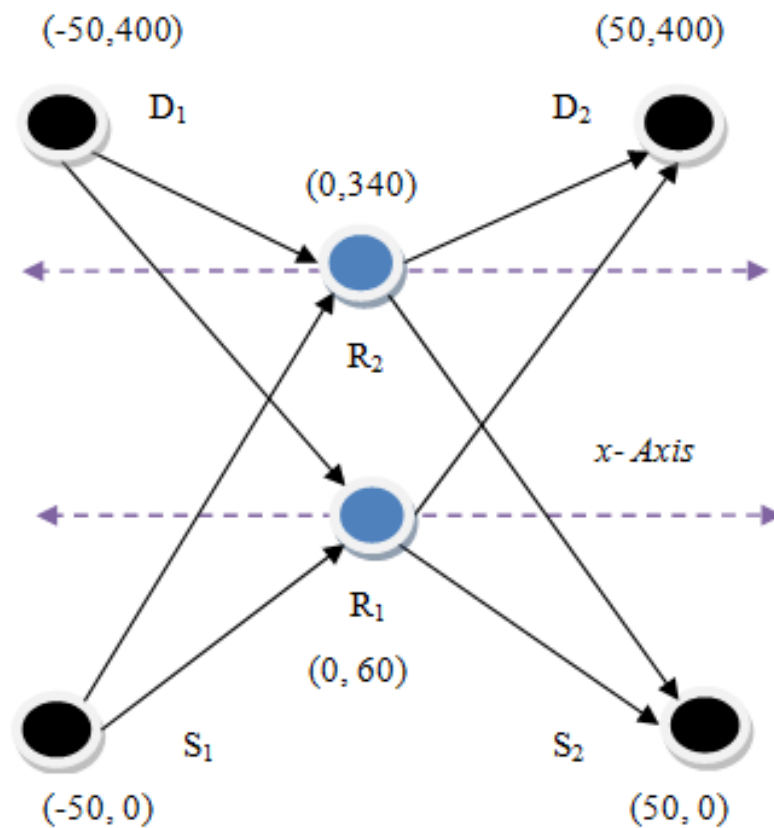


Fig. 4.2: System Diagram, Two Source- Destination pairs and Two Relays.

The relaying nodes are used to improve the reception of the data signal at the receiving nodes using Amplify- and- Forward cooperative communication method. Dealing with Amplify and Forward method, the relaying node scales the data signal it received from the transmitting

node partially or fully and then resend this scaled version of information to the destination node (in a different frequency band) according to the work done in this work in the relaying phase. There should be no overlap of the frequency bands of the users and the relay nodes, so that they can't interfere with each other.

The cooperative transmission includes two stages or time slots. In the Starting Stage (or time period T_1), the transmitting node represented by ' s_i ' broadcasts its data signal simultaneously to the respective receiving node represented by ' d_i ', where $i = \{1, M\}$ and the relaying node represented by r_j , where $j = \{1, N\}$. In this phase, bandwidth W_i is relayed. In the Next Stage (or time period T_2), the relaying node r_j amplifies the obtained signal from the transmitting node s_i and without performing decoding it passes on this data signal to the respective receiving node d_i . Here, instead of relaying the transmitting node directly transmits the data signal to the receiving node with the remaining bandwidth $W - W_i$, where W is the sum bandwidth allocated to every user.

At the receiver maximum ratio combining (MRC) technique is applied and channel state information (CSI) is assumed to be known at the receiving node.

4.1.1 Stage 1- Time Period 1:

The received signals y_{s_i, d_i} and y_{s_i, r_j} at nodes d_i and r_j respectively are given as follows:

$$y_{s_i, d_i} = \sqrt{P_s G_{s_i, d_i}} x_i + n_{s_i, d_i}, \quad (1)$$

$$y_{s_i, r_j} = \sqrt{P_s G_{s_i, r_j}} x_i + n_{s_i, r_j}, \quad (2)$$

where, P_s denotes the transmitted power from transmitting node s_i , x_i is the transmitted symbol of i^{th} user with unit energy ($E\{x_i^2\} = 1$), [14]. G_{s_i, r_j} and G_{s_i, d_i} are the gains of the channeling paths from node s_i to node r_j and to node d_i respectively, n_{s_i, d_i} and n_{s_i, r_j} are the additive white Gaussian noises (AWGNs). Noise power is assumed to be identical for all the channel links and denoted by σ^2 . Given below is the signal to noise ratio (SNR) that results from direct broadcast of information from transmitting node s_i to receiving node d_i without the assistance of relaying node:

$$\Gamma_{s_i, d_i} = \frac{P_s G_{s_i, d_i}}{\sigma^2}, \quad (3)$$

and the rate of the direct broadcast is as given in [14]:

$$R_{s_i,d_i} = (W - W_i) \log_2 \left(1 + \frac{\Gamma_{s_i,d_i}}{\Gamma} \right), \quad (4)$$

where, W is the sum bandwidth assigned to every user for transmission and Γ is an unvarying factor which represents the capacity gap.

4.1.2 Stage 2- Time Period 2:

In this phase, the relaying node r_j performs amplification of the received signal y_{s_i,r_j} and passes it on to the receiving node d_i with P_S as the transmitted power. So, the signal at receiving node d_i is:

$$y_{r_j,d_i} = \sqrt{P_r G_{r_j,d_i}} x_{r_j,d_i} + n_{r_j,d_i}, \quad (5)$$

where,

$$x_{r_j,d_i} = \frac{y_{s_i,r_j}}{|y_{s_i,r_j}|}, \quad (6)$$

is the signal sent from node r_j to node d_i , G_{r_j,d_i} is the gain of the channeling link from node r_j to node d_i , and n_{r_j,d_i} is the received noise.

Replacing (2) into (6), equation (5) can be rewritten as:

$$y_{r_j,d_i} = \frac{\sqrt{P_r G_{r_j,d_i}} \left(\sqrt{P_S G_{s_i,r_j}} X + n_{s_i,r_j} \right)}{\sqrt{P_S G_{s_i,r_j} + \sigma^2}} + n_{r_j,d_i}, \quad (7)$$

Using equation (7), the relayed SNR from transmitting node s_i by relay node r_j is hence given by:

$$\Gamma_{s_i,r_j,d_i} = \frac{P_r P_S G_{r_j,d_i} G_{s_i,r_j}}{\sigma^2 (P_r G_{r_j,d_i} + P_S G_{s_i,r_j} + \sigma^2)}, \quad (8)$$

Now since maximum ratio combining (MRC) detector is used in this work, therefore by using equations (4) and (8), the rate at the output of the detector using single relaying node r_j becomes:

$$R_{S_i, r_j, d_i} = \frac{W_i}{2} \log_2 \left(1 + \frac{\Gamma_{S_i, d_i} + \Gamma_{S_i, r_j, d_i}}{\Gamma} \right), \quad (9)$$

where, factor $\frac{1}{2}$ in equation (9) is due to the fact that two time periods are used for the cooperative communication.

