Development, Simulation and Analysis of Resource Allocation Techniques for Cooperative Wireless Network

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By

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Certificate

This is to certify that the thesis entitled **Development, Simulation and Analysis of Resource Allocation Techniques for Cooperative Wireless Network** has been prepared by **Ms. Upadhyay Manisha (10EXTPHD36)** under my supervision and guidance. The thesis is her own original work completed after careful research and investigation. The work of the thesis is of the standard expected of a candidate for Ph.D. Programme in **Engineering & Technology** and I recommend that it be sent for evaluation.

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Abstract

Wireless Communication has witnessed tremendous growth in last decade. Variety of newer applications encompassing every walks of life are emerging based on wireless communication platform. However, channel interference, fading, providing high speed reliable and secured communication are still the challenges which prevent the wireless communication systems from fulfilling the demands of novel applications. Cooperative communication has shown the capability of making wireless communication ready for challenging applications of the next generation. In cooperative communication wireless nodes cooperate with each other to create virtual spatial diversity to yield the benefits of diversity combining without using multiple antennas. Duplication of transmission, wastage of resources, increased interference, increased traffic and selfish behaviour of the node are the challenges which are the hurdles in the path of implementation of cooperative protocols in the wireless network. Appropriate mechanism of resource allocation can be employed to resolve many issues in the cooperative network.

Resource allocation mechanisms are evolved in this thesis for Centralized, Semi-distributed and Distributed environment. In order to achieve improved data rate in centralized network, transmission power of source & relay and bandwidth are the resources considered for judicious allocation. Three approaches are developed to yield efficiency-fairness trade-off in the network as (a) Utility function based (b) Resource constraint based, and (c) E-F function based approach. A generic utility function is developed to allocate resources to achieve five types of allocation: (i) efficient, (ii) proportional fair, (iii) min-max fair, (iv) minimum delay fair, and (v) desired degree of trade-off between efficiency and fairness. Performance of all approaches are evaluated by extensive simulations. The results exhibits that the proposed approaches are capable to allocate the resources to increase the data rate of users compared to non-cooperation. Also, the approaches have capability to allocate the resources as per the class of services and applications of users.

To eliminate the need of global channel knowledge at the central controller, nodes are motivated to cooperate using the concept of pricing in distributed network. Multi-unit auctioning based on revelation demand curve parameters is proposed in this thesis. The proposed technique has

lower computational complexity, lower overheads and need less time before starting cooperation phase unlike conventional clock auctioning techniques.

Advanced wireless networks are aimed to be fully autonomous, heterogeneous and self-organizing. The price mechanism is supervised by the central controller as discussed in the previous paragraphs and is not suitable for this kind of networks. The mechanism with exchange of resources such as power and bandwidth is considered in the literature as a suitable mechanism to leverage the benefit of cooperation for such networks. Nodes in the network form pairs having complementary resources and share the resource own by it with the partner. A one-shot algorithm, for negotiation between the source and the relay with fewer overheads, is developed and compared with conventional iterative algorithm. The proposed exchange mechanism not only stimulate nodes to stick to cooperation, but also save energy and increase data rate.

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Declaration

I, Upadhyay Manisha, registered as Research Scholar, bearing Registration No. 10EXTPHDE36 for Doctoral Programme under the Faculty of Technology & Engineering of Nirma University do hereby declare that I have completed the course work, pre-synopsis seminar and my research work as prescribed under R. Ph.D. 3.5.

I do hereby declare that the thesis submitted is original and is the outcome of the independent investigations / research carried out by me and contains no plagiarism. The research is leading to the discovery of new facts / techniques / correlation of scientific facts already known. (Please tick whichever is applicable). This work has not been submitted to any other University or Body in quest of a degree, diploma or any other kind of academic award.

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Chapter 1

Introduction

Wireless communication is becoming a popular medium of communication day by day. Apart from basic voice communication, many facades are added to the wireless communication systems like web browsing, gaming, social networking, video sharing etc. The demand for more and more data rate is continuously increasing. Various predictions point the finger towards exponential growth in expected data rate of wireless applications. Fig 1.1 shows the forecast presented by Cisco about the growth of mobile data usage in five years from 2014-2019. It clearly indicates exponential rise in data applications during this half decade. Another survey done by Alcatel-Lucent is reproduced in Fig 1.2. It clearly exhibits tremendous rise in web browsing and video streaming application for the period of 2012 to 2017. However, still there are many technical issues, preventing wireless communication systems from fulfilling the demand of emerging applications.

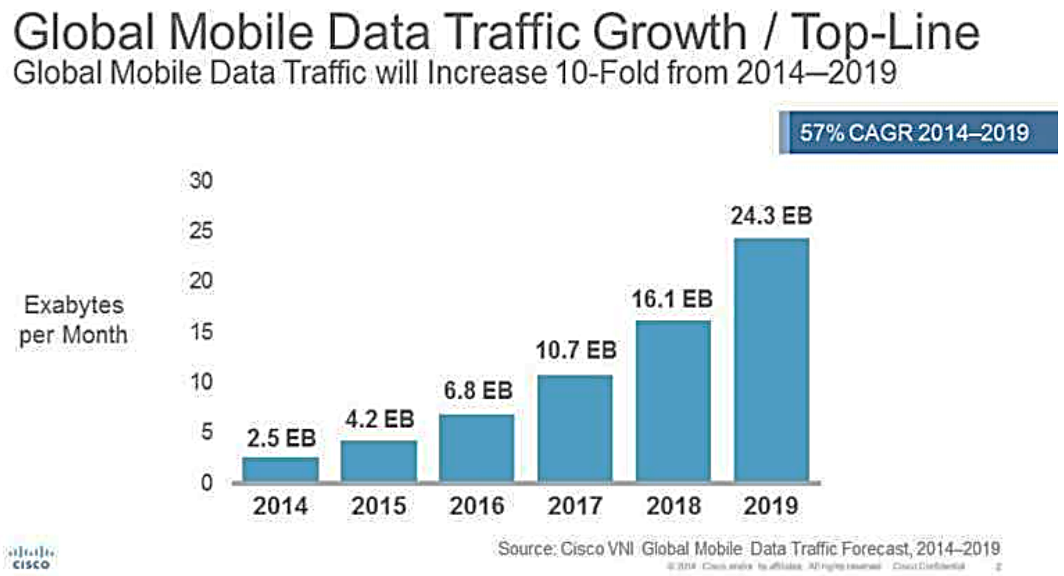


Fig 1.1 Prediction of mobile data traffic growth
Source: Cisco Virtual Networking Index: Global Mobile Data Traffic Forecast Update 2014–2019 White Paper

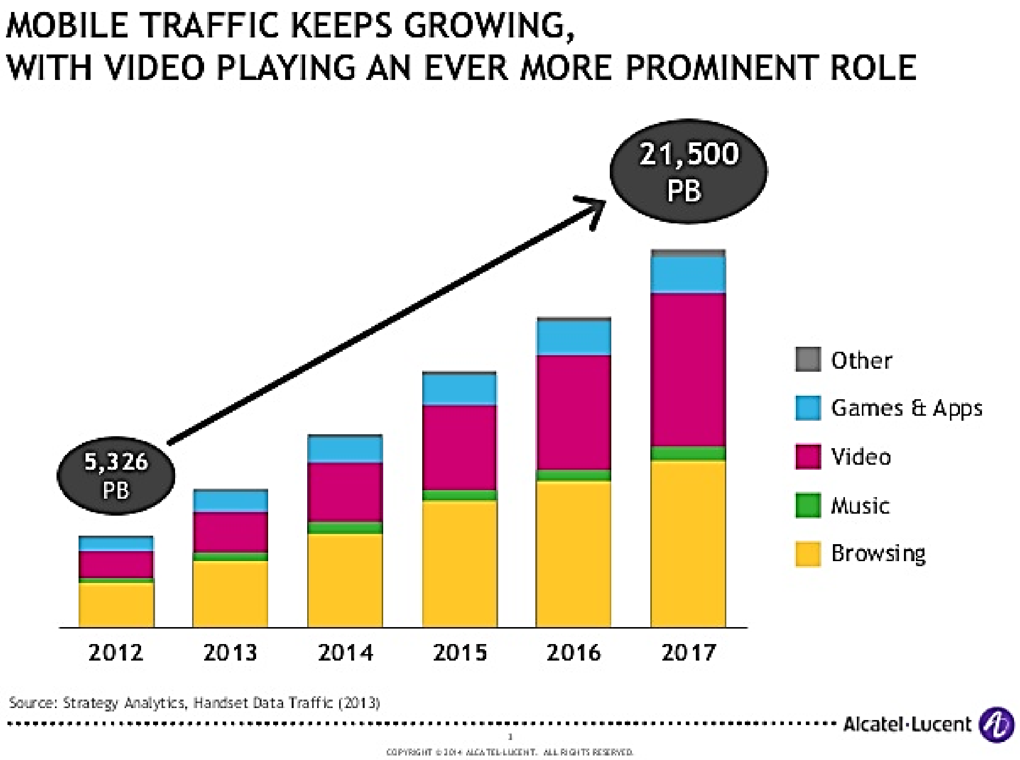


Fig 1.2 Growth prediction of various mobile applications
Source: Strategy Analytics, Handset data traffic, Alcatel-Lucent, 2013

The wireless channel as a medium of transmission is a severe challenge in itself for high speed, reliable communication. It is affected by unpredictable time varying channel impairments during a short period of time. Spatial diversity can effectively combat the effect of the wireless channel impairments. Same signal transmitted from two or more different locations to generate two or more independently faded replicas of the signal at the receiver. The receiver takes benefit of diversity combining to yield combined signal. Cooperative communication is capable of generating such spatial diversity without employing multiple antennas on the mobile device. Instead, wireless nodes mutually cooperate to retransmit signal of each other to form spatial diversity and hence, take benefit of diversity combining. Main idea behind cooperation is to share resources like power and bandwidth with neighbouring nodes to get mutual benefits in terms of increases data rate, improved reliability, extended coverage and saving of resources. Cooperation leads to enhancement of individual node as well as network performance along with savings of overall network resources (J. N. Laneman) (A. E. Sendonaris).

1.1 Resource Allocation in Cooperative Networks

The performance enhancement through cooperation can be achieved in terms of diversity gain, extended coverage, better link reliability and balanced quality of service of all users. The actual realization of cooperation in wireless network poses certain challenges. Duplication of transmission in cooperative mode leads to the issues like increased traffic and interference in the network, wastage of resources, increased handoffs and security of data (Dohler). Careful consideration of these factors while implementing the cooperation can only lead to benefits of using this concept. This thesis addresses the issue of resource optimization. Cooperation leads to interesting trade-offs in resource requirement and achievable data rate (Dohler). On one hand, it seems that duplication of transmission leads to usage of more power and bandwidth. On the other hand, transmission power and/or bandwidth necessary to achieve target data rate will be reduced due to diversity combining. By optimizing the resources, wastage of resources can be eliminated. This, in turn, saves battery power of the user and reduces interference in the network. To achieve same data rate by using less resources or achieve more data rate by using same resources seems attractive to users as well as service provider (Gunduz) (J. e. Yang) (Gong) (B. e. Chen).

The service provider can install the relay nodes to create cooperative diversity and allocate resources to reach desired goal of overall network performance. When nodes do not belong to the same service provider and relays are not installed by the service provider, the issue of selfish node arises. These nodes take benefit of cooperation by using other nodes as relay but they differ from cooperation when their turn to become relay comes. This situation results in end of cooperation in the network. It is necessary to provide motivation to the node so that they would like to stick to cooperation and share their resources to enhance their performance. The motivation to the node to become relay may be in terms of virtual payment (Shastry) (Saraydar) (Q. Y. Cao), reputation index (He) (Anantvalee) (J. J. Jaramillo) (J. J. Jaramillo), concession in rates for own services and exchange of the resource (D. R. Zhang).

1.2 Objectives

In this thesis, resource allocation techniques for centralized network, semi-distributed network and distributed self-configuring network are presented. Utility function based resource allocation is proposed for centrally controlled network, where cooperative relays are installed by the service provider to improve network-wide performance. The proposed utility function is capable to allocate resources to the users to provide desired trade-off between efficiency to the service provider and fairness to the users within the constraint of limited power and bandwidth.

To make cooperation applicable in distributed network, the nodes must be encouraged to act as relay nodes and allocate their resources to source nodes. Pricing is the attractive option for cooperation encouragement. Nodes which act as relays for other nodes, get return in terms of virtual currency or money from the source node. Source nodes check own resources and buy retransmission power from the relay looking at the balance of virtual currency possessed by it. Nodes acting as relay sell the retransmission power to earn maximum amount of virtual currency. Each node manages their account of virtual currency with the help of centralized controller. When the source node finds that it is not able to reach its desired data rate on its own, it spends its virtual currency to buy help of the relay node.

Moving one step further, in fully autonomous, heterogeneous and self-organizing type of network, exchange of resources is the mechanism to establish cooperation and optimize the resource allocation to each node. Without any intervention of the centralized controller, the nodes negotiate with each other to exchange resource, reach their target of data rate and save precious resources like power and bandwidth. Here also, the knowledge of local channel condition is necessary for nodes.

Overall, the objective of the work presented in this thesis is to allocate source power, relay power and bandwidth to the nodes judiciously in cooperative mode by designing appropriate mechanisms. The designed mechanisms are capable of increasing the data rates of the nodes, save resources and encourage nodes to stick to cooperative behaviour to gain mutual benefits. Low computational complexity and less overheads are the parameters which are kept in focus while designing these techniques.

1.3 Contributions of Thesis

Main objective of this thesis is to develop resource allocation techniques for centralized, semi-distributed and distributed cooperative networks. The major issues which are addressed in this thesis are as follows:

1. To allocate source power, relay power and bandwidth judiciously in cooperative environment
2. To achieve higher data rate, taking benefit of virtual spatial diversity
3. To encourage service provider and nodes to stick to cooperative communication

The resource allocation approaches are developed in this thesis applicable for centralized, semi-distributed and distributed network scenario respectively.

- Development of a set of utility functions suitable for delay tolerant data network; Efficiency-fairness trade-off demonstrated by each of them. Step by step development of generic utility function for following types of the allocations: (i) efficient (ii) proportional fair (iii) min-max fair (iv) minimum delay fair and (iv) desired degree of trade-off between efficiency and fairness.

- Development of resource constraint based approach and E-F function based approach for resource allocation in centralized network. Determination of values of coefficients to perform efficiency-fairness trade-off in resource allocation of centralized network. Comparison of these two approaches with utility function based approach.

- Multi-unit auction mechanism based on demand curve for semi-distributed network which eliminates the need of global channel knowledge at the central controller. Source nodes generate linearly decreasing demand curve parameter in terms of units of power for given price per unit. Relay node generates aggregate demand curve and allocate relay power to maximize revenue in terms of price for assigned units of power. Two type of pricing mechanisms are considered: (i) non-discriminatory, and (ii) discriminatory pricing to motivate node to act as relay node and thereby, creating cooperative diversity. Computational complexity of the order of $O(1)$ is obtained irrespective of number of nodes involved. It is compared with clock auctioning technique in which complexity depends on number of nodes participating in cooperation and the difference between demand and available resource. It is also demonstrated that the proposed technique satisfies the desired properties of auction.

- Power-bandwidth exchange based mechanism for distributed network for resource allocation. This technique eliminates any involvement of central controller. The nodes with self-organizing capabilities searches for suitable partner, put or accept offer of resource as an independent decision maker and determine quantity of power – bandwidth exchange to enable them to achieve their desired data rates. A Fast algorithm, with fewer overheads for negotiation, is presented and compared with conventional iterative algorithm. The proposed exchange mechanism only stimulate nodes to stick to cooperation, but also save energy and increase data rate.

1.4 Organization of Thesis

The thesis work is divided into five chapters. The details related to each chapter is as follow:

Chapter 1 Introduction

This chapter contains the motivation for the thesis, objectives and main contributions of the thesis. It also includes organization of the rest of the thesis.

Chapter 2 Literature Review

This chapter presents the concept, protocols, benefits and challenges of cooperative wireless communication network. Various approaches of resource allocation in cooperative wireless network are reviewed. The need for utility function based resource allocation, review of various utility functions, and properties of utility function for different type of traffic is discussed in this chapter. Various cooperation stimulation strategies are also discussed.

Chapter 3 Efficiency-Fairness Trade-off Based Resource Allocation Approaches for Centralized Network

In this chapter the problem of resource allocation is investigated for centralize Network. Utility function based, resource constrained based and E-F function based approaches are evolved. In each case a resource allocation optimization problem formulation is developed Extensive simulation are carried out for performance evaluation and results are discussed. Further a generic single utility function is designed for addressing various types of resource allocations.

Chapter 4 Multi-Unit Auctioning Based Resource Allocation Technique for Semi-Distributed Cooperative Network

This chapter deals with the pricing based resource allocation scheme for semi-distributed cooperative network. The frame work for generation of demand curve by each source node, aggregate demand curve and revenue maximizing allocation by the relay node is presented. Analysis of revenue maximization with discriminatory and non-discriminatory pricing scheme is carried out. The performance is evaluated by simulation and discussed. Complexity of the proposed scheme is compared with the clock auctioning technique.

Chapter 5 Power-Bandwidth Exchange Based Resource Allocation for Distributed Cooperative Network

The framework for power-bandwidth exchange between a pair of users is presented first. It is followed by the analysis of the scheme to evaluate possibility of mutual cooperation. The amount of resources to be exchanged to reach the point of mutual cooperation are determined and tested by simulation. The mechanism is also tested for random channel variations to show the robustness of this scheme against channel variations. This chapter also contains two approaches for establishing successful cooperation- (1) Iterative approach (2) One-shot approach.

Chapter 6 Conclusion and Future Work

The final conclusion of this thesis is presented at the end of the thesis in chapter 6. The points are identified for further research directions based on this work and presented in this chapter.

Chapter 2

Literature Review

Cooperative communication is a technique to generate spatial diversity by taking the benefit of broadcast nature of wireless channel. Mutual cooperation of wireless node is proved to yield many advantages in terms of increasing data rate, extending coverage and improved link reliability. The practical implementation of cooperation in wireless network needs to address certain challenges. Duplication of transmission in cooperative mode leads to the issues like wastage of resources, increased traffic, higher interference, selfishness of nodes, and security of data. Appropriate method of resource allocation is capable of resolving many issues of cooperative communication. In centralized network, the central controller allocates the resources to optimize the performance of entire network. To avoid the issue of selfishness, mechanisms are designed to encourage the nodes to stick to cooperation. Pricing based allocation and reputation based allocation are the mechanisms which bind the nodes to cooperation. Mutual cooperation is established when the nodes exchange their resources with each other to gain mutual benefit in distributed network.

2.1 Cooperative Wireless Communication

Wireless channel is affected severely by fluctuations in signal power caused by fading, in addition to path loss and interference. These impairments together limit the capacity of wireless communication. Time, frequency or space diversity can combat the effects of fading by transmitting a signal via independently faded multiple time slots, channels or antennas, respectively. These independently faded replicas of the signal are combined at the receiver. MIMO communication has been considered as the most appropriate technique to fight against fading by forming spatial diversity between wireless devices with multiple antennas. However, looking at the cost, power consumption and space requirement, it may not be feasible to install multiple antennas in the small, low cost and power constraint wireless devices. Alternatively the idea of cooperative communication has been evolved to achieve spatial diversity without using multiple antennas on the wireless device.

Cooperative communication has been introduced and primarily discussed in (A. E. Sendonaris) (J. N. Laneman) (Nosratinia). Broadcast nature of wireless channel is exploited to transform single-antenna terminals into a virtual multiple-antenna system. Thus, spatial diversity is formed by multiple signals transmitted from source and relay(s) terminals through independent, uncorrelated channels. A simple single relay cooperative network is shown in Fig 2.1.

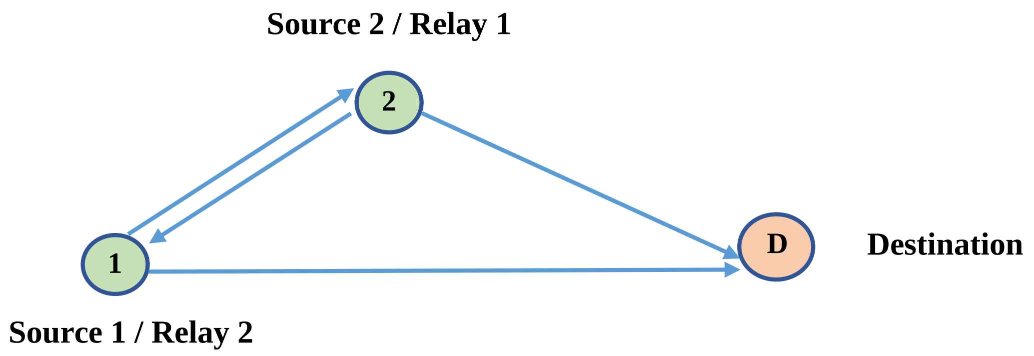


Fig 2.1 Simple Cooperative Network

When node 1 transmits a signal, it is received by node 2 in addition to its destination node D due to broadcast nature of wireless medium. Node 2 re-transmits the signal received from node

1 after applying cooperative protocol, as discussed in the subsequent section. In this case, node 1 is a source and node 2 is a relay node. When node 2 transmits, node 1 cooperates by acting as a relay to retransmit node 2's signal. As a result, there exists two paths between the source node $S_{i,}$ and the destination node D, a direct path (S_i - D) and a relay path (S_i - R_i - D). Thus, the destination node D receives two copies of the signal, one through the direct path (S_i - D) and another one through relay (S_i - R_i - D). At the destination, both the signals are combined to form spatial diversity.

Based on the processing done by the relay, the cooperative communication is classified in various protocols. Cooperative communication protocols found in the literature are presented in the next section.

2.2. Cooperative Communication Protocols

A systematic approach to coordinate the transmissions from different relays has been first proposed in (J. N. Laneman) as repetition based cooperative strategies. The Amplify and Forward (AF) protocol and the Decode and Forward (DF) protocol, have been introduced for forwarding the signal from the source towards the destination. These protocols differ on how the relay process the signal received from the source. It is shown that the repetition-based strategy could achieve the full diversity order in the number of cooperating nodes. The cooperative relaying protocols have been further studied in (Anghel) (D. a. Chen) (Hasna, End-to-end performance of transmission systems with relays over rayleigh–fading channels). When more than one relay cooperate with source, it results in increased diversity order (A. E. Sendonaris) (A. E. Sendonaris). Some of the frequently employed relaying protocols and its variants for cooperative communication are described in the following subsections.

2.2.1 Amplify and Forward (AF) Relaying Protocol

In Amplify and forward relaying protocol, the relay amplifies the received signal with an amplification factor *(G)* and retransmits it. The amplification factor *G* is employed to normalize the received signal. The relay does not require any knowledge regarding encoding or modulation scheme with which the signal from the source is processed. AF protocol is desirable when Source-Relay *(S - R)* link is poor and does not guarantee reliable decoding at the relay (S. B.-C. Yang). Prevention of decoding error and low complexity are the advantages of AF relaying protocol. The destination combines signals from source and relays using either maximum likelihood (ML) detection (J. N. Laneman) or Maximum ratio combing (MRC) detection (Anghel) (Hasna, End-to-end performance of transmission systems with relays over rayleigh–fading channels).

2.2.2 Decode and Forward (DF) Relaying Protocol

In Decode and forward relaying protocol (DF), relay decodes the message received from the source, re-encode and transmit it to assist decoding at the destination. Unlike AF, noise is not amplified in DF relaying protocol. As a result, accumulation of errors is avoided in this protocol. However, bad S-R link results in decoding errors at the relay, which, in turn, results in poor error performance. As a result, this protocol is preferred when the performance of S-R link is not satisfactory. If the relay forwards only the correctly decoded messages, it is referred to as selective DF relaying.

2.2.3 Compress and Forward (CF) Relaying Protocol

In this relaying protocol, the relay detects the signal sent by the source and transmits a quantized and compressed version of the signal to destination. The destination combines full version received from the source and compressed version received from the relay. The relay node is involved in some form of source coding of the received signal. The relay situated close to destination is suitable for this relaying protocol (Liu) (Hu). The relay may estimate modulated symbol and retransmits it using same or the different modulation order. In that case, it is referred to as Estimate and Forward (EF) relaying. The coding techniques applied at the relay are referred to as distributed source coding**.**

In addition to the above mentioned basic protocols, other protocols and its variants like incremental relaying, distributed space-time code base cooperation, and adaptive relaying protocol are also possible. Incremental relaying is the variant of basic AF protocol, in which the relay transmission is done only in case of failure of direct S-D link. Distributed space-time code based protocol is employed when two or more relays are involved in cooperation and source node does not have channel knowledge. In adaptive relaying, the relay node adapts the relaying protocol depending on the S-R link.

2.3 Challenges in Implementation of Cooperative Communication

The essence of the cooperative communication lies in retransmission by the relay node. Additional transmission by the relay node demands additional resources. Moreover, it gives rise to interference. For selecting appropriate relay for source, additional overheads are required. Process at the relay before retransmission adds to the delay in transmission. Moreover, any sort of cooperation always faces a big threat of selfishness of participants. To realize cooperative communication and to leverage its benefits, it is necessary to address following challenges:

i. Duplication of transmission results in increased interference and wastage of resources
ii. Selection of partner or relay for getting maximum benefit of cooperation
iii. Increased overhead for synchronization, cooperation establishment, and security
iv. Processing at the relay increases latency
v. Designing of new protocols

The benefits of cooperation are vanished, if it needs more bandwidth or transmission power. Further, overheads and computational complexity involved in selection of relay and cooperation establishment can be reduced by properly designed mechanism. Above all, the technique must be evolved to attract the relay nodes to retransmit for the benefit of source.

Properly designed resource allocation techniques can resolve these issues. The work in this thesis is focussed on judicious resources allocation namely source power, relay power and bandwidth to ensure increased data rate, and cooperation establishment with low overheads and computational complexity.

2.4 Resource allocation Techniques

In wireless network, transmission power and bandwidth are limited. The cooperation protocols involve retransmission by the relay node which requires transmission power and bandwidth both. Moreover, consuming more power in transmission not only reduces the battery power of the nodes, but also results in interference. Bandwidth is the most valuable resource in wireless networks. It must be allocated optimally. To gain the benefits of cooperation and avoid wastage of the resources, allocation of resources must be done rationally and judiciously and has drawn significant attention of the researchers.

In (Hasna, Optimal power allocation for relayed transmissions over Rayleigh-fading channels), source to destination link, replaced by multi-hop link has been considered with the objective of increasing the coverage. The authors have demonstrated that power can optimally be allocated to each link within the constraint of total transmission power, with the objective of minimizing outage probability of a link. The links are assumed to be differently faded and hence need different power to reduce outage probability. The results have demonstrated that simple non-regenerative protocol with optimum power allocation outperforms complex regenerative protocol. This technique distributes transmission power over several links which results in longer battery life and lower interference.

Significant saving of energy and reduction in outage probability has been achieved with the help of availability of channel state information at the transmitter and optimum power allocation in (Ahmed). The authors have designed a hybrid protocol which selects any one of the two protocols - DF (Decode and Forward) and EF (Estimate and Forward) depending on the location of the relay to maximize the data rate, Power allocation for DF relaying protocol has been carried out in (Luo) with the assumption of knowledge of only mean channel gain at transmitters. For reducing the complexity of finding optimum solution, a sub-optimal scheme has been presented in which fixed fraction of power is allocated to the source node and remaining power is distributed among all the helping relays. The objective of power allocation is to minimize the outage probability.

Multiple sources communicating with their destinations with the help of multiple relay has been considered in (Phan). The relay allocates different amount of power to each source. Allocation of relay power depends on the demand of the source to meet desired quality of service (QoS). The demand of the sources, in turn, depend on the channel experienced by it. Hence, each source-destination pair would get different relay power. Three objectives of power allocation has been considered as (i) To maximize the minimum signal to noise ratio (SNR), (ii) To minimize the maximum required source power, and (iii) To maximize the total throughput. In the network with limited resources, it is not possible to satisfy the quality of service (QoS) requirements of all the users. Hence, power allocation is supplemented by admission control mechanism, which limit the number of users in the network.

Unlike (Phan), in (Xie), allocation of optimum bandwidth has been done by keeping power constant to maximize the capacity. TDMA based scheme provides optimum share of time to the source and the relay and FDMA based scheme shares fraction of bandwidth between the source and the relay as shown in Fig 2.2. In TDMA based scheme, total time T is divided between source and relay. In time T_s, source transmits to relay as well as destination. During remaining time T_r, relay retransmits after applying DF protocol. Out of total bandwidth W, the source uses W_s for transmission and remaining bandwidth is allocated to the relay for the entire duration of transmission. It is shown that FDMA based scheme performs better than TDMA based scheme.

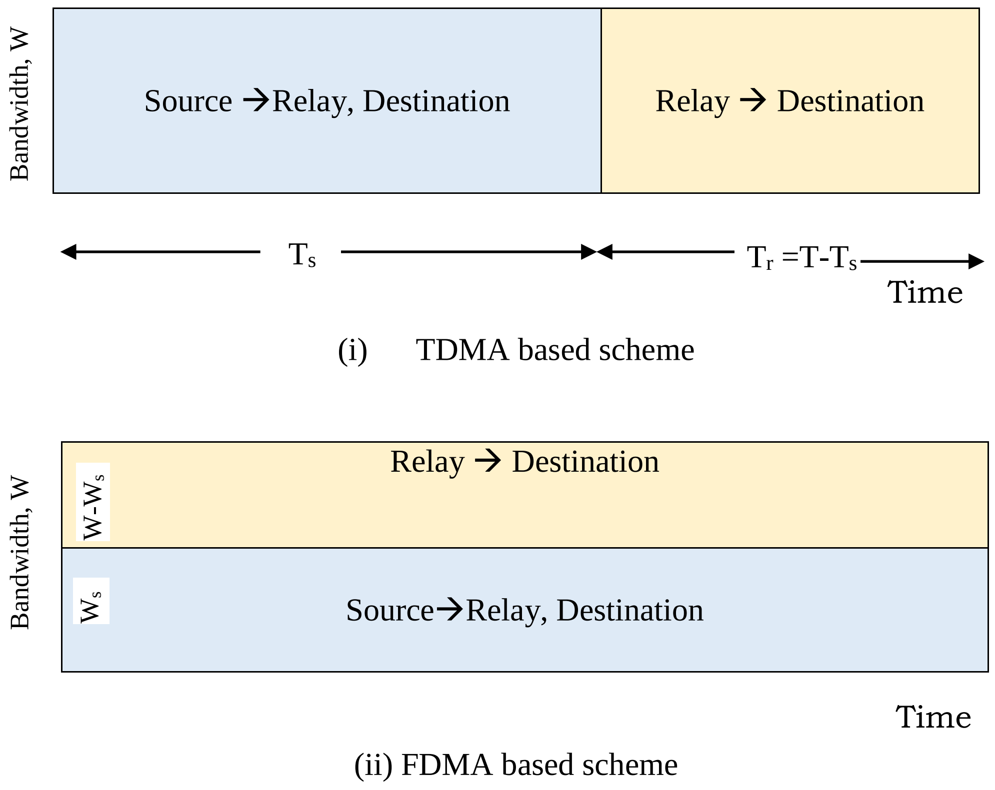


Fig 2.2 TDMA and FDMA based resource allocation (Xie)

This concept has been further extended to joint allocation of power and bandwidth in (Marić) (Gong). Optimum allocation of source bandwidth and relay power in a power-constrained large scale network has been presented in (Marić), with AF and DF relaying strategies. The network under consideration has enough bandwidth but limited power. The authors have presented arguments that in AF protocol, the performance enhancement is not obtained by using more bandwidth as the relay power is wasted in amplifying the noise in the wider bandwidth. To make use of optimum bandwidth, AF protocol is operated in linear region, where data rate increases linearly with transmit power. A set of suitable location of relay nodes for AF protocol has also been identified. DF protocol seems to work efficiently when wider bandwidth is available. The relay location suitable for AF protocol are not appropriate for DF protocol. A new set of relay locations has been identified for DF protocol.

The authors in (Gong) have proposed joint allocation schemes of power and bandwidth for multi-user network with objectives to (i) maximize the sum of capacity (ii) maximize the worst user capacity and (iii) minimize power consumption. It has been shown that optimum allocation of joint power and bandwidth results in more capacity and power saving compared to that of equal power - equal bandwidth allocation and only optimal power allocation schemes. It is demonstrated through simulations that joint optimization of power and bandwidth gives higher sum capacity and worst user capacity compared to other two cases: (i) only power optimization, equal bandwidth (ii) equal power and equal bandwidth.

All these research contributions show that optimized allocation of source power, relay power and bandwidth enhances the performance of cooperative network. Main difficulties in this type of allocation are availability of feedback channel, knowledge of channel state information, tight synchronization, hardware adaptable to change in bandwidth and/or power and computation complexity to find optimum solution. Advanced wireless nodes are capable to cope up with all these challenges. As a result, cooperation in the network would be practically possible by means of optimized resource allocation.

Different researchers have investigated the resource optimization issue with variety of goals in view like

i. Increasing the coverage (Hasna, Optimal power allocation for relayed transmissions over Rayleigh-fading channels)
ii. Maximizing the minimum SNR (Phan)
iii. Minimizing power consumption (Phan) (Gong)
iv. Maximizing the total throughput (Phan) (Gong) (Xie)
v. Maximizing worst user capacity (Gong)
vi. Minimization of outage probability (Ahmed)

It is necessary to determine an appropriate objective function for a given network. In this thesis, a network engaged in providing various class of services is considered. The services are attributed as (a) delay sensitive or delay tolerant (2) fixed data rate or variable data rate (c) predefined QoS (Quality of Service) or best effort as discussed in (Alasti). Establishment of cooperation in the network requires determination of suitable source-relay pairs and allocation of resources to each pair. The demand for variable data rate and delay tolerant categories increases day by day in wireless data network due to internet access, social media, video/audio downloading etc. Cooperation establishment for this category, not only improves resource utilization in the network, but also saves energy of the nodes. Our focus in this thesis is to do resource allocation for such users in (a) Centralized network (b) Semi-distributed network (c) Distributed self-organizing network.

In IEEE 802.16j standard, the relays are installed by the service providers to extend the coverage and provide communication in the regions of deep fade (Hong) (Genc). On the same line, the service provider can be encouraged to make extra efforts for establishing cooperative diversity in the network by installing relays and applying optimum resource allocation to sources and distribute the resources of relays among the sources. We have undertaken this scenario for resource allocation in chapter 3 of this thesis.

Based on the factors such as variety of application supported by network and the time varying fading channel, all the above mentioned techniques cannot satisfy all the users equally. In such scenario, the task of optimum resource allocation with the constraint of limited resources becomes difficult to achieve. In data network, higher satisfaction is related to achieving the necessary data rate for the given application. Two users getting same data rate are not equally satisfied, if they are engaged in different applications. Similarly, two users engaged in same application but facing different channel conditions are also not equally satisfied with equal amount of power and bandwidth resources. The objective of service provider is to maximize satisfaction of all the users, engaged in different services and experiencing different channel conditions. As a result, equal allocation of resources would not result in similar satisfaction of all the users. The service provider allocates the resources in such a way that users' satisfaction is maximized and at the same time efficiency of allocation, in terms of achieved data rate, is also not deteriorated much.

2.4.1 Utility Function Based Resource Allocation

In Utility based resource allocation, the resources are allocated to maximize the satisfaction of the users in the network in place of maximizing the data rate. The degree of satisfaction of user for a given amount of resource can be represented as utility. The application of utility for resource allocation is presented in (Xiao) (Saraydar) (Kuo) (Wang) (Jiang) (Baidas) (Q. Y. Cao) (Shastry) (Feng) (D. X. Yang) (D. G. Yang). The utility is defined as ratio of number of bits received successfully to energy expended to achieve it.

The details of utility functions and the target objectives stated in these references are summarised in Table 2.1. Power control using pricing for a wireless data network has been considered in (Saraydar). In this, the net utility of the users is defined as the difference between the utility achieved and power used for that. Net utility function has been designed to control the transmitted power of the user to reduce interference in the network. On one hand the user is tempted to radiate more power to increase SIR but on the other hand, radiating more power reduces net utility. Once interference is controlled, the user can get higher SIR at a given power and all the users in the network are able to maximize the utility.

Centralized resource allocation for fixed data rate, best effort and mixed traffic network has been considered in (Kuo). For fixed data rate traffic, step utility function is presented. Until sufficient radio resource is given, utility remains 0. On getting adequate bandwidth, it becomes 1. Utility of best effort traffic increase with the bandwidth.

Table 2.1 Utility Functions for resource allocation

Reference	Utility Function	Objective
(Saraydar)	$U = \frac{Throughput}{power}$	Power control in wireless data network
(Kuo)	$U - step\ for\ fixed\ data\ rate$ $U = 1 - e^{R}\ for\ best\ effort$ where, R – radio resource	Radio resource allocation for fixed data rate, best effort and mixed traffic
(Wang)	$U = R_c - M$ where, R_c is the data rate with cooperation M – Price to be paid to relay	Power allocation in cooperative network with Stackelberg game by modelling source as buyer and relay as seller
(Jiang) **(Shastry)**	$U = \frac{Throughput}{power}$	Resource determination for stimulating mutual cooperation in cooperative network using Cooperative game
(Feng)	$U = \frac{Throughput}{power}$ (User centric)	Joint user-centric and network-centric radio resource management
(Baidas)	$U = \Delta R_c - M$ where, ΔR_c is the increase in data rate with cooperation M – Price to be paid to relay	Power allocation in multi-source multi-relay cooperative network using clock auction
(Q. H. Cao) **(Q. Y. Cao)**	$U = SNR_D$ where, SNR_D is the received SNR at destination	Power allocation in multi-user network using bargaining
(D. X. Yang) **(D. G. Yang)**	$U_s = V_s - M$ $U_R = M - V_R$ where, U_s – Utility of source U_R – Utility of relay V_s – Value of cooperation to source M – Price paid V_R – Value of cooperation to relay	Relay resource allocation to source nodes using two sided auction with service provider as auctioneer

The results, obtained in above mentioned references, show that the resource allocation depends on traffic type, available resources and channel quality. Utility function depicted in a (Jiang) (Shastry) and (Feng) are similar and is represented as ratio of throughput to power. Bandwidth is not considered for allocation. In (Q. H. Cao) (Q. Y. Cao), utility is a function of SNR. In multi-user scenario, these function will allocate the maximum resource to the one who can get maximum throughput or maximum SNR. The fairness perspective is not addressed in these functions. We have explored this point further in this thesis in chapter 3. A set of utility functions is evolved to fulfil several requirements of the resource allocation from user's perspective as well as service provider's perspective like efficiency, degree of fairness, proportional fairness, max-min fairness, and minimum delay fairness.