If the relaying nodes which are ready to assist the transmitting node s_i are ranging from $j = [1, 2, N]$, then the rate becomes:

$$R_{S_i, r, d_i} = \frac{W_i}{2} \log_2 \left(1 + \frac{\Gamma_{S_i, d_i} + \sum_{j=1}^N \Gamma_{S_i, r_j, d_i}}{\Gamma} \right), \quad (10)$$

So for the protocol considered above, the attainable data rate R_{S_i, d_i} of the i^{th} user is given as:

$$R_{S_i, d_i} = \frac{W_i}{2} \log_2 \left(1 + \frac{\Gamma_{S_i, d_i} + \sum_{j=1}^N \Gamma_{S_i, r_j, d_i}}{\Gamma} \right) + (W - W_i) \log_2 \left(1 + \frac{\Gamma_{S_i, d_i}}{\Gamma} \right), \quad (11)$$

4.2 PROBLEM FORMULATION

If we want to achieve the cooperative diversity, we need to answer the two fundamental questions which are: 1) which relay nodes will be selected, and 2) what will be the optimum bandwidth for AF scheme? If we solve these issues through Centralized technique, then the overheads will be increased as it requires complete and precise knowledge of CSI. While, if we use the Distributed technique, it reduces the overhead as it only requires the local knowledge of CSI. Now, when we use a multi- user environment, then the nodes can act selfishly or willingly. So in order to attract more nodes for the relaying, incentives are required to be supplied by the transmitting node. Not only this, the transmitting nodes also need to choose the more beneficial relay nodes which can relay more of their bandwidth information. When there are multiple source- destination pairs, then competition among them arises to attract more relay nodes. According to all the above points, a two- level Stackelberg game is employed in this work.

4.2.1 Transmitting Nodes as Purchasers:

The users can be represented as purchasers or followers in this approach, where they have to make more profit compared to others at the smallest achievable expenditure. The utility of the single source node s_i is given as:

$$U_i = \sqrt{ZW_i \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{S_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)} - \sum_{j=1}^N \pi_{r_j} W_i - \frac{Y}{W_{tot} - \sum_{k=1}^M W_k}, \quad (12)$$

where, Y is system constant whose presence depicts that transmitting node's utility function is affected by the quantity of resources available. Z is termed as gain in rate when relaying node is used. π_{r_j} is the bandwidth selling price per unit bandwidth of the relaying node r_j . The accessible bandwidth of the relaying nodes is limited to W_{tot} i.e. $\sum_{i=1}^M W_i \leq W_{tot}$. The bandwidth that can be purchased by the i^{th} user depends on the relay prices of all the helping relays i.e. $\sum_{j=1}^N \pi_{r_j}$. The fight for the resources (bandwidth) among the users is shown as $\frac{Y}{W_{tot} - \sum_{k=1}^M W_k}$.

The overall utility of all the source nodes s_i , where $i = \{1, 2, \dots, M\}$ is given as:

$$U_s = \sum_{i=1}^M \sqrt{ZW_i \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{S_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)} - \sum_{i=1}^M \sum_{j=1}^N \pi_{r_j} W_i - \frac{Y}{W_{tot} - \sum_{k=1}^M W_k}, \quad (13)$$

So, the optimization problem for the i^{th} user (buyer) becomes:

$$\max_{\{W_i\}} U_i \text{ s. t. } \{0 \leq W_i \leq W\}, \quad (14)$$

4.2.2 Relaying Nodes as Vendors:

The relay nodes can be represented as vendors or leaders in this approach. Since they are gone to decide which users should be given their bandwidth, so they decide their charges to be asked for improvisation of their own utility functions respectively. The utility of the relay node r_j is given as:

$$U_{r_j} = (\pi_{r_j} - c) \sum_{i=1}^M W_i, \quad (15)$$

where, c is the charge per unit bandwidth. So, the optimization problem for the relay (seller) becomes:

$$\max_{\{\pi_{r_j}\}} U_{r_j} \text{ s. t. } \{\pi_{r_j} \geq c\}, \quad (16)$$

4.3 INVESTIGATION OF THE PROPOSED GAME

The optimal bandwidth to be assigned to the system and the optimal price per bandwidth is calculated firstly and then the equilibrium for the game is shown. Finally performance of the distributed method adopted in this work is compared to that of a centralized method.

4.3.1 Investigation of Purchaser- Level Game for the transmitting nodes:

At this stage, the transmitting nodes have to decide that which of the surrounding nodes they have to take help from to transmit their information signal to the corresponding receiver nodes. This selection should be done keeping in mind the need to transmit as well as the profit to be made.

The relaying nodes which have good channel conditions and which are more close to transmitting nodes are preferred as compared to the ones with poor channel conditions and which are far away from the transmitting nodes. In this way, the relaying nodes should keep in mind that their charges should not exceed much from the other ones because then their bandwidth would not be purchased. So there is a competition between the relaying nodes and hence an optimal charge should be decided to ask for.

Also there will be competition among transmitting nodes to select the best relaying nodes for bandwidth purchase. This method is distributed in nature.

4.3.1.1 Selection of the relaying nodes by the Transmitting Nodes:

First of all, the transmitting nodes should choose the relaying nodes which possess good channel conditions and reject the ones with bad channel conditions.

4.3.1.2 Optimal Bandwidth Assignment for the Chosen Relaying Nodes:

The optimal Bandwidth W_i^* can be derived after the choosing of the relaying nodes is done, as follows:

$$\frac{\partial U_i}{\partial W_i} = \frac{\sqrt{Z \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)}}{2\sqrt{W_i}} - \pi_{r_j} = 0, \quad (17)$$

So, we get the optimal bandwidth allocated to the user(s_i, d_i) i.e., i^{th} user as:

$$W_i^* = \frac{Z \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)}{4 (\pi_{r_j})^2}, \quad (18)$$

4.3.2 Investigation of the Vendor- Level Game for the relaying nodes

By taking the derivative of U_{r_j} with respect to π_{r_j} we get the optimal price demanded by relay r_j as:

$$\frac{\partial U_{r_j}}{\partial \pi_{r_j}} = \sum_{i=1}^M W_i^* + (\pi_{r_j} - c) \sum_{i=1}^M \frac{\partial W_i^*}{\partial \pi_{r_j}}, \quad (19)$$

Hence the optimal price demanded by the relay r_j becomes:

$$\pi_{r_j}^* = \pi_{r_j}^* \left(\sigma^2, \{G_{s_i, r_j}\}, \{G_{r_j, d_i}\} \right), \quad (20)$$

4.3.3 Investigation of the Equilibrium for the Proposed Game

This section proves that the optimal solutions W_i^* in (18) and $\pi_{r_j}^*$ in (20) are the Stackelberg Equilibrium (SE) for the designed game by the following properties.

Definition- W_i^{SE} and $\pi_{r_j}^{SE}$ are the SE of the game designed above if

$$U_i(\{W_i^{SE}\}) = \sup U_i(\{W_i\}), \{W_i\} \geq 0, \quad (21)$$

for every relaying node i.e., ' r_j ', where $j = \{1, N\}$ and every user (s_i, d_i) where $i = \{1, M\}$, when π_{r_j} is fixed

and when W_i is fixed

$$U_{r_j}(\{\pi_{r_j}^{SE}\}) = \sup U_{r_j}(\{\pi_{r_j}\}), \pi_{r_j} > c, \quad (22)$$

4.3.3.1 Properties-

i) The utility U_i of the i^{th} user is concave in $\{W_i\}_{i=1}^M$, where $\{W_i\} \geq 0$, and π_{r_j} is unchanging, $\forall i$.