The references mentioned in Table 2.1, except (Saraydar) and (Kuo), employ game theory tool for resource allocation after constructing suitable utility function. Some concepts of game theory are presented in the next subsection.

2.4.1.1 Game Theory Concepts for Resource Allocation (Osborne) (Vazirani)

Game theory is the formal study of conflict and cooperation. It is a branch of applied mathematics which helps independent decision makers to analyse conflict situations and choose the best strategy to reach his goal. Game theoretic concepts apply whenever the actions of several agents are interdependent. For resource allocation, users and service provider are two players of the resource allocation game having different but interdependent objectives. Users require more network resources to increase individual data rate and improve signal quality. On the other hand, the service provider desires to serve more number of users with the same limited network resources. There arises the conflicting situation. Such situation can be modelled as a Game. Theoretically, a game consists of three basic components: a set of players, a set of strategies/actions for each player and a set of preferences over possible outcomes. The preferred outcome is represented as payoff or utility. The participants of the game are players, who choose their strategies in each stage of the game. The choices of a strategy by one player influences the outcome of the game for each player. Each player selects a strategy from a set of strategies which can maximize his utility (or payoff). Detailed classification of games is available in literature of game theory (Osborne) (M. a. Upadhyay). If the players take their action one after the other looking at the strategy of opponents, it is referred to as sequential game. If all the players act simultaneously and then review the outcome before going to the next stage is called simultaneous game. Benefit of one player is at the cost of loss of other, it is called as zero-sum game. If all the players are fully aware of the common knowledge of game, it is referred to as game of complete information. A sequential game would be the game of perfect information, if a player exactly knows the outcome of the game due to opponents' strategy in the previous stage of the game.

A game can be referred to as non-cooperative, if players of the game take decision for maximizing own utility only. Contrast to that, cooperative game, also called coalition game, in which players form group, decide the division of benefit earned by cooperation and then cooperatively maximize the total benefit. Resource allocation for cooperative network can be represented as a cooperative game (Jiang) (Shastry) (Q. Y. Cao) or non-cooperative game (Wang) (Feng). Resource allocation can be a sequential game as in (Wang) (Feng) (Baidas) or a simultaneous (D. G. Yang) (D. X. Yang). The solution of the game is the strategy to which all the players stick to for gaining more utility. Nash equilibrium is one of the solution concept of non-cooperative game. Bargaining game can be solved with Nash bargaining solution (Vazirani) (Osborne).

The generic model of cooperative network is presented in Table 2.2 based on well-known Prisoner's Dilemma Game (Vazirani). In this game there exists four strategies for (Node1, Node2): (C, C), (C, NC), (NC, C) and (NC, NC). When both the nodes cooperate with each other by re-transmitting each other's signal, both can get higher data rate. It is represented as utility 1 in Table 2.2. (Considering identical channel condition for both). If node 1 cooperates and node 2 does not cooperate, node 2 can achieve benefit of cooperation, represented as utility 1. Node 1 has spent power but does not get any benefit so the utility of node 1 is –X. For (C, NC) strategy, utility is (-X, 1). Similarly, for (NC, C) strategy, the utility is (1, -X). When both the node does not cooperate, there is no gain and no loss. Therefore, utility of (NC, NC) is (0, 0). As the nodes are assumed to be rational decision makers, they calculates utility for all the entries of the strategy set. When node 1 is not sure about node 2's behaviour, it would select strategy NC because risk of loss is minimum. 2nd row of the Table 2.3 shows that node 1 can get either 1 or 0 by choosing NC. Utility of node 1 would by –X, if node 1 choses C and node

2 choses NC. Similarly, node 2 also finds NC as favourable strategy and finally the game ends in no cooperation. (NC, NC) is referred to as equilibrium strategy of the game.

Table 2.2 Modelling cooperative communication in strategic form

	Node 2-C	Node 2-NC
Node 1-C	(1, 1)	(-X, 1)
Node 1-NC	(1, -X)	(0, 0)

C- Cooperates, NC – Does not cooperate

Table 2.3 Decision of Node 1

	Node 2-C	Node 2-NC
Node 1-C	(1, 1)	(-X, 1)
Node 1-NC	(1, -X)	(0, 0)

C- Cooperates, NC – Does not cooperate

This equilibrium in not optimal as both the nodes could get utility (1, 1), in place of (0, 0). In such situation, some stimulant is essential to move equilibrium from (NC, NC) to (C, C). Pricing based mechanism for resource allocation is one of the stimulants to make equilibrium optimal. The modelling of such resource allocation is presented in next subsection.

2.4.1.2 Modelling of Resource Allocation as Non-Cooperative Game

To present the resource allocation as a game, the scenario in (Wang) (Baidas) consider source node as a buyer and relay node as a seller of resource. The interaction between them has been represented as Stackelberg game in (Wang) and auction game in (Baidas) Source is assumed to have virtual currency to 'buy' relaying power from the relay node. Node acting as relay 'sell' the power for cooperating with others when finds good channel condition with the destination and it does not have own data to send. The node acting as relay takes the benefit of this situation and increases the account of virtual currency, which can be used to 'buy' power when it faces bad channel acting as source.

With the relaying power, the source is able to increase the data rate. In return, the source has to pay price per unit of power to the relay node. The utility of the source is given as

$$U_s = (\mathrm{a} * \Delta R_c) - M \tag{2.1}$$

where, ΔR_c is the increase in the data rate due to cooperation, *a* is the factor to compare data rate with price and *M* is the total price paid, also called virtual currency, is computed as the product of units of power and price per unit of the power. Utility of the relay is given as

$$U_R = M - C_c \tag{2.2}$$

where, C_c is the cost incurred by the relay in terms of processing power used by the relay for retransmission. This situation can be represented in strategic form as shown in Table 2.4

Table 2.4 Resource allocation as a non-cooperative buyer-seller game

	Relay-C	Relay-NC
Source-C	(U_s, U_R)	(0,0)
Source-NC	(0,0)	(0,0)

C- Cooperates, NC – Does not cooperate

Table 2.4 shows the utility of source and relay in all four strategies. Source as an independent rational player decides the strategy looking for more benefit. If source selects NC, irrespective of the strategy of the relay, it would get 0 utility. Similarly, if relay chooses NC, it would get 0 utility. Source would be tempted to choose C if $U_S > 0$. Similarly, relay selects C if $U_R > 0$. Source could get positive utility, if the total price paid for buying cooperation is less than the advantage of data rate. Virtual currency earned by the relay is more than cost of cooperation, relay would be agree to remain in cooperation. Except (Saraydar) and (Kuo) all other reference mentioned in Table 2.1 reflect scenario of this kind. Mechanism to establish such equilibrium for resource allocation is further discussed in section 2.4.3.

The problem of resource allocation from user's perspective as well as network's perspective have been jointly undertaken in (Feng) for distributed network. Utility function of user is number of bits received by consuming given amount of power. The utility of the network is to maximize total revenue earned from the network, which in turn, is the product of unit price and total throughput. Net utility of the user is price subtracted from utility. The existence of Nash equilibrium is proved using semi-analytic approach. Power control using Stackelberg (buyer-seller) game as depicted in Table 2.4 has been presented in (Wang), in which the source-relay have been shown as buyer-seller of the power in multi-user cooperative communication network. Sources are the wireless nodes that want to buy the power from the relay in lieu of retransmitting its signal by paying certain price. Utility function for the source (or buyer) is the increased data rate due to cooperation minus the price paid for buying cooperation. The same for the relay is the price obtained from cooperation minus the cost of the power used for the source. Analysis has been presented to evaluate optimal relay power allocation to maximize the sum of the utility of all the sources and relays as well.

In (Jiang), cooperation is stimulated between a pair of users by making utility maximization based decision. The source node sends some bits of information directly by paying price to base station only and some bits through relay node by paying price to relay. The relay node transmits own information by sparing a fraction of bandwidth to re-transmit source node's bits in exchange of the price per unit of resource. The price per unit of resource used for direct transmission and re-transmission and the amount of information bits re-transmitted are optimized by employing utility maximization framework. Multi-sources are facilitated cooperation by a single relay in (Q. Y. Cao) employing the concept of Bargaining. Utility function is defined as effective signal-to-noise achieved by the source. It is calculated in different conditions: (i) without cooperation (ii) at disagreement point with cooperation. Disagreement point is the value of utility below which the source preferred to transmit non-cooperatively. Then Nash Bargaining Solution (NBS) is applied to calculate optimum relay power to maximize the sum of net utility of all the sources.

Above mentioned references show that properly designed utility function is capable of satisfying various objectives of the cooperative wireless communication network. We have explored this point further in this thesis in chapter 3. A set of utility functions are evolved to fulfil several requirements of the resource allocation from user's perspective as well as from service provider's perspective such as efficiency, degree of fairness, proportional fairness, max-min fairness, and minimum delay fairness.

2.4.2 Cooperation Stimulation Mechanisms

Benefits of cooperation in wireless network as mentioned in section 2.3 make it very attractive. However, many challenges must be complied with in order to achieve the benefits of cooperation. When a network belongs to any single authority, cooperation can be implemented naturally and systematically. It is very much optimistic to expect full altruistic behaviour from the nodes of a distributed, self-organizing network. Re-transmission involves resources and processing power of the relay node. Any node does not like to spare own resources for helping others, if similar behaviour is not reciprocated. Threat of selfish behaviour of some nodes fends off cooperation establishment in the network. There arises a need of mechanism to stimulate and encourage long lasting cooperation in the network. Different mechanisms have been evolved in the literature based on pricing in (Q. H. Cao) (Q. Y. Cao) (Wang) (Shastry) (Ileri) (Feng) (Baidas) (Mukherjee) (D. G. Yang) (D. X. Yang) (LI), reputation in (He) (Anantvalee) (Trestian) (J. J. Jaramillo) (J. J. Jaramillo) and resource exchange (Simeone) (Toroujeni) (D. R. Zhang) (Jayaweera) (Islam) (Xu) (D. R. Zhang).

2.4.2.1 Pricing Based Mechanism

In order to encourage node to act as a relay, price of cooperation can be paid by the source. This price can be in the form of virtual currency or token. The interaction between the source and the relay can be modelled as buyer and seller of the relay resource. Distributed resource allocation in multi-user cooperative network has been modelled using Stackelberg Game as discussed in section 2.4.1.

The authors in (Q. Y. Cao) (Q. H. Cao) have applied bargaining theory (Fudenberg) (Vazirani) to model negotiation between source and relay in multi-source single relay network. In (cao), the interaction between the sources and the relay has been modelled as buyer (or follower) and seller (or leader) employing Stackelberg game. Relay as a leader sets price and sources adjusts their power to maximize the transmission rates. For sharing the power of the relay, sources employed Kalai - Smorodinsky bargaining solution (KSBS) to maximize the network throughput compared to equal allocation. Utility of the sources without cooperation U_{NC} is the signal to noise ratio of direct S-D link SNR_{SD}. When relay power is allocated, the utility of the source U_C is signal to noise ratio of combined S-R-D and S-D links ($SNR_{SRD} + SNR_{SD}$) minus the price paid.

$$U_{NC} = SNR_{SD} \tag{2.3}$$

$$U_C = (SNR_{SRD} + SNR_{SD}) - M \tag{2.4}$$

where, *M* is the total price paid (i.e. product of price per unit of power and units of power). Each source has predetermined ideal utility U_I, which represents the maximum achievable rate by that source, if sufficient relay power is given. If the utility of the source with cooperation is no more than the utility without cooperation U_{NC}, the source would not enter in cooperation. The utility U_{NC} is called the disagreement point for the source. First the relay as a leader of the game declares price which can maximize the revenue. The relay power is then shared such that it maximizes the ratio $\frac{U_C - U_{NC}}{U_I - U_{NC}}$ for each source. The meaning of maximizing this ratio is to allocate the relay power to increase U_C of the sources based on their difference between the ideal and NC utility. The results in this reference show that allocation of relay power as per KSBS solution provides more fairness compared to maximizing through put solution. In (Q. H. Cao), the utility function of the user is defined as the combined signal to noise ratio of S - D path and S - R - D path, employing AF protocol at relay. Each source has been assigned priority of service which is used as their bargaining power in allocation. Source with high bargaining power receives more power from the relay. If relay does not cooperate with significant power, the utility would be smaller. Each source has predetermined dis-agreement point of utility, below which, source would prefer to transmit without the cooperation of the relay, similar to

(Q. Y. Cao). Nash Bargaining Solution (NBS) is applied to evaluate equilibrium of the trade compared to KSBS in (Q. Y. Cao). Distributed relay power allocation has been shown to yield good compromise between sum data rate of network and user fairness.

Pricing is employed to stimulate cooperation diversity in wireless ad-hoc network in (Shastry). In this paper, access point declares a set of prices for each source-relay pair in the network. Node acting as a source has to pay to forwarding relay as well as to the access point. When the same node acts as a relay, it gets reimbursement for forwarding source's information. This trade is shown to achieve equilibrium where all the nodes maximize their benefit either in term of diversity gain as a source and monetary return as a relay. Similar pricing scheme for encouraging relay for forwarding in self-configuring ad-hoc network has been presented in (Feng) (Ileri). Satisfaction of the user has been indicated by the ratio of individual throughput achieved to energy spent to achieve it. Network satisfaction has been measured by the revenue generated by utilizing the network resource. The approach followed by the authors is to maximize revenue of the network and utility of the node at the same time.

Payment and compensation has been employed to avoid selfish behaviour of the node in the cooperative wireless ad-hoc network in (LI). The network is modelled as a market in which relays are the supplier of the services and sources are the buyers. Initially, source nodes broadcast request for retransmission. The interested relay nodes reply with their prices. Sources follow linear price-demand function to select the one or more relays in terms of number of packet being carried by each of them. Each packet is transmitted with sending fees. The node transmitting the packet takes its share out of that fees. Prior to sending the packet, the source has to determine the total cost a packet needs till destination through all the hops. The source selects relays based on sending more number of packets with minimum cost. If the relay node replies higher price, source does not select it and hence that relay deprives of the revenue. The flavour of competition forces relays to reveal true price.

The trade between source and relay has been modelled as ascending clock auction in (Baidas). The process of clock auction for multi-source single relay is shown in Fig 2.3. In this paper, relay announces the price, then sources send their requirement of relay power in terms of bids. Relay increases the price, if the demand of the sources are more than the available relay power.

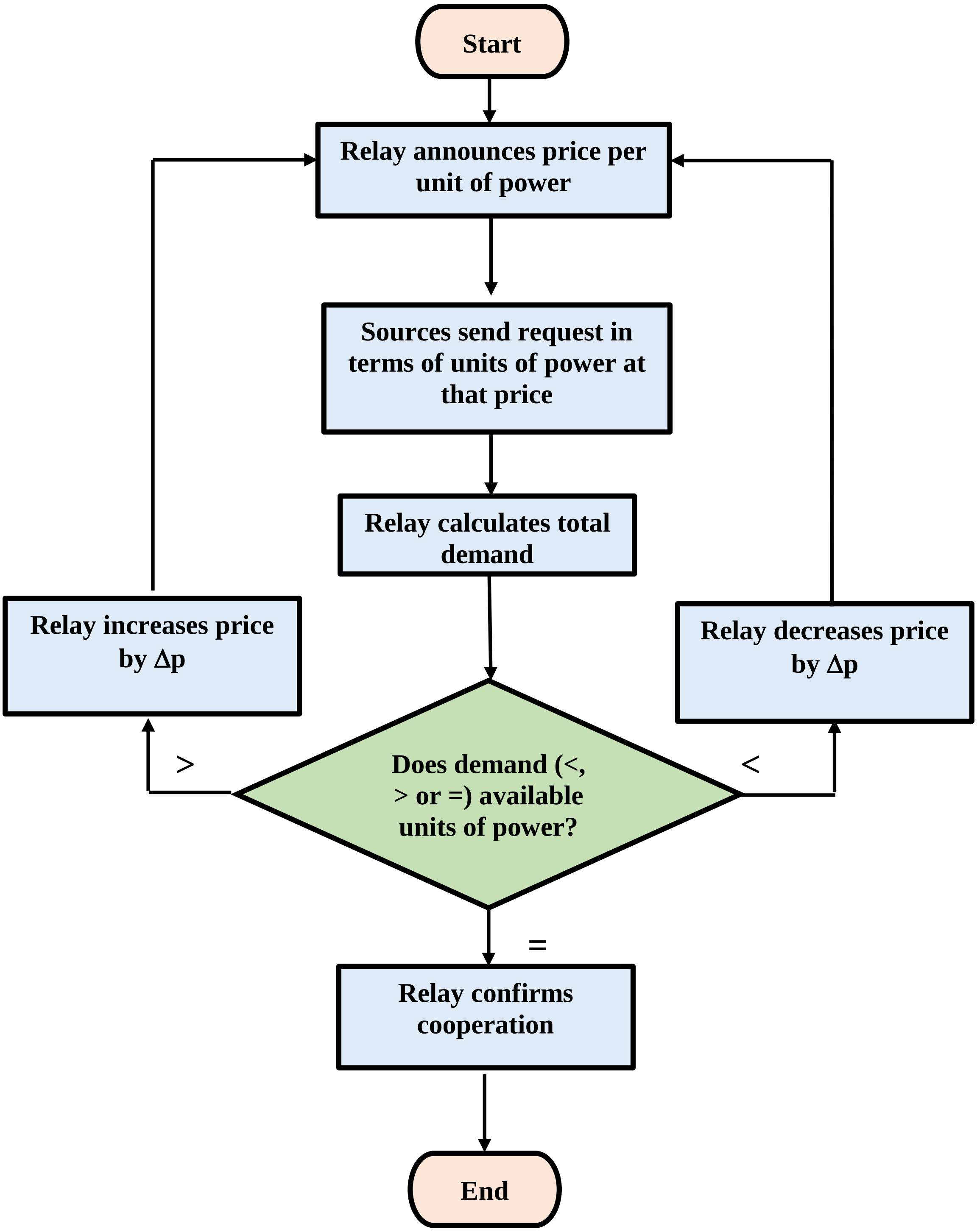


Fig 2.3 Clock auctioning technique

If demand of the sources are less than the available power, relay reduces the price. Again, the sources send their bids at the new price. The equilibrium is reached when relay's surplus power and sources' demand meet. Time taken for reaching the equilibrium depends on the gap between the available relay power and sources' demand and the step size by which the relay increases or decreases the price. This technique enforces sources to put forward their real demand and relay to ask genuine price. Also, it is shown that the equilibrium is achieved in finite number of steps.

Single object second price auction has been employed in (Mukherjee) for distributed partner selection in self-configuring wireless cooperative network. Second price auction motivates the buyers to bid higher amount. In first price auction, the object is given to the buyer who bids the maximum amount and the buyer has to pay that amount. In second price auction, the object is given to the buyer who bids the maximum but the buyer has to pay the price of second highest bid. The second price auction motivates the buyers to bid higher value. The node with good channel condition with destination acts as a potential helper. In the beginning, the potential helper initiate auction by broadcasting its capacity to provide data rate. The nodes in need send their request in terms of desired data rate to potential helper. The helper selects some or all requesting nodes depending upon its capacity. The request received in-between is not entertained.

To establish cooperation and determine the amount of cooperation, overhead bits are required. Number of overhead bits required for different cases of single partner selection and multiple partner selection have been calculated and presented. It shows that number of overheads bits depend upon total number of nodes in need of cooperation, number of bids, and number of selected nodes in single partner selection in distributed manner. Number of overhead bits required for centralised scheme is more that distributed scheme. Overheads bits increases when switched from single partner to multi partner and distributed to centralized technique.

In (D. G. Yang) (D. X. Yang), centrally controlled cooperative wireless network has been considered in which the base station acts as an auctioneer. Single round multi-unit sealed bid auction has been employed to model the trade of cooperation between source nodes, relay nodes and base station. In sealed bid auction, the sources are unaware of each other's bid. Sources $S_i, i = \{1, \dots, M\}$ calculate the true value V_i of the cooperation provided by the relays in the vicinity. Then sources send a sealed bid B_i to the auctioneer about its offer to buy relay services, which is less than or equal to the true valuation. The relays $R_j, j = \{1, \dots, N\}$ calculate the minimum cost C_j of cooperation and send their demands A_j to auctioneer. The demand of the relay is greater than or equal to its true cost. The difference between the bid and ask is the profit of the auctioneer. Utility of the sources and utility of relays are given as

$$U_{Si} = V_i - B_i \;\; i = \{1, \dots, M\} \tag{2.5}$$

$$U_{Rj} = A_j - C_j \;\; j = \{1, \dots, N\} \tag{2.6}$$

One relay is assumed to cooperate with one source only. Auctioneer selects the pair of source and relay to satisfy objectives like maximizing the total data rate of the network or maximizing the minimum data rate. After making the pair, the task of winners declaration and price determination are undertaken by the auctioneer separately. Bipartite graph method is employed to declare the winners of the auction and the common price applicable to all. For that, the bids of sources are arranged in non-increasing order and asks of relays are arranged in non-decreasing order. The auctioneer selects the nodes (sources and relays) for which bid is greater than or equal to ask in the sorted list. Let the threshold value of bid and ask be B_{th} and A_{th} and $M' = N'$ sources and relays are selected to cooperate. All the M'sources have to pay the price equal to B_{th} and all the relays would get payment of A_{th}. The profit of auctioneer can be given as

$$profit = (M' * B_{th}) - (N' * A_{th}) \tag{2.7}$$

Contradictory to auction techniques presented in (Baidas) (Mukherjee), this technique is only for centralized network in which the service provider earn profit by providing necessary frame work for cooperation. The sources are forced to reveal their true values because if they bid smaller than their true valuation of relay cooperation, they would not get selected by the auctioneer. Similarly, relays do not demand very high value of cooperation as high value of ask would put the relay backward in the non-decreasing sorted list. Low valuation and high demand both are avoided by the matching algorithm employed in this reference.

In this way, pricing based mechanism encourages node to participate in cooperative network as relay and earn virtual currency which can be spent by the relay for buying cooperation in the time of need. The approaches discussed above needs more overhead bits (Mukherjee) or delay in establishing optimal trade (Baidas) or needs central control (D. G. Yang) (D. X. Yang). In wireless network, channel keeps on changing. Moreover, the location of nodes also keeps on changing due to mobility. The equilibrium in source-relay trade highly depends on channel condition. The optimal decision would no longer remain optimal.

We have focused on the limitations of the above mentioned references in chapter 4 of the thesis. The limitations considered are: (i) the delay incurred in clock auctioning technique depends on the difference in demand and supply and step size to match demand with supply (ii) more overheads are required for finalizing the resource allocation and price (iii) computational complexity depends on number of nodes involved, step size and difference in demand and supply. Clock auctioning gives optimum performance in terms of data rate of source and maximum revenue for relay. However, optimum result depends on the channel condition. In time varying channel, it would not remain optimum longer. As channel changes, entire process of clock auctioning is to be repeated again. In chapter 4, a sub-optimal technique is presented for data network which needs fewer overheads and is less computationally complex. It results in instantaneous higher data rate compared to direct mode, encourages nodes to become relay by maximizing relay revenue and saves power of the source nodes.

2.4.3.2 Reputation Based Mechanism

Another approach to encourage cooperation in the network is reputation based mechanism. This approach has extensively employed in wireless ad-hoc network for encouraging forwarding through multiple hops. In place of giving or receiving virtual currency or token, the node can increase its reputation in the network by cooperating with other nodes. Reputation index built by the node makes it trust worthy and hence, it could get cooperation of the neighbouring nodes. Selfish nodes could not increase their reputation index and hence, the cooperation could not be reciprocated to them.

Neighbour monitoring based reputation scheme for enabling forwarding in wireless ad-hoc network has been presented in (He). Each node updates evaluation record of neighbour nodes in terms of two parameters: (i) number of request successfully forwarded, and (ii) confidence about its own judgement. This evaluation record is propagated to inform nearby nodes about the behaviour of a particular node. If any node acts selfishly, all the neighbouring nodes come to know about it and hence the packets of the selfish node are dropped by the neighbouring nodes statistically to punish it.

Reputation based network selection done by nodes in heterogeneous multi-technology scenario has been depicted in (Trestian), where the nodes select the network based upon the reputation. Reputation management system has been presented in (Anantvalee) to detect and punish selfish nodes. Unlike the earlier schemes, three types of nodes are defined: (i) Cooperative node, (ii) Selfish node, and (iii) Suspicious node. Benefit of doubt is given to the node by declaring it suspicious, in place of directly declaring it selfish. Suspicious node can improve its reputation by cooperating with others and becomes cooperative node. Once declared as selfish, the node is placed in the avoid list. Nodes find it advantageous to cooperate and maintain their reputation in the network. It is noted that the reputation based mechanisms discussed so far have a drawback. A node is cooperative but the monitoring neighbour does not get indication of cooperation due to bad channel between the cooperative node and neighbour node, collision or interference. This erroneous declaration of cooperative node as selfish hampers the performance of the network. In (J. J. Jaramillo) (J. J. Jaramillo), distributed and adaptive mechanism have been presented which can quickly restore cooperation after false declaration of selfish node.

In this way, the nodes adhere to cooperation with the fear of punishment of not getting cooperation in reputation based mechanism. The difficulty with this approach is maintenance of reputation index. Moreover, temper proof hardware is required to avoid cheating. One more limitation is that it is suitable where nodes have limited mobility.

2.4.3.3 Resource Exchange Based Mechanism

Another powerful approach to bind nodes in cooperation is to make pair of nodes having complementary resources and allow them to exchange the resources to enhance mutual performance. This mechanism is mainly applicable in self-configuring adaptive network where nodes are capable to, estimate amount of exchange and reassign its resources to others. In (Simeone), a network with primary (licensed) and secondary (unlicensed) users has been considered. The primary users assigns a fraction of transmission time in exchange of retransmission by the secondary users. Sharing of transmission time between primary and secondary users is as shown in Fig 2.4

The primary user decides whether to use the entire slot for direct transmission to its destination or to spare fraction of time to secondary users of ad-hoc network in exchange of their cooperation in terms of retransmission power. The slot is, thus, divided in three parts as shown in Fig 2.4. Primary user uses $(1 - \alpha)$, $0 \leq \alpha \leq 1$ portion of slot for direct transmission which may or may not be received by its destination. It is surely received by the secondary users. Remaining α portion of the slot is further divided in two parts: (i) In $\alpha * \beta$, $(0 \leq \alpha \leq 1$ and $0 \leq \beta \leq 1)$ portion of time slot, the secondary users acts as relay to re-transmit primary user's signal using space time coding. (ii) In remaining $\alpha * (\beta - 1)$, secondary users send own signal to respective secondary receivers using distributed power control. The primary user selects the secondary users as relay which can either maximize the data rate or reduce outage probability. It is assumed that the relay nodes have full channel information so that they can process signal of the source nodes using distributed space-time coding.

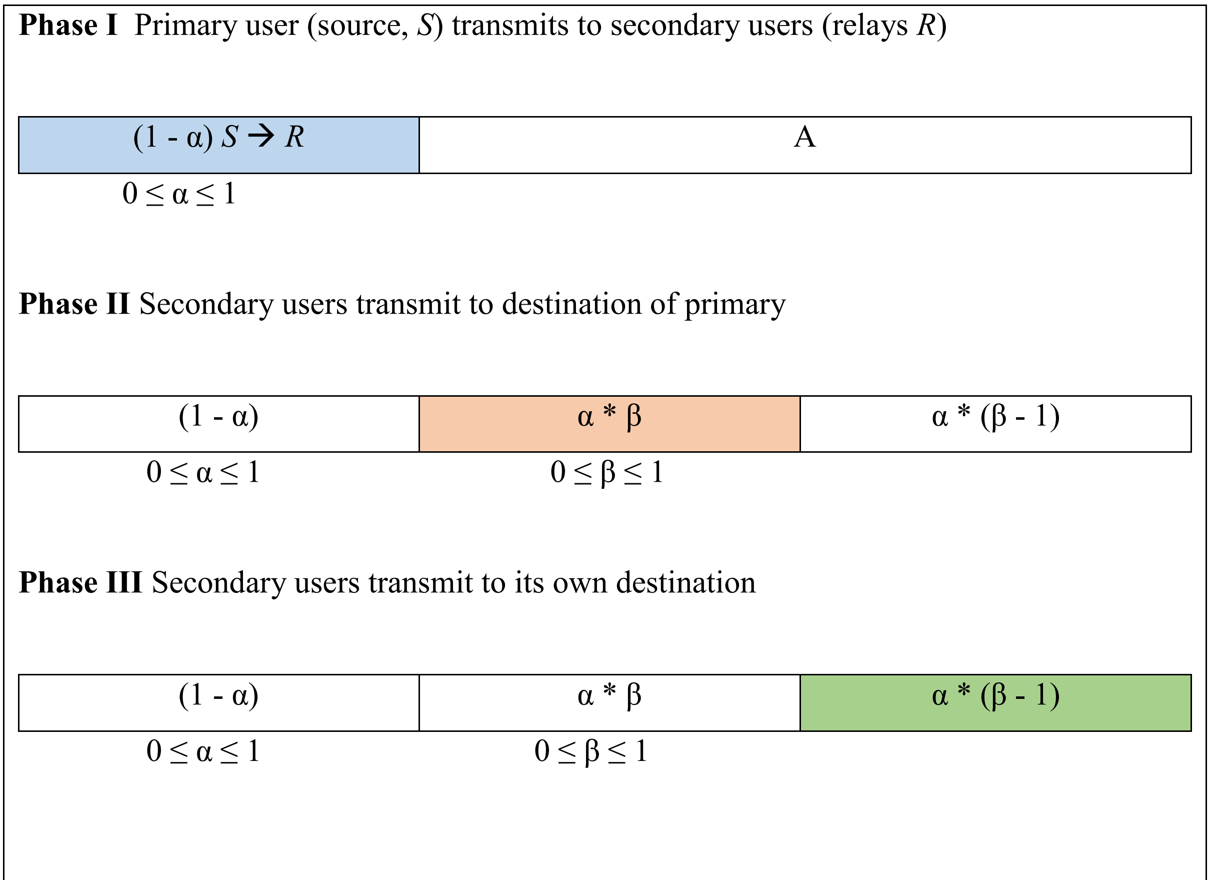


Fig 2.4 Amount of resources exchanged in cooperation

Similar resource exchange in OFDMA based cognitive network has been proposed in (Toroujeni). The primary user assigns the spectrum to secondary user on the time sharing basis. First, primary user transmits using whole spectrum during certain time period. Then, for rest of the time, secondary user uses a part of the spectrum to retransmit source's signal and remaining spectrum is used for transmission of its own signal. The technique presented in (Toroujeni) is different from (Simeone) in the phase II and phase III. In (Simeone), secondary transmits in whole spectrum on time division basis in phase II and phase III, whereas in (Toroujeni), secondary transmission in phase II and phase III are for whole time by dividing spectrum. The division of time and frequency between the primary and the secondary users has been done to optimize data rate of both in frequency selective fading channel.

Bandwidth exchange to incentivize cooperation in wireless network has been presented in (D. R. Zhang). When the direct link between source node and destination is under outage, source encourages another node to forward its signal by offering a part of spectrum as an incentive for forwarding. The source keeps a portion of the bandwidth for its own transmission to ensure minimum targeted data rate and assigns remaining bandwidth to relay node. The relay uses the extra bandwidth to transmit source's data and its own data to common destination. When direct link between source and destination is bad, the source uses option of direct transmission only with increased transmission power or Cooperation by sparing bandwidth. The later option is proved to be energy efficient in the presence of suitable relay in the network. It has been shown that when the quality of direct link is not sufficient to provide desired QoS, the source node can save energy by opting for bandwidth exchange scheme. Nash bargaining solution is used to find the equilibrium of this exchange. The authors have claimed that this type of bandwidth exchange is suitably possible for OFDMA based advanced wireless networks and cognitive radio networks.

In (Jayaweera), the secondary users or relays initiate cooperation by showing the willingness to re-transmit in exchange of bandwidth. The offer of relay encourages primary users (source nodes) to share bandwidth in exchange of relay power. All the relay nodes send bid in terms of the power they can offer to source node. In return, the source nodes offer the fraction of bandwidth spared by them in exchange of relay power. The trade between the source and the relay is carried out using auction theoretic approach as shown in Fig 2.5. If the relay's present offer does not find suitable partner, it employs reinforcement learning by modifying the offer to source. Similarly, the source's current offer does not suit with the requirement of relay, relay denies cooperation. The source can again modify the offer of fraction of bandwidth in order to get its offer selected. Source-relay match making is done either centralized or in distributed manner. In centralized approach, an entity called secondary system decision centre (SSDC) takes decision and generate source-relay pair on behalf of all secondary nodes. However, if the decision is not acceptable to source, the source can deny. In distributed approach, as shown in Fig 2.5, each relay put a bid to each source-destination channel. The destination decides the bid which can maximize the saving of source power. The relays can improve their bids using reinforcement learning to increase the possibility of getting selected for cooperation.

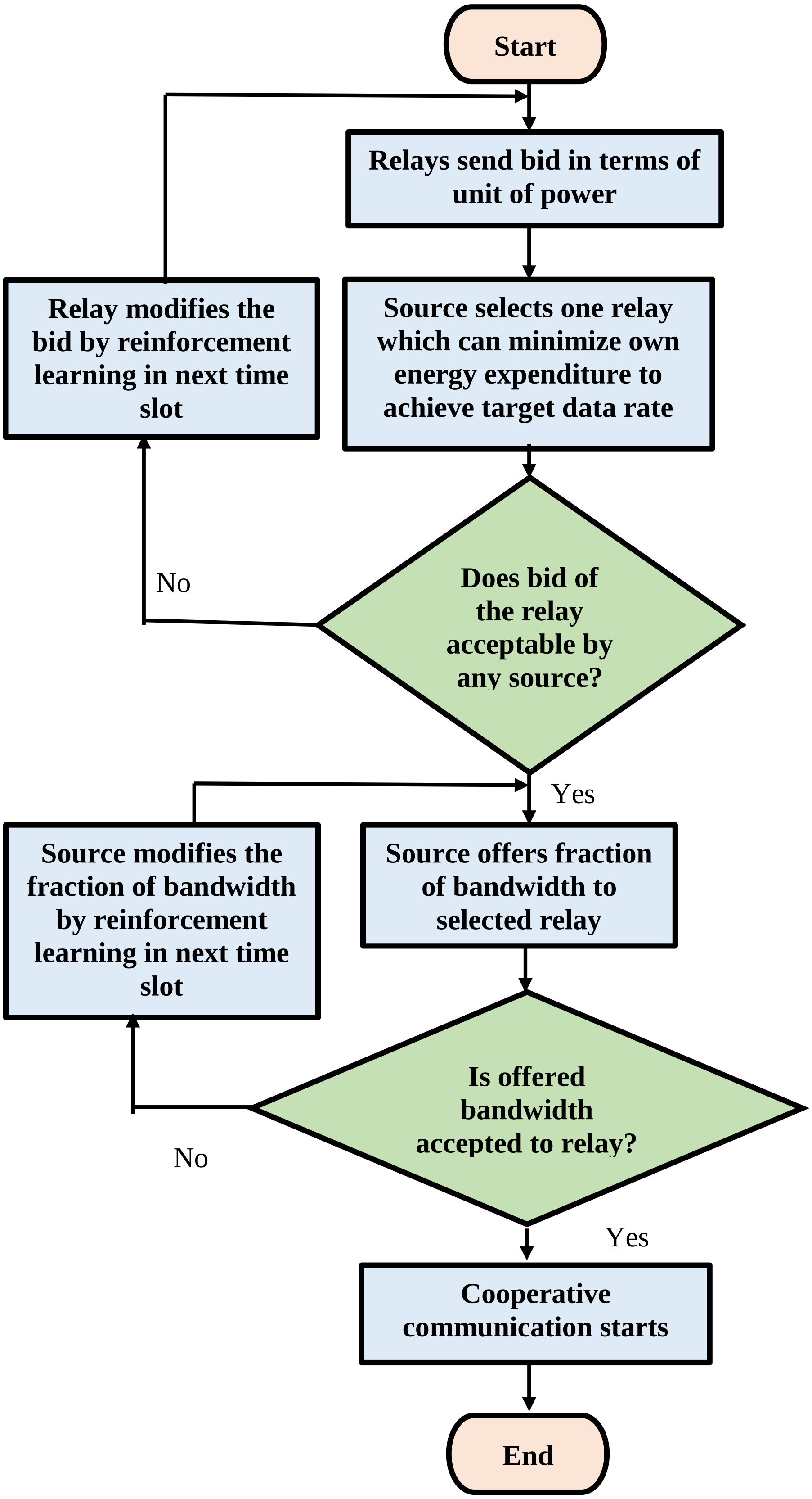


Fig 2.5 Auctioning technique for distributed resource exchange

The concept to allocation of a portion of time slot of TDMA based system to encourage cooperation has been explored in (Islam). The source node assigns a part of its time slot as an incentive to relaying node. The authors have also proposed hardware realization of this mechanism on ORBIT indoor test bed consists of USRP nodes enabled by software defined radio. The selection of source-relay pair can be achieved based on maximizing the throughput or providing proportional fairness. Different objective functions are used to achieve these two differing goals. The concept of resource exchange in (Xu) is based on division of channel on time basis. Cooperative cognitive network has been considered for flexible channel cooperation in which one secondary (relay) node re-transmit information of more than one primary (source) node and its own information by selecting the appropriate channel. For example, if one relay helps two sources, it has two options of channels available, which is spared by two sources as an incentive. Out of these, the relay chooses the channel for sources' transmission and its own transmission depending on the channel condition and targeted data rate expected by the sources. Relay node may use one channel for own transmission and another channel for combined transmission of both the sources. Alternatively, it may send part of its information of both the channel along with sources' information. The authors have also presented centralized and distributed resource optimization framework based upon Nash bargaining solution.

Two nodes mutually cooperate by relaying each other's signal have been considered in (D. R. Zhang). In frequency division multiple access (FDMA) based network, each user calculates its utility with and without cooperation. Here, utility is defined as a ratio of data rate achieved to power spent to achieve it. The optimum allocation problem is then solved by applying either Nash bargaining or Kalai-Smorodinsky bargaining solution. Based on computation and comparison of fairness index in each case, authors have concluded that the Kalai-Smorodinsky solution provides better fairness.