Proof: By taking the double derivative of the individual user utility, it can be seen that every i^{th} user's utility function is continuous and hence concave in W_i .

$$\frac{\partial^2 U_i}{\partial W_i^2} = -\frac{1}{4} \left(\frac{\sqrt{Z \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)}}{W_i^{\frac{3}{2}}} \right), \quad (23)$$

Since $Z > 0$, $\Gamma_{s_i, d_i} > 0$, $\Gamma_{s_i, r_j, d_i} > 0$, and $W_i \geq 0$, therefore as a result, $\frac{\partial^2 U_i}{\partial W_i^2} < 0$. Hence it can be said that U_i is continuous and concave in $W_i, \forall i$, when $W_i \geq 0$.

From *Property i)* and equation (18), W_i^* obtained is the optimal bandwidth value which will maximize U_i . Therefore, solution of equation (21) is given by this W_i^* which becomes the Stackelberg Equilibrium W_i^{SE} .

Furthermore, it can be said that the i^{th} user gets its optimal bandwidth by increasing the obtained bandwidth step by step from each relay node until U_i arrives at its highest value.

From the coming properties, it is verified that the relaying nodes can't ask randomly high charges from the users and increase U_{r_j} infinitely.

ii) W_i^* for relaying node r_j reduces with its charge π_{r_j} when remaining relay nodes' charges are unchanging.

Proof: By taking the double derivative of the optimal bandwidth of the i^{th} user with respect to the price charged by the relaying node, it can be seen that as the relaying node decreases its charge more of its bandwidth is purchased, while as the it increases the charge , the bandwidth purchase from that node decreases.

$$\frac{\partial W_i^*}{\partial \pi_{r_j}} = -\frac{1}{2} \left(\frac{Z \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)}{\pi_{r_j}^3} \right) < 0, \quad (24)$$

From (24), it can be seen that W_i^* is decreasing with π_{r_j} which depicts that if any relaying node tries to increase its charge while the charges of other relaying nodes are unvarying, the users will purchase less bandwidth from that relaying node.

This proof shows that the bandwidth allocation and the price distribution are inversely proportional to each other in nature and the relaying nodes can't arbitrarily set any random value for their charges to be asked from the users.

So there is a trade-off for each relaying node to ask a suitable charge due to reason shown in following property:

iii) Utility U_{r_j} of each relaying node is concave in its own charge π_{r_j} when their demanded bandwidth from the user is optimal as derived in (18) and the remaining relaying nodes' charges are unvarying.

Proof: From equations (25) and (26) given below, it is proved that W_i^* is continuous in π_{r_j} , so U_{r_j} is continuous in π_{r_j} too.

$$\frac{\partial U_{r_j}}{\partial \pi_{r_j}} = \sum_{i=1}^M W_i^* + (\pi_{r_j} - c) \sum_{i=1}^M \left(\frac{-Z \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)}{2\pi_{r_j}^3} \right), \quad (25)$$

and further,

$$\begin{aligned} \frac{\partial^2 U_{r_j}}{\partial \pi_{r_j}^2} = & \sum_{i=1}^M \frac{-Z \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)}{\pi_{r_j}^3} \\ & + (\pi_{r_j} - c) \sum_{i=1}^M \frac{3Z \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)}{2\pi_{r_j}^4}, \end{aligned} \quad (26)$$

Since $Z > 0$, $\Gamma_{s_i, d_i} > 0$, $\Gamma_{s_i, r_j, d_i} > 0$, and $\pi_{r_j} > c$, we have $\frac{\partial^2 U_{r_j}}{\partial \pi_{r_j}^2} < 0$. Therefore, U_{r_j} is concave with respect to π_{r_j} .

4.3.4 Performance Comparison of the Designed Distributed Method with the Centralized Method

The centralized optimal bandwidth allocation can be modelled as:

$$\begin{aligned} \max_{W_i} \sum_{i=1}^M \sqrt{Z W_i \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)} \\ \text{s. t. } \sum_{i=1}^M W_i \leq W_{tot}, 0 \leq W_i \leq W_{max}, \end{aligned} \quad (27)$$

The solution of (27) can be given by using the Lagrangian Multiplier λ as:

$$\sum_{i=1}^M \sqrt{Z W_i \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)} - \sum_{i=1}^M \lambda_i W_i = J, \quad (28)$$

Differentiating (28) with respect to W_i we get-

$$\frac{\partial J}{\partial W_i} = \frac{\sqrt{Z \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)}}{2\sqrt{W_i}} - \lambda_i = 0, \quad (29)$$

Hence the solution of (29) becomes:

$$W_i^{cen} = \left(\frac{Z \log_2 \left(\frac{1 + \Gamma_{s_i, d_i} + \sum_{j=1}^N \Gamma_{s_i, r_j, d_i}}{1 + \Gamma_{s_i, d_i}} \right)}{4\lambda_i^2} \right)^{W_{max}}_0, \quad (30)$$

where, λ_i is a constant Lagrangian Multiplier for i^{th} user for $i=\{1,2,\dots,M\}$ and $(y)_l^u$ is given as:

$$(y)_l^u = \begin{cases} l, & y < l \\ y, & l \leq y \leq u, \\ u, & u < y \end{cases} \quad (31)$$

For the Distributed Scheme, by varying Z and including the different W_{tot} constraints, we can also analyze various total bandwidth consumptions and related maximal rates. In part IV, we will see the result of the analogous performance of the Centralized method and the designed Distributed method.

Thus we can see that the distributed approach that has been designed in this work using the dynamic or extensive form of game theory i.e. Stackelberg Game is giving comparable result to that if we design a Centralised Scheme.

This helps in reducing the overheads and signalling since the Distributed approach does not require any precise knowledge of Channel State Information (CSI) which makes this approach quite efficient too.

This is the conclusion of chapter 4 where the techniques applied i.e. Stackelberg Game and Amplify- and- Forward Relaying technique and the system model of multi- user, multi- relay cooperative communication system is fully described by which bandwidth allocation is done to the users, which has not been performed till now in the literature.

CHAPTER 5

RESULTS AND DISCUSSIONS

In this chapter, all the results that are achieved from the techniques and the system model discussed in the Chapter 4 are discussed. This chapter deals with the distribution of the optimal bandwidth, optimal price for the two users, single relay as well as for the two users, two relays case. It also deals with the average utility functions of both the users as well as the helping nodes. Further, the distribution for average bandwidth for multiple users and the distribution for average price for multiple relaying nodes is also shown.