In all approaches presented in section 2.4.3.3, time slot, frequency band or both are exchanged for getting cooperative relaying by another node. The purpose of source node is to get desired QoS, target data rate, outage probability or save power. In all these approaches, for negotiation, Auction theory, Nash bargaining solution, Stackelberg game or Kalai-Smorodinsky bargaining solution are employed to reach equilibrium which is acceptable to all participating nodes. It is noted that all these approaches suffers from one or more of the following issues (i) higher overhead, (ii) delay in finding optimum solution, (iii) additional infrastructure requirement, (iv) computationally complex, and (v) requirement of global Channel state information. In Chapter 5 of this thesis we have evolved a power-bandwidth exchange based cooperation approach. It is applicable in self-organizing heterogeneous network. Our approach needs local channel state information only and needs fewer overhead to accomplish negotiation. Moreover, the negotiation completes in single round so the delay in negotiation can be avoided. Advanced wireless nodes are designed to be location aware. For such nodes, the framework for determining the region of probable partner location is also created. A comparison of resource exchange in centralized and distributed network is also presented. Reputation based mechanisms, as discussed in 2.4.3.2, requires tamper proof hardware and applicable to only limited mobility nodes. This mechanism is not addressed in this thesis.

2.5 Conclusion

In this chapter, introduction of the concept of cooperative communication and relaying protocols are discussed. The challenges which prevents practical realization of cooperative communication have are also presented. Utility functions utilized for the purpose of resource allocation are reviewed. The concept of Game theory and game theoretic models for resource allocation are also presented and discussed. Then, it is shown that appropriate resource allocation techniques not only enhances the performance of nodes and network, but it also encourages nodes to stick to the cooperation. Detailed review of such techniques, namely pricing based, reputation based and resource-exchange based, is presented to demonstrate the interest of research community in this area. From this rigorous survey, we have observed the following shortcomings: (1) Utility function address any one parameter (2) Pricing techniques have higher computational complexity, needs more overheads and large delay in allocation (3) In resource exchange, relay nodes are not enough motivated. These issues are addressed in the succeeding chapters of the thesis: (1)Efficiency–fairness trade-off using utility function for centralized network in chapter 3, (2) Multi0unit auctioning based pricing mechanism for semi-distributed network in chapter 4 and (3) Resource exchange based mechanism for distributed network in chapter 5.

Chapter 3

Efficiency-Fairness Trade-off Based Resource Allocation Approaches for Centralized Network

This chapter focuses on utility function based resource allocation for centralized wireless network for the users, engaged in best effort type of applications. In the beginning of the chapter, the essentiality and adequacy of utility function based allocation for cooperative scenario is advocated. Then, types and properties of utility function to cater different traffic is presented followed by system model and optimization problem formulation. Total data rate, individual data rate, fairness index and price of fairness are the performance metrics to evaluate and compare the results. Utility functions are designed with the perspective of satisfying various degrees of efficiency and fairness of resource allocation. In addition to utility function based approach, resource constraint based approach and E-F function based approach for performing efficiency-fairness trade-off are also discussed and compared. At last, a generic utility function is developed to satisfy many criteria of resource allocation.

3.1 Motivation and Problem Analysis

In cooperative network, relay helps one or more sources to achieve spatial diversity at the destination. The relay can be deployed by the service provider to enhance the performance of the network. In such network, the resources-source power, relay power, and bandwidth are to be allocated judiciously to each source as well as relay to help each source. The service provider installs relay with the objective of maximizing the sum total data rate of the network from the point of view to maximize its data dependent revenue. All the sources experience different channels with the destination. If equal resources are given to them, they would not be able to achieve equal data rate due to different channels with the destination. The source experiencing good channel achieves higher data rate compared to the one experiencing the bad channel. Equal allocation of the resources would be sub-optimal allocation from the service provider's point of view as it would not yield maximum revenue. If resources are allocated to maximize total data rate of the network, then the sources with good channel condition would get more resource compared to that with poor channel condition. This approach, in turn, affects quality of service criteria to all the sources in the network as promised by the service provider. If resources are allocated by keeping the sources with worse channel in mind, the target of total data rate of the network cannot be achieved which may result in loss of revenue to the service provider. Moreover, in the present scenario with variety of applications, the demand of the sources in network varies over a wide spectrum of expected data rate and real time constraints. Even if the resources are allocated to provide equal data rate to every source, it could not satisfy them equally because their requirement of data rate is different.

It seems that the issue of optimum resource allocation cannot be handled by the conventional method in all respect. However, it would be a better strategy if the allocation is done to maximize sum of satisfaction of the users in the network. The satisfaction of the source can be represented as Utility. Several utility functions with required properties are developed and efficiency-fairness trade-off offered by them are investigated in this chapter. The developed techniques are such that it would encourage service provider to install relays and provide better services to the users (or sources). The users can be given the choice to transmit cooperatively or non-cooperatively. Higher data rate and better link reliability encourage users to pay more for cooperative mode. As a result, the service provider can increase the revenue. In this way, the resource allocation techniques discussed in this chapter provide cooperation encouragement also.

Efficiency – fairness trade-off in resource allocation can be achieved by ensuring minimum amount of resource to any one source and by putting restriction on maximum amount of resource that can be allocated to any single source. We have refereed this technique as resource constraint based allocation. This is explored in in section 3.4 of this chapter. Further, an E-F function is developed for the purpose of efficiency-fairness trade-off in section 3.5. Selection of the values of parameter *E* and *F* determines the type of allocation viz. fair, efficient and proportionally fair. Resource allocation can also be done to satisfy other criteria also viz. max-min fairness, proportional fairness, weighted fairness etc. A generic function is developed to cater various goals of allocation as per the requirements in section 3.6. This function is capable of allocating the resources to satisfy various criteria of allocation by selecting appropriate value of only one coefficient.

3.2 Utility Function

A function which maps physical quantity to the degree of satisfaction of a user is called Utility. The concept of utility is taken from microeconomics (Fudenberg). Utility is a unit less quantity showing the perceived value of the goods or services to the user. In wireless network, the end user viz. source can perceive the quality of the communication. Source cannot realize the amount of power or bandwidth assigned to it, the data rate received by it or the channel condition experienced by the terminal. The user only understands the degree of goodness or badness of the end application. For example, for voice communication, threshold of bit error rate (BER) is 10^{-3}. With any amount of resources and under any channel, if the source gets sufficient signal to noise ratio (SNR) to obtain desired BER, the user is fully satisfied and utility is maximum. If user cannot listen or understand the conversation due to degraded SNR or increased BER, the utility for him would be lower. Real time applications give binary utility whereas in best effort data network, utility varies over a certain range between maximum and minimum. Utility as a function of SNR for real time and best effort applications are shown in Fig. 3.1.

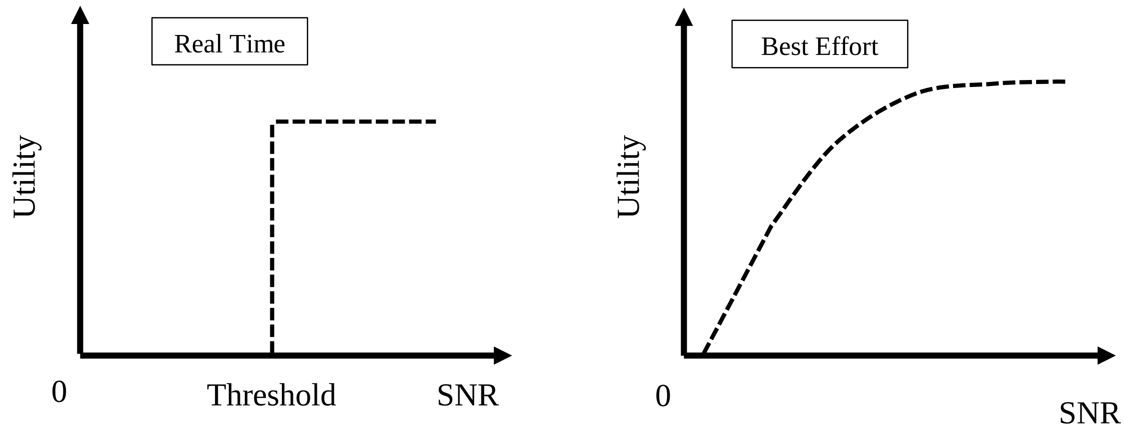


Fig 3.1 Utility functions of real time and best efforts applications

3.2.1 Utility Functions for resource allocation in Literature

Utility has been demonstrated as a function of signal to interference ratio (SIR) in (Xiao). The authors have considered that $U(0) = 0$ and $U(\infty) = 1$. As SIR increases, the quality of service (QoS) improves and the user becomes more satisfied. In (Saraydar), the utility function has been defined as number of information bits received successfully per unit of energy. If L bits are transmitted at power p watts at a rate of R bits/sec in a packet size of M bits ($M > L$) and frame success rate of P_c, then the utility is given as Utiltiy $= \frac{L.R.P_c}{M.p} \frac{bits}{Joules}$. Utility as a function of resource allocated has been defined in (Kuo).

In (Wang), utility function for source and relay are defined as buyer and seller of cooperation. Utility of source is the improvement in data rate minus the price to be paid for achieving it. Utility of the relay is the revenue earned in cooperation minus the cost of cooperation. Utility as a ratio of information bits to transmitted power has been modified by adding pricing and resource sharing components in (Jiang). Utility function similar to (Wang) has been defined in (Baidas) for the purpose of auctioning based power allocation in cooperative network. In (Q. H. Cao), utility as a function of received SNR has been considered and it has been utilized in bargaining based power allocation. Power allocation to sources and relays are done to maximize the signal to noise ratio in the cooperative mode. These references show that well defined utility function could be employed in cooperative wireless network for resource allocation.

3.2.2 Properties of Utility Function

When utility function is employed for the purpose of resource allocation, more is always preferred to less. Utility function is a twice-differentiable function (Fudenberg). Let the parameter be ‘ρ’. It can be SIR, SNR or the other parameters as discussed in 3.2. The utility function established must have following properties.

Property 1: The utility function is monotonically increasing function of parameter, ρ.
$U'(\rho) > 0$, i.e. utility increases with the increase in ρ.

Property 2: The utility function follows the law of diminishing marginal utility, $U''(\rho) < 0$, i.e. the rate of change of utility with parameter ρ reduces with increase in ρ. The utility is a concave function of ρ.

In the following section, we propose new utility function based approach for optimized resource allocation for multi-user network environment.

3.3 Utility Maximizing Resource Allocation in Multi-User Network

The user would be satisfied by the given data rate depending upon the application. Data rate can be increased by increasing the amount of resources allocated to the user in cooperative mode. In our work, we have considered utility as a function of data rate achieved by the user, which in turn, depends on the amount of allocated resources. Three resources are considered for optimum allocation: (i) Source power (ii) Relay power (iii) Bandwidth. Following different utility functions are considered as a function of data rate.

$$U_1 = \log R \tag{3.1}$$

$$U_2 = 1 - e^{-a.R} \qquad a > 0 \tag{3.2}$$

$$U_3 = R^{b-1}/c \qquad b > 0, c < 1 \tag{3.3}$$

$$U_4 = R^{(1-d)}/(1-d) \qquad d < 1 \tag{3.4}$$

Where, $U_j,\ j = \{1,2,3,4\}$ represents utility as a function of data rate *R* and a, b, c and *d* are the coefficient determining the shape and range of the utility function.

Table 3.1 Notations

Notation	Meaning
$\boldsymbol{R_i^{NC}}$	Data rate achieved by source *i* without cooperation
$\boldsymbol{R_i^{C}}$	Data rate achieved by source *i* with cooperation
$\boldsymbol{\Gamma_i^{SD}}$	Signal to noise ratio of source-destination link of source *i*
$\boldsymbol{\Gamma_i^{SR}}$	Signal to noise ratio of source-relay link of source *i*
$\boldsymbol{\Gamma_i^{RD}}$	Signal to noise ratio of relay-destination link of source *i*
$\boldsymbol{h_i^{SD}}$	Channel gain of source-destination link of source *i*
$\boldsymbol{h_i^{SR}}$	Channel gain of source-relay link of source *i*
$\boldsymbol{h^{RD}}$	Channel gain of relay-destination
$\boldsymbol{P_i^{S}}$	Power allocated to source *i*
$\boldsymbol{P_i^{R}}$	Power allocated to relay to cooperate with Source *i*
$\boldsymbol{W_i^{S}}$	Bandwidth allocated to source *i*
$\boldsymbol{P_{max}^{S}}$	Maximum available power with sources
$\boldsymbol{P_{max}^{R}}$	Maximum available power with relay
$\boldsymbol{W_{max}^{S}}$	Maximum available bandwidth for allocation
$\boldsymbol{n_R}$	Additive white gaussian noise at relay with variance $\boldsymbol{\sigma_R^2}$
$\boldsymbol{n_D}$	Additive white gaussian noise at destination with variance $\boldsymbol{\sigma_D^2}$

3.3.1 System Model

a). System Platform and assumptions: A network with *N* sources communicating with the help of one relay to a common destination is considered. The relay is installed by the service provider to create cooperative diversity at the destination. It is assumed that destination has perfect channel state information of all source-relay and relay-destination links. The destination calculates optimum source power, relay power and bandwidth for each source to maximize the sum of their utility. The destination, through the reverse control channel, informs all the sources about the power to be transmitted by them and the bandwidth allocation. It is assumed that channels allocated to the sources are free from interference. The channels between nodes are assumed to remain stationary at least for few symbols. At regular interval, the destination modifies the resource allocation, if necessary and informs sources and relay.

The relay follows half-duplex Amplify and Forward protocol. Cooperative communication is divided in two phases. In phase I, sources transmits information signal which is received by the destination as well as the relay. In phase II, relay transmits the amplified version of the source's signal. The destination combines the signal received in phase I and Phase II. The relay is assumed to amplify the signal of different sources with different power as informed by the destination through control channel.

b). Mathematical Analysis: All the notations used in this section are defined in table 3.1. Let X_{Si} be the signal transmitted by the source i, *i={1,2,..N}* in Phase 1. Due to the broadcast nature of the wireless channel, the relay and the destination will receive signal with noise. The signal received by the relay is given as

$$Y_{Ri} = \sqrt{P_i^S} X_{Si} h_i^{SR} + n_R \tag{3.5}$$

(All the symbols carry the meaning as shown in Table 3.1)

The signal received at the destination in phase - 1 is given as

$$Y_{Di}^{1} = \sqrt{P_i^S} X_{Si} h_i^{SD} + n_D \tag{3.6}$$

The relay is assumed to have perfect channel state information (CSI). Therefore, the relay scales the received signal by the factor which is inversely proportional to the received power to equalize the effect of the channel between the source and the relay. The relay amplifies the signal with gain G_{AF} which can be given as

$$G_{AF} = \frac{1}{\sqrt{P_i^S \left|h_i^{SR}\right|^2 + \sigma_R^2}} \tag{3.7}$$

The relay normalize the signal as

$$X_{Ri} = G_{AF} * Y_{Ri} \tag{3.8}$$

The relay, then, forwards the signal with power P_i^R to the destination. The received signal at the destination in phase - 2 can be given as,

$$Y_{Di}^{2} = \sqrt{P_R}\; h^{RD} X_{Ri} + n_D \tag{3.9}$$

$$= \sqrt{\frac{P_i^S P_i^R}{P_i^S \left|h_i^{SR}\right|^2 + \sigma_R^2}} h_i^{SR} h^{RD} X_S + \sqrt{\frac{P_i^R}{P_i^S \left|h_i^{SR}\right|^2 + \sigma_R^2}}\; h^{RD} n_R \; + \; n_D \tag{3.10}$$

The destination combines the signals received during phase 1 and 2 using maximal ratio combining (MRC) technique (Liu). Combining equations (1) and (3) yields

$$Y_{Di} = \frac{\sqrt{P_i^S}\; h_i^{SD}}{\sigma_D^2} Y_{Di}^{1} + \frac{\sqrt{\frac{P_i^S P_i^R}{P_i^S \left|h_i^{SR}\right|^2 + \sigma_R^2}} h_i^{SR} h^{RD}}{\frac{P_i^R}{P_i^S \left|h_i^{SR}\right|^2 + \sigma_R^2} \left|h^{RD}\right|^2 \sigma_R^2 + \sigma_D^2} Y_{Di}^{2} \tag{3.11}$$

The combined signal to noise ratio (SNR) at the output of the MRC, Γ_{AF} is given by,

$$\Gamma_{AF} = \frac{P_i^S |h_i^{SD}|^2}{\sigma_R^2} + \frac{\frac{P_i^S |h_i^{SR}|^2 * P_i^R |h^{RD}|^2}{\sigma_R^2 * \sigma_D^2}}{\frac{P_i^S |h_i^{SR}|^2}{\sigma_R^2} + \frac{P_i^R |h^{RD}|^2}{\sigma_D^2} + 1} = \Gamma_{SD} + \frac{\Gamma_{SR}\Gamma_{RD}}{\Gamma_{SR}+\Gamma_{RD}+1} \quad (3.12)$$

Maximum achievable transmission rate for direct link can be given as,

$$R_i^{NC} = log_2(1 + \Gamma_{SD}) \quad (3.13)$$

Assuming perfect cooperation using AF protocol at the relay, achievable data rate can be computed as,

$$R_i^C = log_2\left(1 + \Gamma_{SD} + \frac{\Gamma_{SR}\Gamma_{RD}}{\Gamma_{SR}+\Gamma_{RD}+1}\right) \quad (3.14)$$

`

Assuming source assigns half of the time slot or frequency spectrum to the relay for re-transmission, the maximum achievable transmission rate for half-duplex relaying can be computed as

$$R_i^C = \frac{1}{2} * \ log_2\left(1 + \Gamma_{SD} + \frac{\Gamma_{SR}\Gamma_{RD}}{\Gamma_{SR}+\Gamma_{RD}+1}\right) \quad (3.15)$$

3.3.2 Resource Optimization Problem Formulation

In this section, the problem formulation of optimised utility based resource allocation is presented. Following resources are considered foe developing the objective function - source power, relay power and bandwidth. Multiple sources seek help of single relay for communicating with common destination. Source achieves data rate by utilizing the allocated resources as shown in (3.15). Utility function depicted in (3.1-3.4) converts data rate achieved by the user in a unit-less number – utility, which indicates satisfaction achieved by the user after getting the data rate R_i^C as per (3.15). The resources are allocated to maximize the sum of the utility of all the sources in the network.

The optimization problem formed by the destination is stated as,

$$\max_{\{W_i\, P_i^S\, P_i^R\}} \; \sum_i U(R_i^C) \qquad [A]$$

$$subject\ \ to$$

$$\sum_i P_i^S \ \le P_{max}^S,\ P_i^S > 0 \ \ ...(i)$$

$$\sum_i P_i^R \ \le P_{max}^R\ P_i^R > 0 \ \ ...(ii)$$

$$\sum_i W_i \le W_{max}, W_i > 0 \ \ ...(iii)$$

In place of maximizing the total data rate of all the users, the sum of the utility of all the user is maximized. Constraints *(i-iii)* indicate that each node is assigned minimum non-zero resource and the sum of resources allocated to sources and relay are limited to the upper bound of maximum source power P_{max}^S, relay power P_{max}^R, and bandwidth W_{max}.

3.3.3 Performance metrics

Three performance metrics are considered for evaluating different the utility functions, namely achievable data rate, fairness index, and price of fairness. These are described in the following subsections.

3.3.3.1 Achievable Total Data Rate

The efficiency of resource allocation is demonstrated by total data rate achievable by the all the sources served by a relay by utilizing given resources. For AF transmission protocol, the data rate achievable is given as (3.15).

3.3.3.2 Fairness Index (Jain's Fairness Index) (Jain)

In (Joe-Wong) (Lan) (Sediq), the fairness of resource allocation has been measured by Jain's fairness index. Jain's fairness index *F(x)* is defined as

$$F(x) = (\sum_{i=1}^{n} x_i)^2 / (n * \sum_{i=1}^{n} x_i^2) \tag{3.16}$$

where, n is the number of users and x_i is the benefit obtained by user i in resource allocation. When any one user gets all the resources, the fairness seems to be completely absent. In that case, the minimum value of fairness index would be $(1/n)$. When all the users get equal amount benefit, the ratio becomes 1. We have computed the fairness index using (3.16).

This index is applicable to any resource sharing or allocation problem. It is independent of the amount of the resource. Its value is upper bounded by 1, which indicates the highest degree of fairness of allocation. The minimum value of the index is inverse of the number of candidates contesting for resources. A value of fairness index of 0.1 for resource allocation among 10 participants indicates that the allocation is unfair to the 9 out of 10 participants. As per (Jain), this index exhibits the following properties:

(1) Population size independence
(2) Scale and metric independence
(3) Boundedness
(4) Continuity

3.3.3.3 Price of Fairness (PoF)

Any attempt to increase fairness index results in decrease in efficiency. The amount of data rate to be sacrificed for achieving higher fairness index is defined as Price of Fairness (PoF). It can also be referred to as loss in efficiency. Mathematically PoF is expressed as

$$PoF = \left(R_e - R_f\right)/R_f \tag{3.17}$$

where, R_e is maximum total data rate with efficient allocation and R_f is the total data rate with fair allocation. Though efficiency and fairness seem to be difficult to obtain at the same time, the utility functions (1-4) considered in section 3.3 can achieve reasonable fairness with nominal price of fairness.

Efficient allocation considers the maximum outcome obtained with the help of resource. Hence, it allocates resource to maximize the outcome. The efficient allocation may not be fair as it does not allocate any resource to the participant who is not able to contribute in maximizing the outcome using the allocated resource. Therefore, any attempt to improve fairness of allocation imposes penalty on the efficiency of the allocation. Price of fairness parameter indicates the loss in efficiency from its maximum value as a consequence of performing fair allocation. In other words, price of fairness can be defined as a loss of efficiency. The price of fairness value 0 indicates that the allocation is efficient. Higher value of price of fairness indicates fairness of allocation.

These two parameters fairness index and price of fairness together are the indicators of the efficiency-fairness trade-off.

3.3.4 Performance Evaluation and Discussion

The performance of resource allocation technique with various utility functions is evaluated by extensive simulation. The simulation environment with assumptions, results and discussion on the same is presented in the following subsections. Efficiency-fairness trade-off involving each utility function is also demonstrated with the help of simulations.

3.3.4.1 Simulation Model

Wireless nodes in need of cooperation are considered as source nodes. The relay node is either installed by service provider to facilitate cooperation in centrally controlled network. Source nodes communicate with common destination. A multi-user network considered in simulation consists of 4 source nodes (S_1 to S_4) communicating with a common destination node (D) with the help of a relay node (R) as shown in Fig 3.2. Path loss channel model with exponent 3 is assumed for the sake of simplicity. However, the proposed technique is applicable to fading channel with Rayleigh distribution as well. Channel bandwidth, source power and relay power under consideration for allocation are normalized to 1 so that the allocation indicates the percentage of the total resource assigned to a particular node to satisfy various criteria of efficiency and fairness. The distance between the nodes is assumed in the range of few tens of meters. The central controller at destination determines the amount of resources to be used by each node and informs all through reverse control channel at regular interval. The distances between the nodes are considered such that path loss is minimum for user 4 and gradually increased for user 3, 2 and 1 respectively. User 1 faces the worst channel. The destination uses the channel knowledge between each pair of nodes and appropriate utility function to determine optimum allocation of the source power, relay power and bandwidth for each source. The destination is assumed to employ combining of direct signal from source and relayed signal from the relay using maximal ratio combining technique. It is further assumed that the relays follow Amplify and forward protocol of cooperative communication. The data rate with cooperation is calculated by using the (3.15).

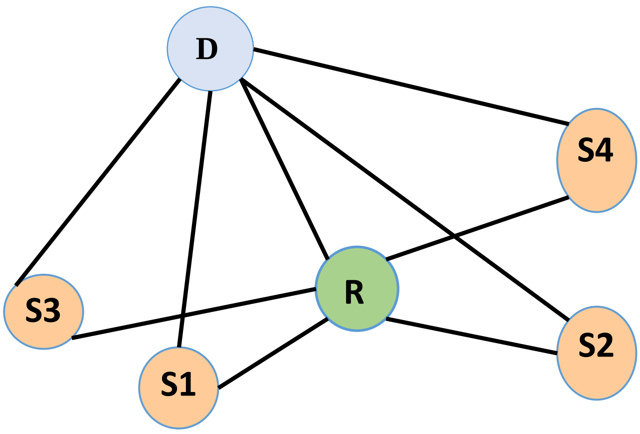


Fig 3.2 Simulation model

3.3.4.2 Simulation Results and Discussion

Utility functions from (3.1) to (3.4) are applied to the optimization problem [A] and the modified optimization problem is shown in Table 3.2 marked as A-I to A-V.

Table 3.2 Modified optimization problems used in simulation

Objective	**Utility Function**	
Maximization of total data rate	$U = \sum_{i=1}^{N} R_i$	[A-I]
Maximization of sum of log of data rate	$U = \sum_{i=1}^{N} \log R_i$	[A-II]
Maximization of sum of utility function (3.2)	$U = \sum_{i=1}^{N} 1 - exp^{-a.R_i}$	[A-III]
Maximization of sum of utility function (3.3)	$U = \sum_{i=1}^{N} {R_i}^b - 1/c$	[A-IV]
Maximization of sum of utility function (3.4)	$U = \sum_{i=1}^{N} {R_i}^{(1-d}/(1-d)$	[A-V]

In A-I, utility is represented by total data rate. Maximization of utility results in maximization of the sum of the data rate of network. In this case, the resources are allocated to maximize the total data rate of all the sources. In this system model, source 4 experiences the best channel, followed by source 3 and source 2. Source 1 has the worst channel. Resource allocation by A-I is shown as “Max Total” in Fig 3.3 to Fig 3.9. Maximum amount of source power, relay power and bandwidth are assigned to source 4 because of the best channel. Hence, the given resources result in the highest data rate. Total data rate achieved in this case is 0.379 units. As the network of 4 sources is under consideration, the fairness index for this type of allocation would be 0.251 (i.e. *1/N*) and price of fairness would be zero as per the definition of PoF given in (3.17). Problem A-II, log utility function, is proportionally fair. It results in total data rate of 0.304, fairness index of 0.962 and price of fairness 0.247. The attempt of increasing fairness index from 0.251 in A-I to 0.962 in A-II, incurs reduction in total data rate from 0.379 units to 0.304 units. A more detailed discussion on proportional fairness is given in section 3.7.

Optimization problems A-III, A-IV and A-V consist of coefficients *a, b, c* and *d.* The value of these coefficients result in efficiency-fairness trade-off. The trade-off provided by optimization problem A- III is depicted in Table 3.3. It can be seen from Table 3.3 that as the value of coefficient *a,* increases, more emphasis is given to fairness. However, the price of fairness also increases with *a*. The attempt to achieve high fairness incurs 25.2% to 27.1% penalty in data rate. Allocation of source power, relay power and bandwidth is shown in Fig 3.3, Fig 3.4 and Fig 3.5, respectively.

Table 3.3 Trade-off in A-III for different values of coefficient *a*

A	Total data rate units	Fairness Index	Price of fairness
1	0.363	0.443	0.044
2	0.349	0.577	0.085
5	0.324	0.806	0.170
15	0.302	0.969	0.252
25	0.298	0.988	0.271
Comparing with A-I			
	0.379	0.251	0.000

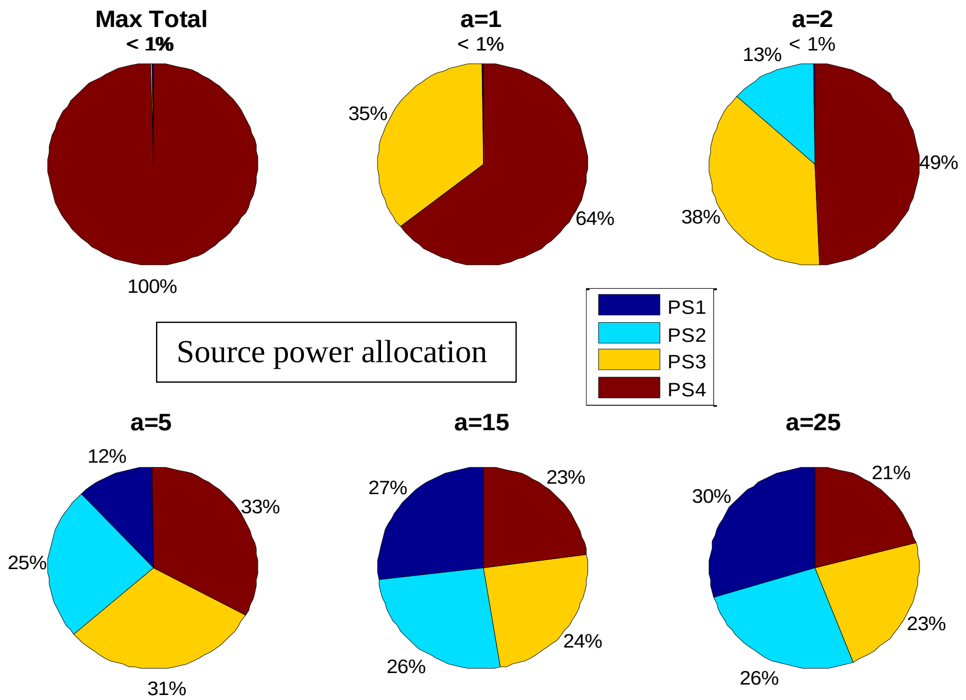


Fig 3.3 Allocation of source power for different values of *a* in Problem A-III

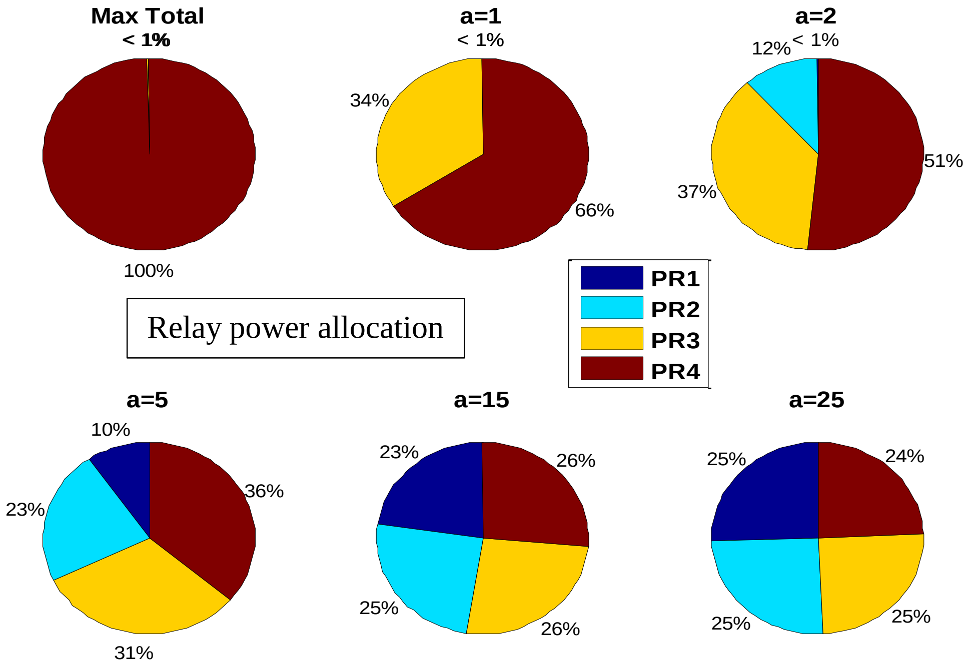


Fig 3.4 Allocation of relay power for different values of *a* in Problem A-III

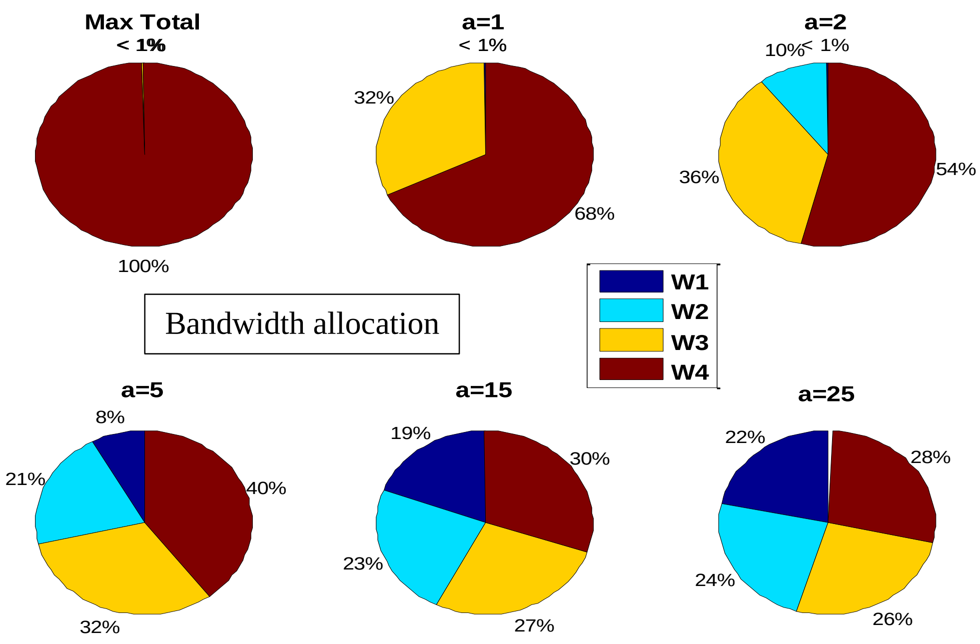


Fig 3.5 Allocation of bandwidth for different values of *a* in Problem A-III

When *a* = 1, source 3 is able to get 35% source power, 34% relay power and 32% bandwidth. As *a* = 15, all the four sources are allocated the resources in a fair way approaching towards the equal share of resources. As *a* increase further, it is clearly visible from Fig 3.3 to Fig 3.5, that the resources are allocated quite fairly.

Optimization problem A-IV consists of two variable *b* and *c*. Total data rate, Fairness index and Price of fairness obtained for different values of *b* and *c* are as shown in Table 3.4. The allocation of source power, relay power bandwidth to all the 4 users considering different set of values for coefficient b and c are plotted in Fig 3.6 to Fig. 3.8 respectively. It is evident from the above table that for *b* > *c*, the performance of this utility function is same as that of A-I. For *b* < *c*, the allocation shows trade-off between fairness and efficiency. For smaller value of *b*, fairness index as high as 0.958 can be achieved with total data rate of 0.304 units. Therefore, price of fairness of 0.244 indicates 24.4% loss in total data rate. When *b* = 0.7, moderate fairness index of 0.747 can be achieved with 15% loss in total data rate. It is further noted that resource allocation is very fair for *b* = 0.05 and *c* = 0.9 as all the four sources are getting 24-26% of source power, 22-28% of relay power and 19-32% of bandwidth compared to almost 100% to source 4 in A-I. For *b* = 1.1 and *c* = 0.9, resource allocation is done in the same way as that in A-I. Allocation of resources for above mentioned cases is demonstrated in Fig 3.6, Fig 3.7 and Fig 3.8. It may be concluded that by appropriately selecting the values of coefficients, desired trade-off can be achieved in the network.

Table 3.4 Trade-off in A-IV for different values of coefficient *b* and *c*

b, c	**Total data rate units**	**Fairness Index**	**Price of fairness**
0.05, 0.9	0.304	0.958	0.244
0.3, 0.9	0.308	0.929	0.227
0.5, 0.9	0.314	0.881	0.204
0.7, 0.9	0.328	0.747	0.153
1.1, 0.9	0.379	0.251	0.000
Comparing with A-I			
	0.379	0.251	0.000

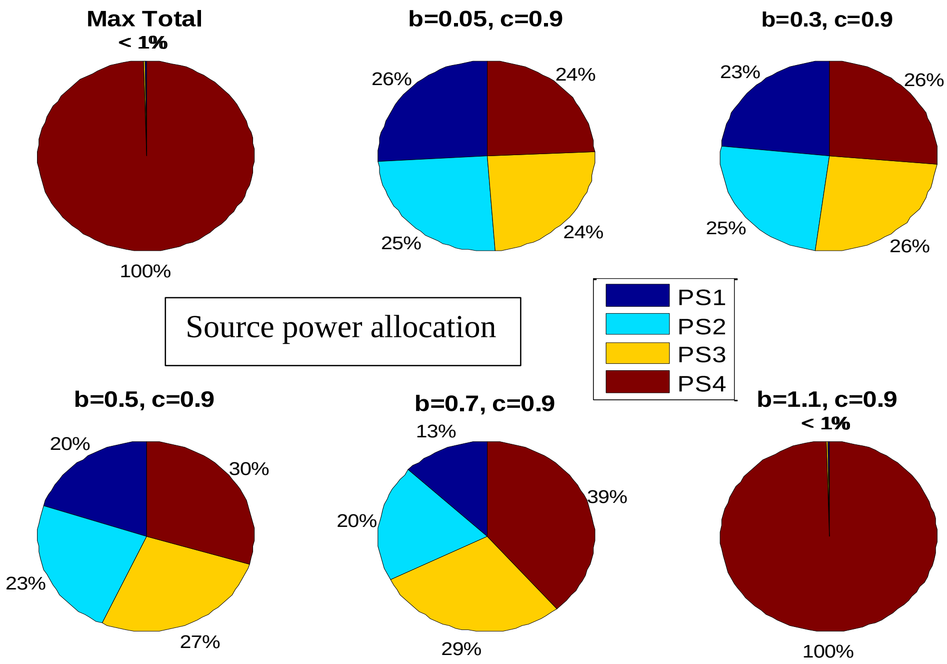


Fig 3.6 Allocation of source power for different values of *b* and *c* in Problem A-IV