5.1 ONE RELAY- TWO USERS CASE

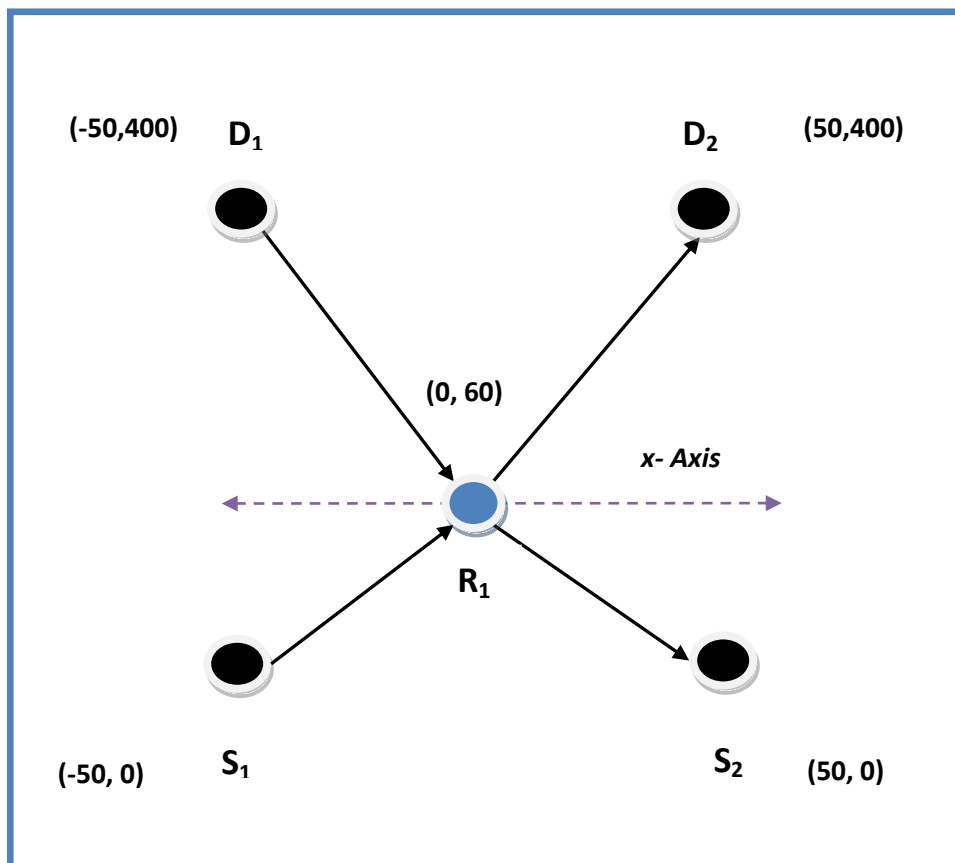


Fig. 5.1: Two Source- Destination pairs and Single Relay Cooperative Communication system.

There are two source- destination pairs. S_1, D_1, S_2, D_2 are fixed at co-ordinates $[-50\text{m}, 0\text{m}]$, $[-50\text{m}, 400\text{m}]$, $[50\text{m}, 0\text{m}]$ and $[50\text{m}, 400\text{m}]$ respectively as shown in Fig.5.1. The relay node's y-coordinate is set at 60m and the x-coordinate ranges from -500m to 500m.

W_{max} is considered to be equal to 2MHz, propagation loss factor=2, source power P_S is constant for both the sources at 10mWatt, capacity gap $\Gamma =1$, cost per unit bandwidth= 10^{-3} unit price/Hz, $Y=1$, $Z = \sqrt{\frac{0.5}{\log 2}}$ and the noise power $\sigma^2 = 10^{-8}$ Watt as in [14].

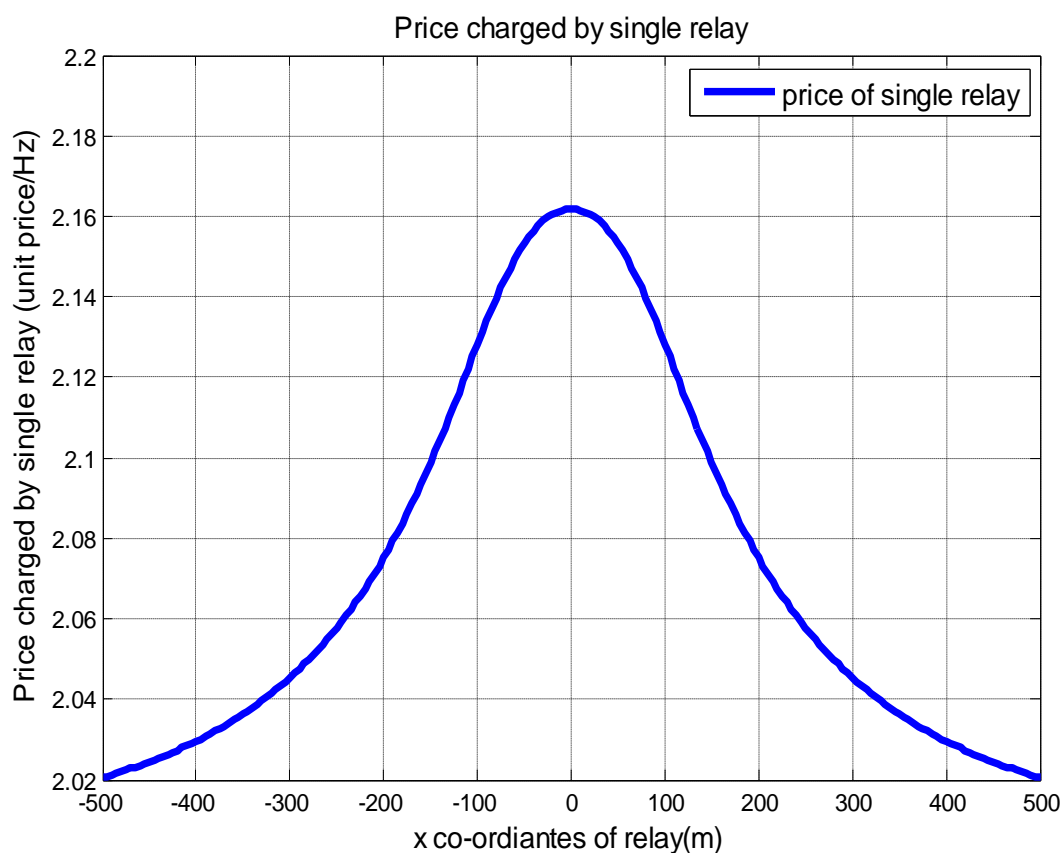


Fig.5.2: Bandwidth Price distribution.

From the Fig.5.2, the price charged by the single relay R_1 from the users (S_1, D_1) and (S_2, D_2) is shown against the x co- ordinates of the relay. It can be seen that the price charged by the relay is concave in nature. In this simulation, relaying node R_1 moves along a line or x- axis from -500m to 500m.

It is observed that when we move from the region of -50m to 0m, the price is seemed to be increasing. This is because when the relaying node R_1 is closer to user1 i.e. (S_1, D_1) , it asks

lesser price as compared to when it moves far from the user1, so that user1 can buy more of its bandwidth. It happens because when R_1 is far from the user1 it has to increase its revenue so as to increase its own utility, while when it is closer to user1 it asks an optimal amount. And if we move from the region of -50m to -500m, the price is decreasing to the minimum possible amount as there are no users in that area. Also when the total user demand decreases, the relaying node R_1 has to decrease the price too. Same case happens with user2.

When the relaying node R_1 moves to (0m, 60m), a fair resource allocation between the two users is achieved because both the two users have the same channel conditions to R_1 . So the revenue of the relaying node R_1 is highest at this point between user1 and user2 where it is equally far from both the users and the users have to compete to attain the bandwidth of this single relay present, since the total demand of the users and the price are highest at this point.

From the Fig.5.3, it can be seen that the region from -500m to 0m is more favourable for S_1 , where relaying node R_1 is more near to S_1 as compared to S_2 . S_1 buys more bandwidth from the relay than S_2 in this region. Similarly, for the region 0m to 500m, S_2 buys more bandwidth than S_1 . At 0m, both S_1 and S_2 have almost same channel conditions to the relaying node R_1 . Hence, both the users purchased the same amount of bandwidth.