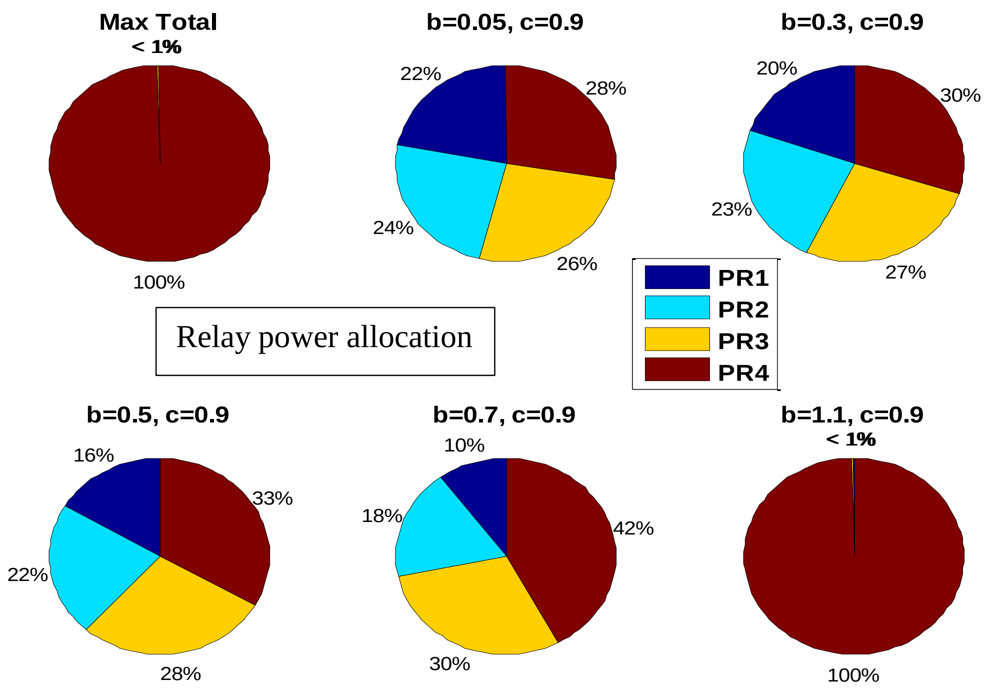


Fig 3.7 Allocation of relay power for different values of *b* and *c* in Problem A-IV

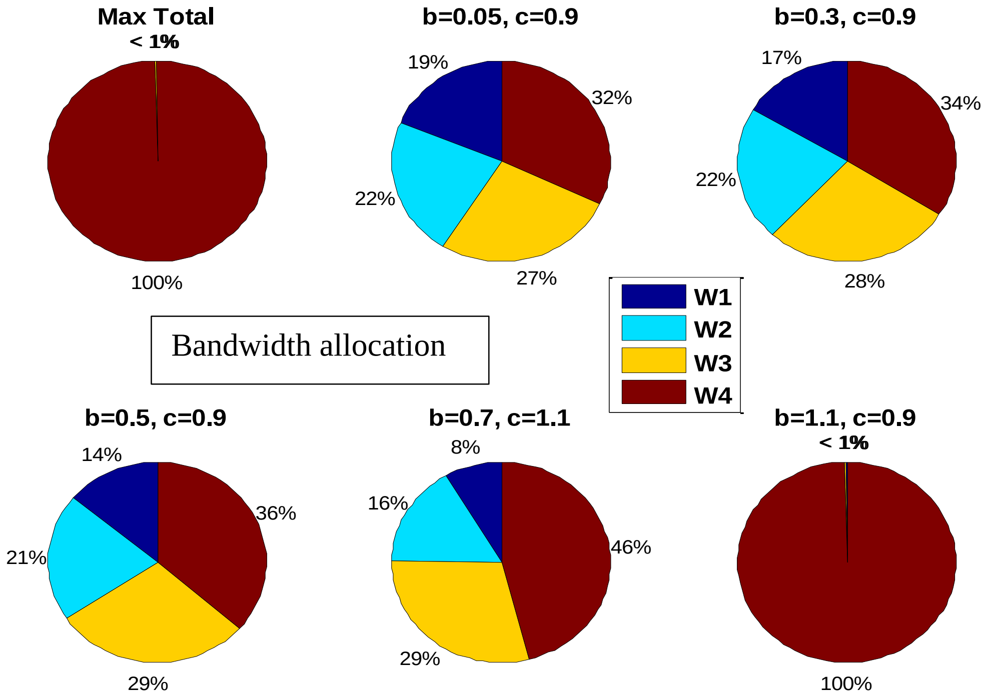


Fig 3.8 Allocation of relay power for different values of *b* and *c* in Problem A-IV

Optimization problem A-V consists of coefficient *d*. The performance metrics for different values of *d* is as shown in Table 3.5.

Table 3.5 Trade-off in A-V for different values of coefficient *d*

d	**Total data rate units**	**Fairness Index**	**Price of fairness**
0.1	0.363	0.406	0.043
0.3	0.329	0.743	0.152
0.5	0.315	0.876	0.202
0.7	0.308	0.929	0.227
0.9	0.305	0.954	0.242
Comparing with A-I			
	0.379	0.251	0.000

Table 3.5 shows that small value of *d* puts more emphasis on efficiency. For *d* = 0.1 incurs 4.3% loss in efficiency for improving fairness index from 0.25 to 0.4. As *d* approaches 1, fairness becomes prominent with 24.2% loss in efficiency for *d* = 0.9. Allocation of source power, relay power and bandwidth for problem A-V is shown in Fig 3.9, Fig 3.10 and Fig 3.11. For *d* = 0.1, source 4 gets 72-75% resources, source 3 gets 21-23 % resources, source 2 gets 4-5% of resources and source1 gets only 1% of resources. This condition is reflected by fairness index 0.406 in Table 3.5. As *d* increase, allocation introduces more and more fairness at the penalty of price of fairness. For *d* = 0.9, 24-26% of source power, 22-28% of relay power and 18-32% of bandwidth are allocated to each source. It results in 24.2% reduction in total data rate of the network. Though the performance of this utility function is in line with that of A-III, it is commonly employed for resource allocation problems (Mo) (Pratt) (Masato) (Srikant) (Borst) as a special case of this utility function shows proportional fairness. Proportional fairness utility function allocates the resources in proportion with demand or channel condition of the sources. Therefore, it is commonly used for solving resource allocation problem. This function is explored in more detail in section 3.7.

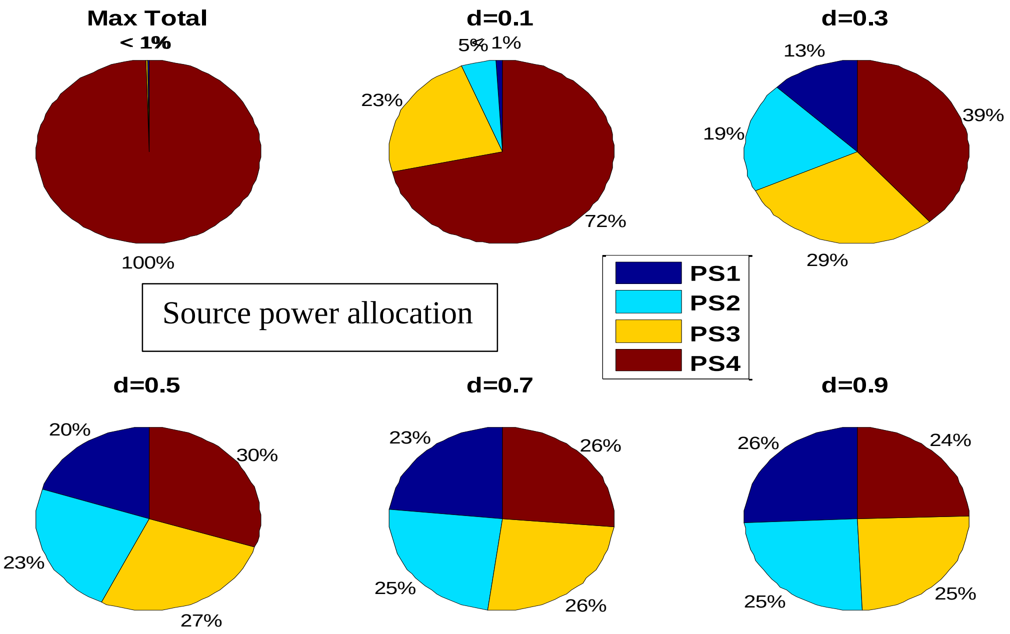


Fig 3.9 Allocation of source power for different values of *d* in Problem A-V

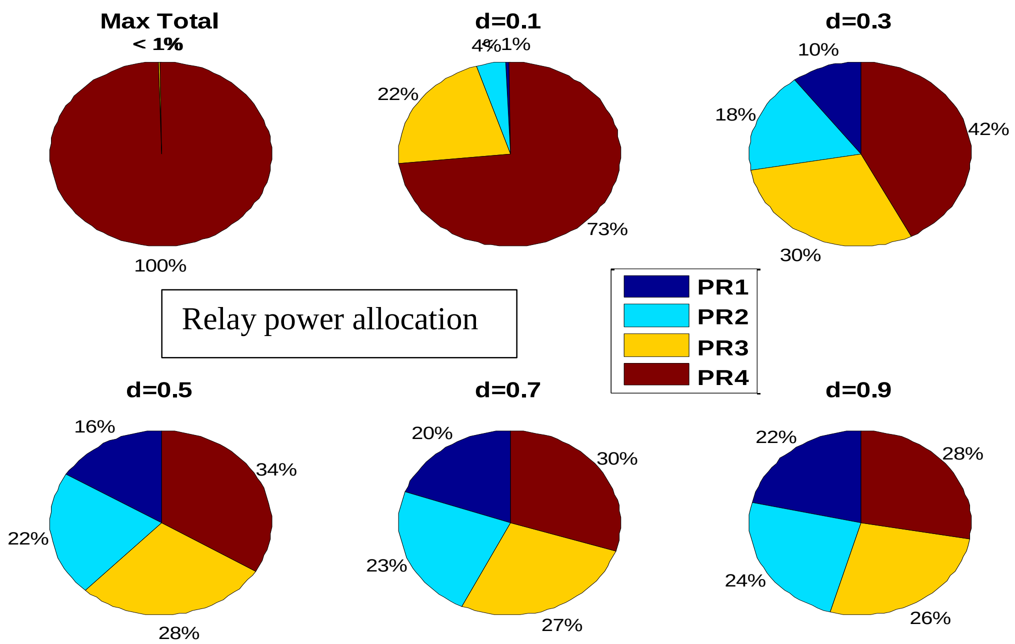


Fig3.10 Allocation of relay power for different values of *d* in Problem A-V

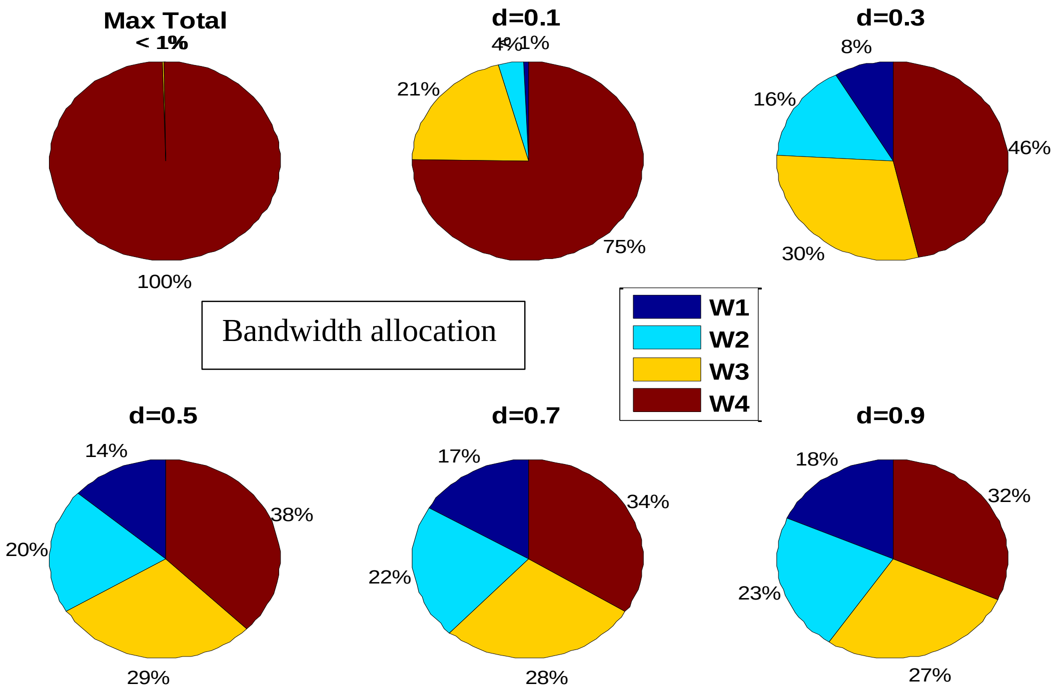


Fig 3.11 Allocation of bandwidth for different values of *d* in Problem A-V

The simulation results discussed above very clearly exhibit that the utility function based resource allocation is capable of providing desired degree of efficiency and fairness trade-off for resource allocation in cooperative communication network. To obtain judicious efficiency and fairness trade-off during resource allocation, in our approach, we have introduced coefficients *a, b, c* and *d* in different utility functions. By appropriately setting the values of these coefficient, desired trade-off can be achieved. It is verified by simulation results.

In the next section we propose another resource allocation technique based on resource constrained approach which further provides desired efficiency – Fairness trade off.

3.4 Resource Constraint Based Approach

In order to achieve efficiency-fairness trade-off, restriction can be put on minimum and maximum resources which can be assigned to single source. In multi-source wireless network, each source faces different channel. The efficiency perspective is to assign more resources to the source with good channel condition to maximize sum data rate of the network. But this perspective is very much 'unfair' to the source with bad channel condition. As a trade-off, an approach can be employed to assign certain minimum resource to each source so that even the worst channel user would not be deprived of resources completely. Remaining resources are then distributed among the sources to maximize sum data rate of the network. Maximum amount of resources that can be given to any one source is also restricted. Allocation of resources for satisfying desired fairness - efficiency trade-off can be achieved by this mechanism. As per our knowledge, this approach is not employed for resource allocation in cooperative network in literature.

3.4.1 Resource Constrained Allocation Mechanism

Source power, relay power and bandwidth are the three resources which are allocated by the controller at the destination. The concept is explored with the help of allocation of one resource, in general. The same concept then can be extended to all the three resources. Consider multiple units of a resource R to be distributed among N sources. The equal share given to each of them would be R/N. Minimum and maximum resource assigned to any one source will be A times R/N and B times R/N, respectively within the constraint of limited total resource. If $A = B = 1$, all users will be assigned equal share *R/N*. When $A << 1$, small portion of equal resource *R/N* is ensured to the each source and the remaining portion of the resource is distributed among all the sources to maximize total data rate of the network to achieve efficiency. Maximum amount of resource given to any one source is *B*(R/N)*. Higher value of *B* yields better efficiency. The term A is identified as fairness parameter with $0 \leq A \leq 1$ and the term B is introduced as efficiency parameter with $1 \leq B \leq B_{max}$. The value of *B* which results in the highest efficiency for a given value of *A* is derived in next subsection.

3.4.1.1 Determination of B_{max}

Let Maximum available resource be X_{AV}, where *X* – source power, relay power and bandwidth. X_{eq} be the equal allocation of the resource and *N* be the number of sources.
Minimum resource X_{min} to be allocated to each source is $A * X_{eq}$. Resource remaining after allocation of minimum resource

$$X_{rem} = X_{AV} - (N * A * X_{eq}) \tag{3.18}$$

Maximum resource given to any one source would be possible when B possess the highest value. To calculate the maximum value of *B*, consider the case when all the remaining resource is being allocated to any one source. That source has all the remaining resource in addition to its share of minimum resource. Maximum resource with any one source can be given as

$$X_{max} = X_{rem} + (A * X_{eq}) \tag{3.19}$$

which is equal to $B * X_{eq}$.

Combining (3.18) and (3.19)

$$B * X_{eq} = X_{AV} - \left(N * A * X_{eq}\right) + \left(A * X_{eq}\right)$$

$$\therefore B = (X_{AV} + \left(A * X_{eq}\right) * (1 - \mathrm{N})) / X_{eq} \tag{3.20}$$

Numerical Example

No. of sources, $N = 4$

Resource available for allocation = 1 unit

$X_{eq}=0.25$ $\quad X_{min} = A * X_{eq},\quad X_{max} = B * X_{eq}$

For $A = 0.5$, $X_{min} = 0.5 * 0.25 = 0.125$

$X_{rem} = 1 - (0.125 * 4) = 0.5$

$X_{max} = 0.5 + 0.125 = 0.625$ which is equal to $B_{max} * X_{eq}$

$\therefore\ B_{max} = \frac{0.625}{0.25} = 2.5$

Table: 3.6 shows B_{max} for $0 \leq A \leq 1$ for N=4.

Table 3.6 Evaluation of B_{max} for N=4

A	$\boldsymbol{B_{max}}$
0	4
0.1	3.7
0.3	3.1
0.5	2.5
0.7	1.9
0.9	1.3
1	1

Table 3.6 demonstrates that for smaller value of *A*, the value of B_{max} is large. Therefore, any one source can be assigned large quantity of given resource to yield efficiency. For larger *A*, most part of the resource is distributed equally among the sources which leads to higher fairness index. For *A* = *B* = *1*, leads to exactly equal allocation of resource to all the sources.

3.4.2 Optimization problem formulation

The optimization problem for resource constraint based approach is formulated in this sub-section. The objective is to maximize the sum of the data rate of all the sources R_i^C in the network. R_i^C is derived in (3.15).

$$\max_{\{W_i \, P_i^S \, P_i^R\}} \; \sum_i (R_i^C) \qquad [B]$$

$$subject\ to$$

$$\sum_i P_i^S \le P_{max}^S, \qquad P_i^S \ge A * P_{eq}^s, \qquad P_i^S \le B * P_{eq}^s \quad \ldots(i)$$

$$\sum_i P_i^R \le P_{max}^R, \qquad P_i^R \ge A * P_{eq}^R, \qquad P_i^R \le B * P_{eq}^R \quad \ldots(ii)$$

$$\sum_i W_i \le W_{max}, \qquad W_i \ge A * W_{eq}, \qquad W_i \le B * W_{eq} \; \ldots(iii)$$

$$0 \le A \le 1\,, \qquad 1 \le B \le B_{max} \;\; \ldots(iv)$$

where P_{eq}^S, P_{eq}^R and W_{eq} are equal allocation of source power, relay power and bandwidth to all the sources, respectively. The constraints show that the source power, relay power and bandwidth are upper bounded by P_{max}^S, P_{max}^R and W_{max}, respectively. Each source must be assigned minimum $A * X_{eq}$ resource i.e. A times the equal allocation and remaining resources are to distributed among all users such that maximum resource given to any user is $B * X_{eq}$ i.e B times the equal allocation. By selecting appropriate values of A and B, desired degree of efficiency and fairness can be achieved.

3.4.3 Performance Evaluation and Discussion

The simulation model considered in section 3.3.4.1 is used here also. The minimum value of parameter A is assumed as 0.2 to start with. The fairness parameter A is varied from 0.2 to 1 and the efficiency parameter is varied from 1 to 2.5. The price of fairness is calculated by comparing total data rate with maximum total data rate which is obtained in Optimization problem A-I in section 3.2.2. Fig 3.12 shows fairness index and price of fairness for various combinations of A and B. For B = 1, fairness index of 0.963 is guaranteed as maximum amount of resource allocated to any single source is same as equal share. In this case, all the sources can achieve data rate as per their channel condition with equal amount of resources. As efficiency parameter B increases, fairness index reduces for given value of parameter A. By keeping B constant and increasing A results in more fairness. For B = 2, fairness index is 0.559 for A = 0.2 and 0.962 for A = 1. For higher value of A, the change in B does not result in significant change in fairness index as high value of A indicates higher portion of resources are distributed equally and very little is left to increase efficiency. Higher value of fairness index results in higher loss in efficiency in terms of higher value of price of fairness. For B = 2.5, price of fairness varies from 0.074 to 0.258 as A varies from 0.2 to 1. Table 3.7 summarizes the values of performance metrics obtained for B = 1 and B = 2 with A varies from 0.2 to 1.