When we move from the point -500m to -150m, user2's bandwidth demand is almost zero, while user1's demand gradually increases to the maximum at point -50m. This happens because in this area, the separation between the relaying node R_1 and user2 is so long that user2 can't get any profits through cooperative transmission. From the point of -150m to 0m, user2 increases its demand gradually even with an increasing price because its channel condition to the relaying node R_1 is becoming better. At this stage, user1 has to decrease its demand since the user2 is becoming more competitive than it was in the region of (-500, -50) metres and also because the price is increasing in this region as shown in Fig. 5.2.

When the relaying node R_1 moves to (0m, 60m), an equal resource allocation between the two users is attained because both the two users have the same channel conditions to R_1 . In the region of 0m to 50m, user1 keeps decreasing its demand even with a decreasing price, since its channel condition to the relaying node R_1 becomes worse.

User2 can continue increasing its demand since user1 is becoming less competitive than it was, and also because of the decreasing price. As the relaying node moves away from the user2, i.e. from 50m to 500m, user2's demand gradually decreases and user1's demand tends to be zero.

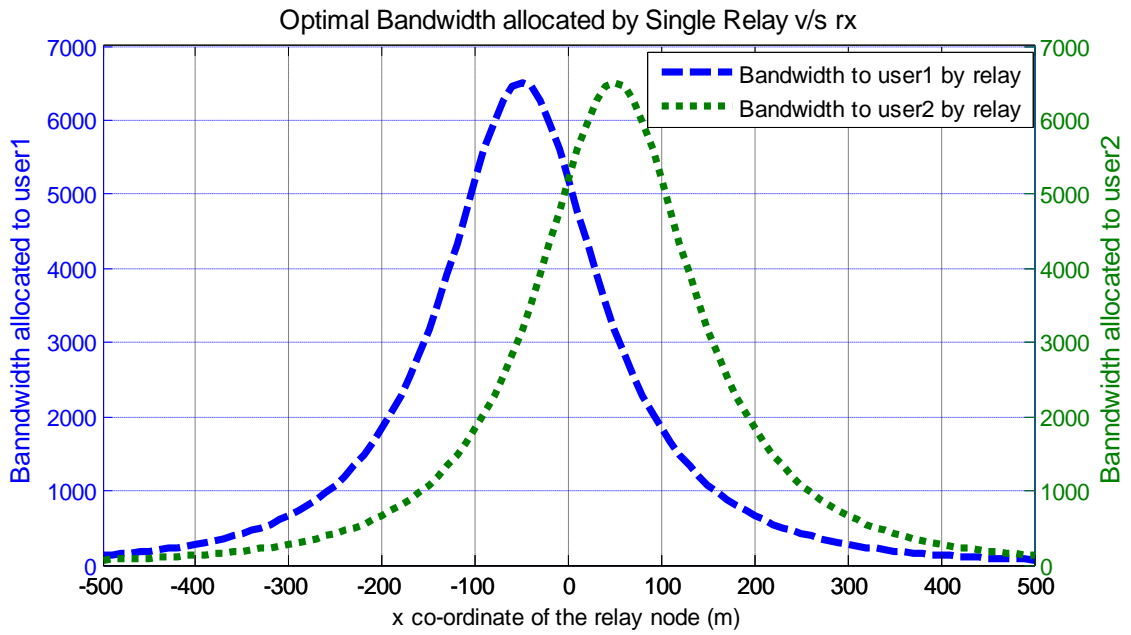


Fig. 5.3: Bandwidth Allocation Profiles.

5.2 TWO USERS- TWO RELAYS CASE

This case is same as previous case with the addition of one more relay node whose y-coordinate is set at 340m and x-coordinate ranges from -500m to 500m. So now there are two relay nodes, one at (0m, 60m) and another at (0m, 340m) both moving along the x-axis from one user to another user between -500m and 500m, and hence it becomes a multi-user, multi-relay system as shown in Fig. 5.4 given below.

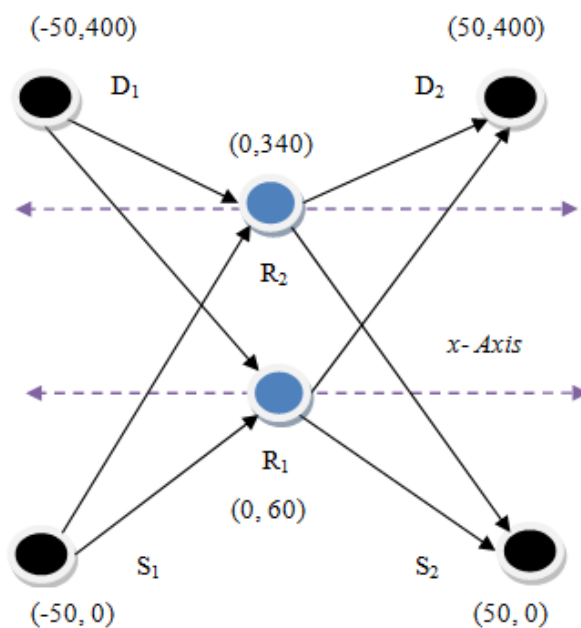


Fig. 5.4: Two Users- Two Relays Cooperative Communication system.

From Fig. 5.5, it is observed that when we move from the region of -50m to 0m, the price is seemed to be increasing. This is because when the relaying nodes R_1 and R_2 are closer to user1 i.e. (S_1, D_1) , they asks lesser price as compared to when they move far from the user1, so that user1 can buy more of their bandwidth. It happens because when R_1 and R_2 are far from the user1 they have to increase their revenue so as to increase their own utilities, while when they are closer to user1 they ask an optimal amount.

And if we move from the region of -50m to -500m, the price is decreasing to the minimum possible amount as there are no users in that area. Also when the total user demand decreases, the relaying nodes R_1 and R_2 have to decrease their prices too. Same case happens with user2.

When the relaying node R_1 and R_2 move to 0m, an equal resource allocation between the two users is attained because both the two users have the same channel conditions to R_1 and R_2 . So the revenues of the relaying nodes R_1 and R_2 are highest at this point between user1 and user2 where they are equally far from both the users and the users have to compete to attain the bandwidth of these relays present, since the total demand of the users and the price are highest at this point.

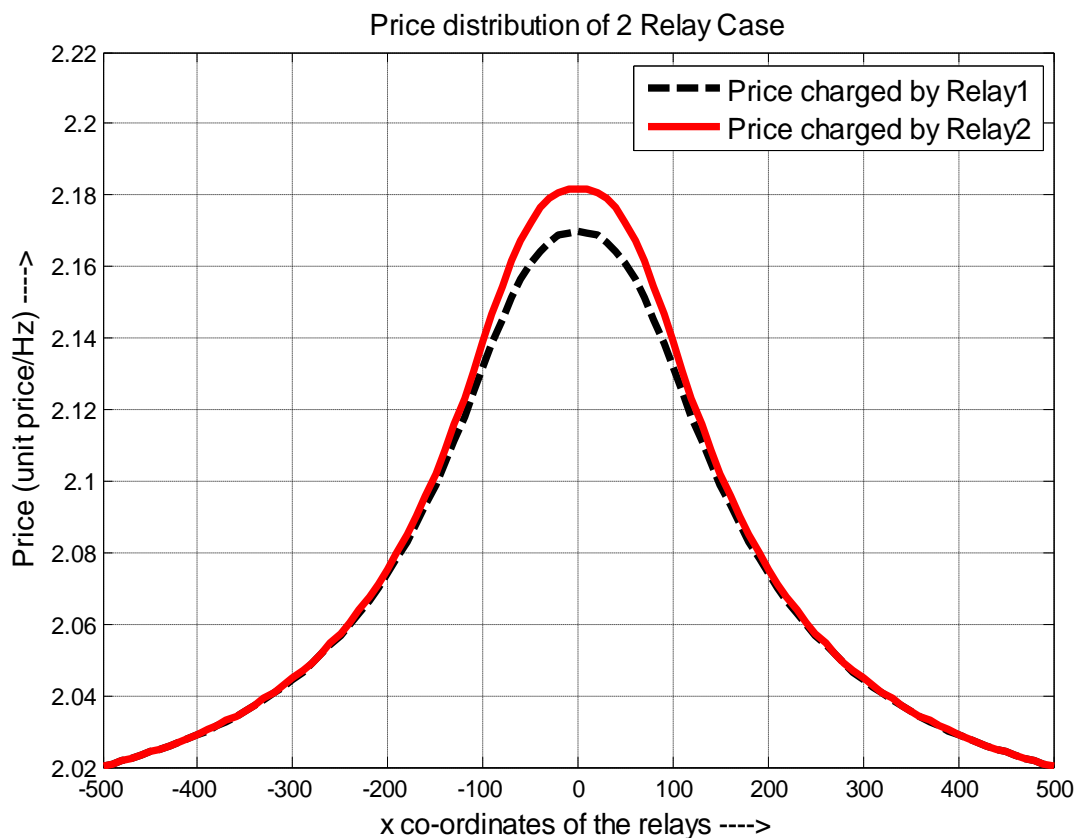


Fig. 5.5: Price Distribution of Multi users- Multi relays case.

Also the price charged by the relaying node R_2 is more than the relaying node R_1 at every point since the relaying node R_2 is far from the source nodes and is closer to destination nodes at (0m, 340m) as compared to the relaying node R_1 which is at (0m, 60m). Therefore, R_2 has to ask for more prices from the users to increase its utility as opposed to R_1 which can attract both the users to buy its bandwidth.

From Fig. 5.6, it is experiential that when both the relaying nodes R_1 and R_2 are closer to user1 then bandwidth allocated by relaying node R_1 to the user1 is more as compared to that by relaying node R_2 since relay R_1 is nearer to source node of user1 than relaying node R_2 so the bandwidth allocation to user2 decreases in this area because of its increasing distance from both the relays and vice versa.

At 0m, both S_1 and S_2 have almost same channel conditions to the relaying node R_1 . Hence, both the users purchased the same amount of bandwidth from R_1 . Also at this point, both users have almost same channel conditions to R_2 too. So, they purchased the same amount of bandwidth from R_2 but which is lesser than the one purchased from R_1 .

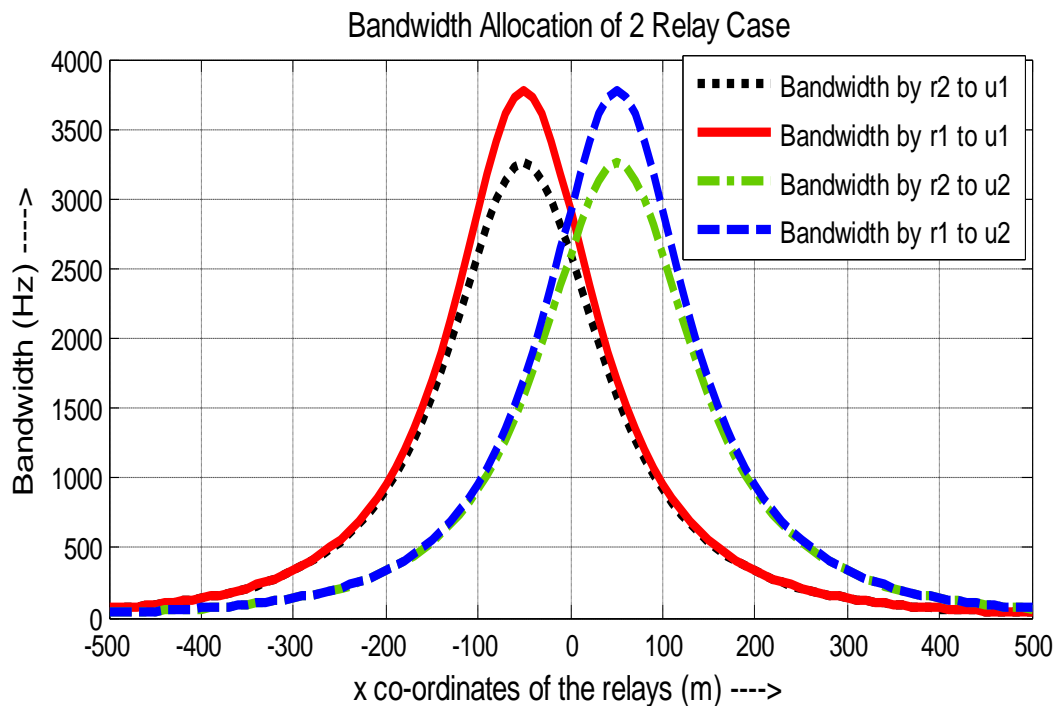


Fig. 5.6: Bandwidth Allocation of Multi users- Multi Relays Case.

When we move from the point -500m to -150m, user2's bandwidth demand is almost zero, while user1's demand gradually increases to the maximum at point -50m. This happens

because in this region, the separation between the relaying nodes R_1 , R_2 and user2 is so long that user2 can't get any profits through cooperative transmission here.

From the region of -150m to 0m , user2 increases its demand gradually even with an increasing price because its channel conditions to the relaying nodes R_1 and R_2 are becoming better. Better channel conditions are for relaying node R_1 than R_2 . At this stage, user1 has to decrease its demand since the user2 is becoming more competitive than it was in the region of $(-500\text{m}, -50\text{m})$ and also because the price is increasing in this region as shown in Fig. 5.5.

In the region of 0m to 50m , user1 keeps decreasing its demand even with a decreasing price, since its channel conditions to the relaying nodes R_1 and R_2 become worse. User2 can continue increasing its demand since user1 is becoming less competitive than it was, and also because of the decreasing price. As the relaying nodes move away from the user2, i.e. from 50m to 500m , user2's demand gradually decreases and user1's demand tends to be zero.

5.3 MULTI USERS- MULTI RELAYS CASE

Now for the generalisation of the above described two cases, multiple users and multiple relays case where the number of both the nodes is more than 2 is finally discussed for the bandwidth allocation using Stackelberg Game theory for Amplify- and- Forward (AF) cooperative communication systems.

5.3.1 Multiple Users- Single Relay Setup:

In this case, first multiple number of users are considered in which the single relaying node is positioned at $(0\text{m}, 0\text{m})$. The users i.e. source- destination pairs are randomly positioned inside a circular field with the center being the origin and whose radius being 150m .

From Fig. 5.7, it is experiential that as the users are boosted in number, the price charged by a single relay is increased because of competition among the users to attract the relay while the average bandwidth allotted to each user decreases.

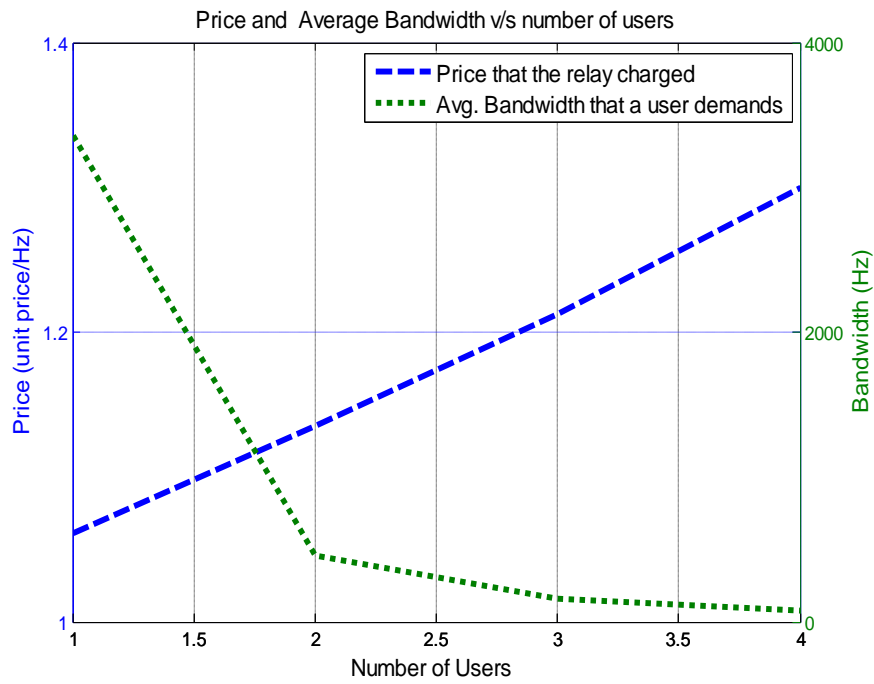


Fig. 5.7: Bandwidth demand and Price for Multi-user system.

Fig. 5.8 shows that the average relay utility increases as the number of users are boosted in number. For a single relay, if users increase, then the options of selling bandwidth to any user increases for the relay. It can now demand higher prices from the users to increase its utility.

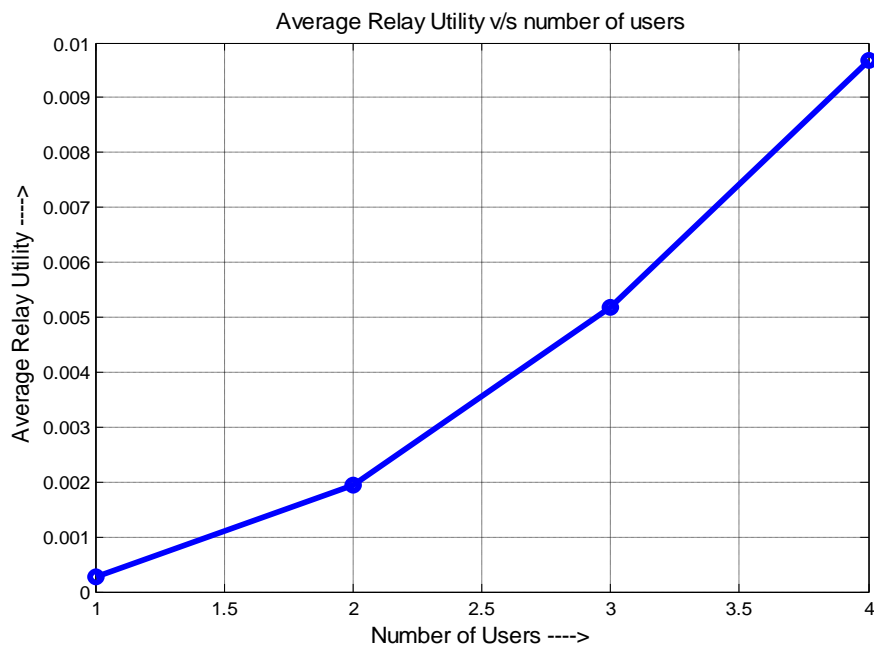


Fig. 5.8: Average relay utility for multi-user system.

5.3.2 Multiple Relays- Single User Setup:

Next for the multiple relaying nodes, single user setup, the source node is positioned at (100m, 0m) while the destination node is positioned at (0m, 0m). The relaying nodes are uniformly positioned within the range of [-50m, 150m] in the x-axis and [0m, 20m] in the y-axis. So, from Fig. 5.9, it is experiential that as the relay nodes are boosted in number, the average price that each relay charges decreases because the competition among different relay nodes increases and the average bandwidth that the relays can allocate to the user decreases as it buys more bandwidth from more number of relays.

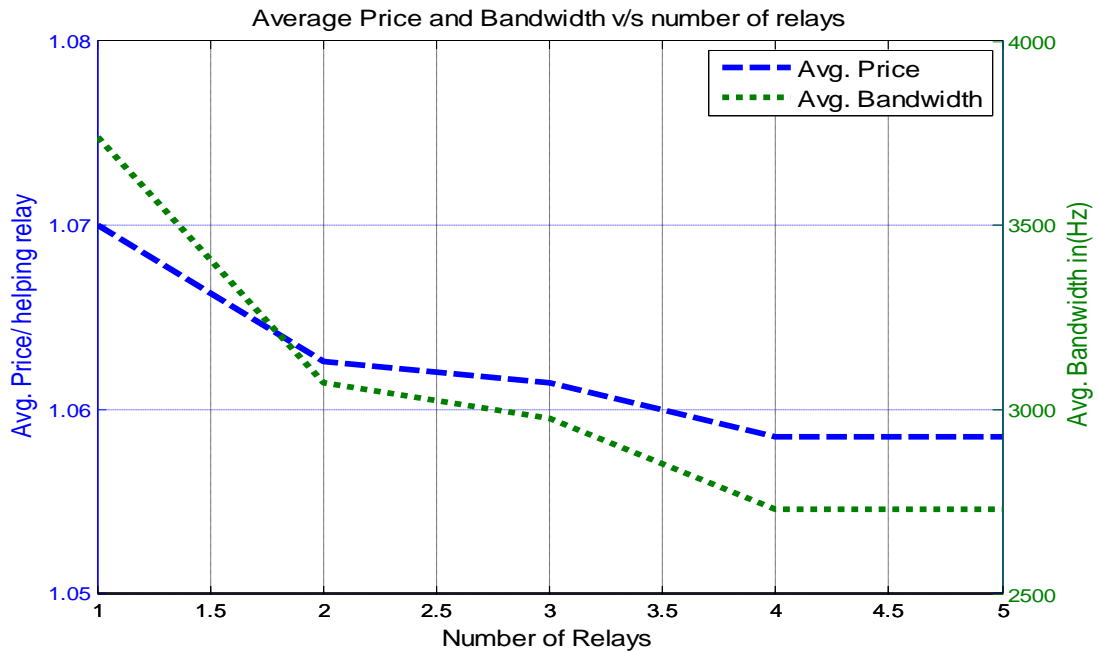


Fig. 5.9: Average Bandwidth allocation and price for Multi-relay system.

Fig. 5.10 shows that the average user utility increases as the number of relaying nodes boosts. For a single user, if relaying nodes are boosted in number, then the options for buying bandwidth from any relay node increases for the user. It will opt for relay nodes with good channel conditions, also the total payback from the user is shared by more relaying nodes that leads to less average payback from the user, i.e., user has to pay less with increasing number of relay nodes.

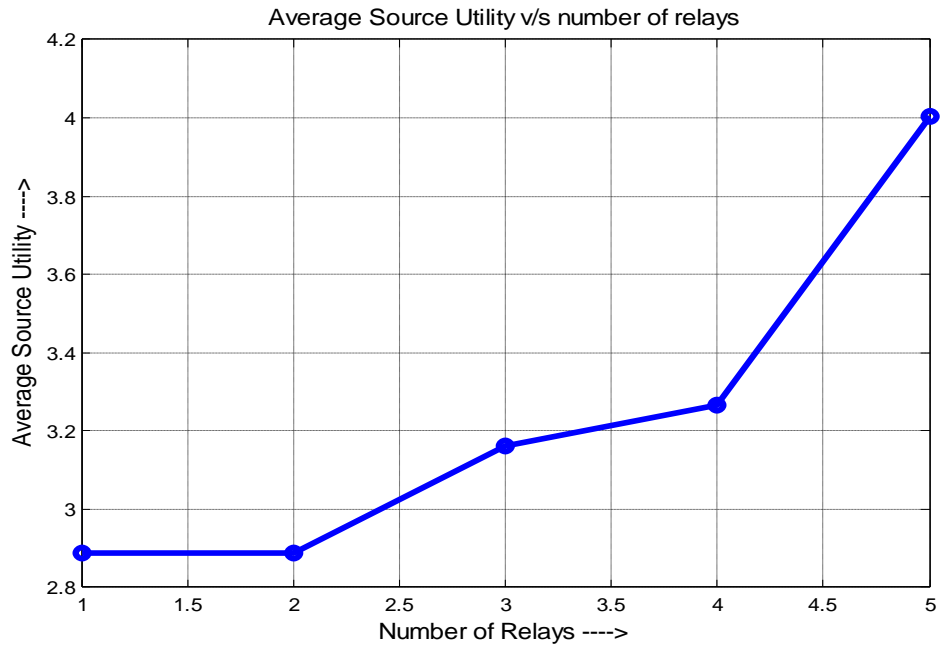


Fig. 5.10: Average source utility for multi-relay system.

5.4 RESULT OF COMPARISON BETWEEN THE DESIGNED DISTRIBUTED APPROACH AND A CENTRALIZED APPROACH

Finally, from Fig. 5.11 it is experiential that the designed game attains approximately analogous rates as the centralized method when the similar total bandwidth allotment is taken, where W_{tot} varies within the range of [200 Hz, 1000 Hz] and we set $W_{max} = 200$ Hz.

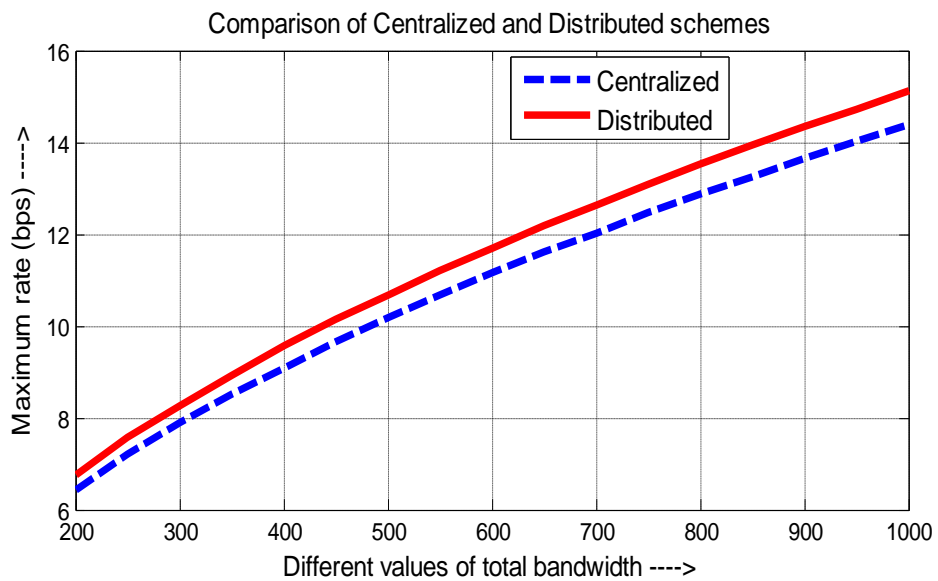


Fig. 5.11: Optimal rate in distributed and centralized schemes.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION OF THE WORK DONE:

This thesis evaluates a multi- user, multi- relay cooperative diversity model for the proper allocation of the bandwidth and the channels to the system since bandwidth is a limited and costly resource. The efficient distribution of bandwidth to the users is essential in the modern day- scenario when the number of users and technologies have been scaled to much higher levels. Since, the channels or the frequencies are limited in amount and also the link is prone to several kinds of noises such as Inter Symbol Interference (ISI), Inter Channel Interference (ICI), Additive White Gaussian Noise (AWGN), etc. effective ways should be adopted to allocate the bandwidth channels to mitigate their effects. In this work, the improvement in the performance has been obtained by employing a two- level game theoretic optimization technique. Taken into account the fact that the broadcasting nature of the wireless medium permits cooperative diversity to be used in wireless communication to combat the fading effect, hence a node can use antennas of neighbouring devices to pass on its own information. Thus without deploying actual multiple antennas we can enjoy the benefits of diversity through cooperative communication. The following conclusion can be drawn from respective chapters. From Chapter 3, it can be analysed that how the allocation of power is done to the user for transmission of information in the case of single relay as well as multiple relays. The bandwidth is considered to be fixed here. The basic cooperative communication model is explained with the help of Amplify- and- Forward (AF) relaying scheme. Through the two- level Stackelberg Game, the transmitting nodes are termed as buyers and the receiving nodes are termed as sellers. This is important to understand how the resource allocation is done in a cooperative environment.

In this work, a Distributed method for allotment of the resources is suggested, that is divided into two levels. The proposed approach for multi- user, multi- relay cooperative communication networks gives us two benefits: 1) relay selection is done, i.e., who will be the helping relay nodes for which user and 2) how much bandwidth will be allocated to each user. The other thing achieved in this work is the setting of relay prices according to their channel conditions and distance from the users. If a relay node has good channel conditions, it can demand higher price from the user so as to maximize its own utility. While, if it has poor channel conditions, it can demand lower price to attract the users.

If the relay nodes boost in number, users' utilities increase as the average price demanded by the relays decreases and also the average bandwidth per relay node that they can allocate decreases. While if the total number of users increases, relays' utilities increase as the average price charged by the relays increases, but the average bandwidth demand of the users will decrease. Finally a comparable performance between the Distributed proposal and the usual Centralized method is achieved which shows that the overheads and signaling are reduced since without any precise knowledge of Channel State Information (CSI), efficient performance is achieved.

6.2 FUTURE SCOPE:

For the future possibility, coalition using Shapley values among the relaying nodes and the transmitting nodes can be calculated to get better results. Also, the work can be extended to real-time heterogeneous networks in which the users may have different needs due to different kinds of traffic that they experience thereby changes the type of their utility functions in contrast to the homogeneous networks that are considered in this work.

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- [1] Priyanka Rahi and Dr. Sanjay Sharma, “Bandwidth allocation and Distributed Relay Selection for multiple- user and multiple- relay Cooperative Systems Using Stackelberg Game”, *International Journal of Communication Systems*, June 2017, [Under Review].
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