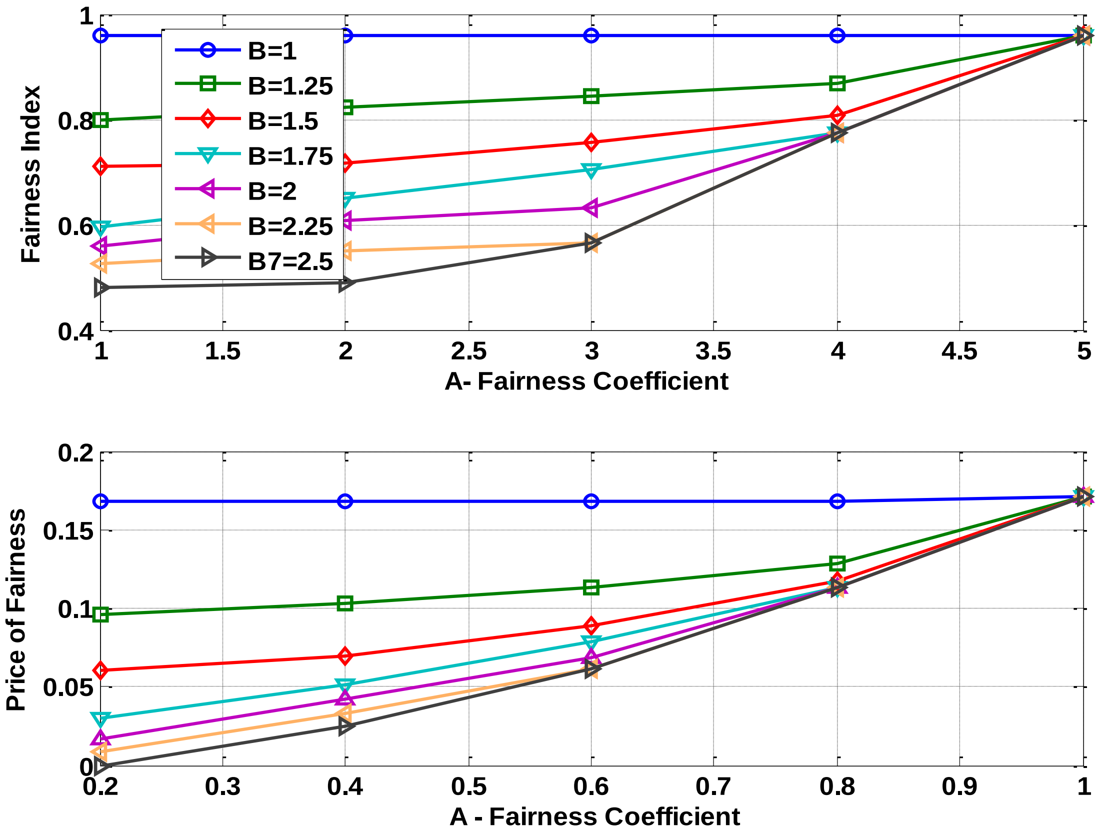


Fig 3.12 Fairness index and price of fairness for 0.2 $\leq A \leq 1$ and 1 $\leq B \leq 2.5$

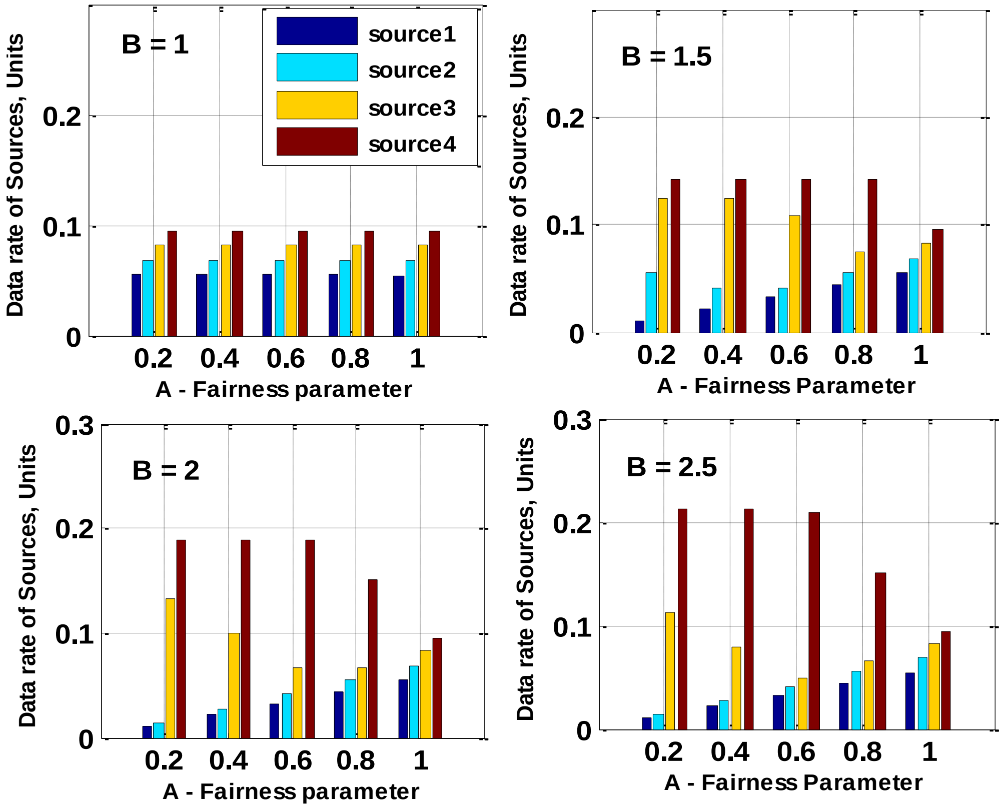


Fig 3.13 Data rate achieved by sources 1 to 4 for 0.2 $\leq A \leq 1$ and B = 1, 1.5, 2, 2.5

Fig 3.13 shows data rate achieved by an individual source with different combinations of *A* and *B*. When *B* = 1, irrespective of *A*, each source is given equal share of resource. They can achieve data rate as per their channel condition. In this simulation model, source 4 experiences the best channel followed by source 3, 2 and 1. As a result, source 4 achieves the highest data rate and source 1 achieves the lowest. When *B* = 1.5, and *A* = 0.2, efficiency is given more emphasis by allocating very little amount of resources equally and remaining resources are distributed to increase efficiency. As parameter *A* further increases and reaches *A* = 1, the effect of parameter B diminishes. All the sources get data rate as per the case of *B* = 1. Similar scenario can be seen for *B* = 2 and *B* = 2.5. Highest data rate of 0.353 units can be achieved by source 4 when *B* = 2.5 and *A* = 0.2, as shown in Table 3.7

Table 3.7 Comparison of trade-off for A = 0.2, 0.4, 0.6, 0.8, 1 and B = 1, 2

	B=1					***B=2.5***				
	A=0.2	***A=0.4***	***A=0.6***	***A=0.8***	***A=1***	***A=0.2***	***A=0.4***	***A=0.6***	***A=0.8***	***A=1***
Total data rate	**0.302**	**0.302**	**0.302**	**0.302**	**0.301**	**0.353**	**0.344**	**0.332**	**0.317**	**0.301**
Fairness Index	**0.963**	**0.963**	**0.963**	**0.963**	**0.963**	**0.481**	**0.489**	**0.567**	**0.776**	**0.962**
Price of Fairness	**0.255**	**0.255**	**0.255**	**0.255**	**0.258**	**0.074**	**0.101**	**0.140**	**0.196**	**0.258**

This approach of resource allocation is capable of making desired trade-off between efficiency and fairness depending upon the class of service of the sources. It enables the service provider to perform priority based allocation also by selecting appropriate values of A and B.

We have considered 0 < F < 1. Table 3.8 shows type of the allocation achieved by setting the values of parameters E and F. If F = (1 / 1+E) in (3.21), the allocation is called proportional fair as per the definition given in (3.23). For F < (1 / 1+E), the fairness index will be higher which leads to higher value of price of fairness and lower value of total data rate. This scenario is depicted in Fig (3.16) and Fig (3.17).

3.5 E-F Function Based Approach

In this section, a function reflecting efficiency and fairness as its components is presented for resource allocation. This function is mentioned in (Joe-Wong) for CPU and memory allocation in data centres. It consists of two parameters F and E such that $F \in \mathbb{R}, E \in \mathbb{R}$. Parameter F determines fairness and E decides efficiency.

$$\varphi_{EF}^{R} = sign\,(1-F)\left\{\sum_{i=1}^{N}\left(\frac{R_i^C}{\sum_{j=1}^{N}R_j^C}\right)^{1-F}\right\}^{\frac{1}{F}}\left(\sum_{i=1}^{N}R_i^C\right)^{E}, \quad F \in \mathbb{R}, E \in \mathbb{R} \tag{3.21}$$

where, R_i^C is the data rate achieved by user source *i* in cooperative mode. *i = {1, 2… N}* set of sources, *F* is fairness function and *E* determines efficiency and φ_{EF}^{R} is the function which performs efficiency-fairness trade-off depending upon the values of *E* and *F*. The value of F determines the type and degree of fairness. Type of the fairness is determined by the value of *F* as max-min fairness, proportional fairness, and α-fairness. In this section, we have applied this function for source power, relay power and bandwidth allocation in cooperative network. The limiting case of value of *F* ∈*(0,1)* is considered which gives α-fairness. The relation between the value of *E* and *F* is given in Table 3.8. To reflect all three scenario, the range of *E* is chosen from 1 to 2.

Table 3.8 Relation of E and F determines type of allocation

F < $\mathbf{\frac{1}{1+E}}$	More fairness
F = $\frac{1}{1+E}$	Proportional Fairness
F > $\frac{1}{1+E}$	More efficiency

For example, for *E* = 1, as per *F* = $\frac{1}{1+E}$, *F* would be 0.5. The combination of *E* = 1 and *F* < 0.5 puts more emphasis on fairness, *F* > 0.5 gives more efficiency and *F* = 0.5 is proportional fair. (Proportional fairness is discussed in more detail in section 3.7 in detail). In this function, smaller value of *F* ensures more fairness and large *E* ensures efficiency.

3.5.1 Optimization Problem Formulation

The optimization problem is formed as shown below.

$$\max_{\{W_i\, P_i^S\, P_i^R\}} \sum_i \varphi_{EF}^R \qquad [C]$$

$$subject\ \ to$$

$$\sum_i P_i^S \ \leq P_{max}^S, P_i^S > 0 \ \dots . (i)$$

$$\sum_i P_i^R \ \leq P_{max}^R \ P_i^R > 0 \ \dots . (ii)$$

$$\sum_i W_i \leq W_{max}, W_i > 0 \ \dots . (iii)$$

The source power, relay power and bandwidth are allocated to maximize the *E-F* function with appropriate weight to fairness and efficiency. Constraints ***(i-iii)*** indicate that each node is assigned minimum non-zero resource and the sum of resources allocated to sources and relay are limited to the upper bound of maximum source power P_{max}^S, relay power P_{max}^R, bandwidth W_{max}.

3.5.2 Performance Evaluation and Discussion

Same simulation model and assumptions as section 3.3 are applied for this simulation. Simulation is carried out to find total data rate, fairness index and price of fairness for all combinations of E and F factors. Fig 3.14 and Fig 3.15 show total data rate and fairness index, respectively for $0.1 \leq FF \leq 0.9$ and $0.1 \leq EF \leq 1.9$, where, *FF* is the fairness factor and *EF* is the efficiency factor. It show that small *FF* and *EF* results in less data rate and more fairness.

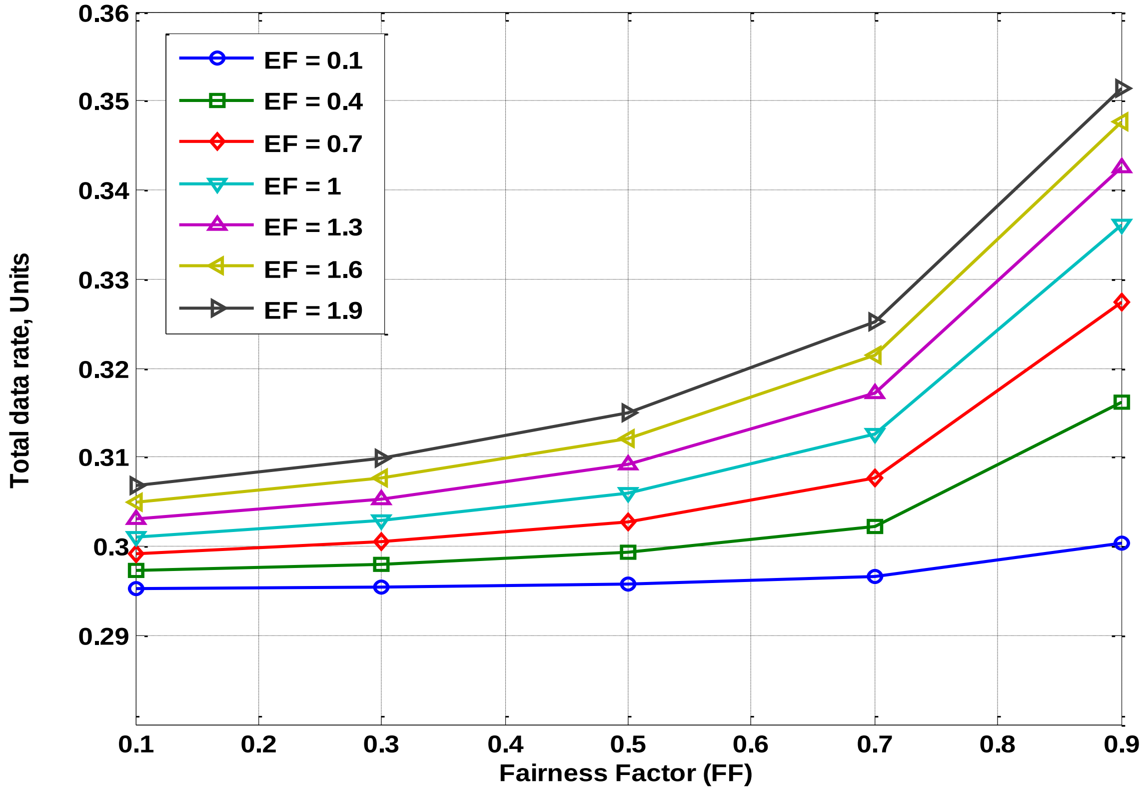


Fig 3.14 Total data rate for $0.1 \leq F \leq 0.9$ and $0.1 \leq E \leq 1.9$

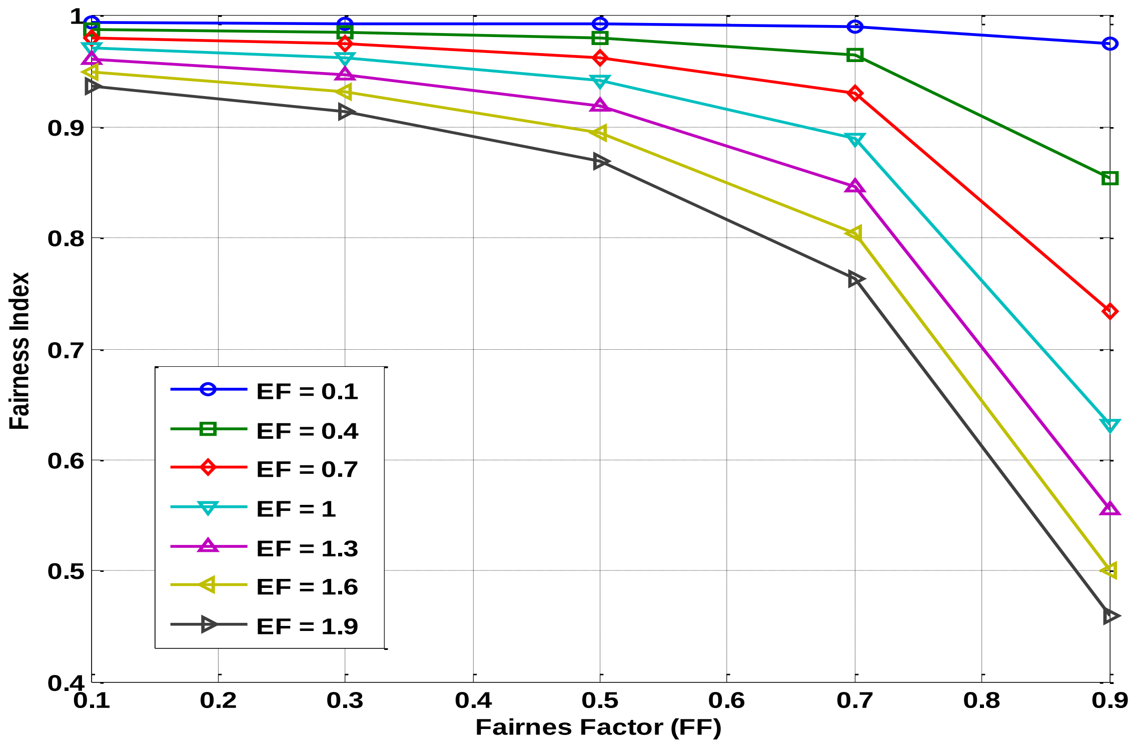


Fig 3.15 Fairness index for $0.1 \leq F \leq 0.9$ and $0.1 \leq E \leq 1.9$

Fairness index as high as 0.994 is achieved with *FF* = 0.1 and *EF* = 0.1. As *E* is increased by keeping *FF* constant at 0.1, data rate increases and fairness index reduces to 0.975. Increase in *EF* results in more efficiency. *EF*=1.9 and *FF*=0.9 results in the highest data rate of 0.351 units. For the given value of *FF*, data rate increases as *EF* increases and fairness index reduces. For given value of *EF*, data rate increases and fairness reduces with increase in *FF*. Comparison of combination of two extreme cases of *EF* and *FF* is depicted in Table 3. 9.

Table 3.9 E-F function based allocation: efficiency-fairness trade-off

	EF = 0.1		*EF* = 2	
	FF = 0.1	*FF* = 0.9	*FF* = 0.1	*FF* = 0.9
Total data rate	0.295	0.300	0.307	0.351
Fairness Index	0.994	0.975	0.937	0.459
Price of Fairness	0.284	0.262	0.235	0.078

Fairness index varies from 0.459 to 0.994 with corresponding price of fairness from 0.284 to 0.078. The price of fairness is calculated by comparing total data rate with maximum total data rate which is obtained in Optimization problem A-I in section 3.2.2.

As shown in Table 3.8, the relation of factors *E* and *F* represents three types of allocation: Efficient, fair and proportional fair. For example, for *EF* = 0.7, *FF* = 0.588 results in proportional fair. *FF* > 0.588 gives higher data rate and *FF* < 0.588 gives more fairness. The regions of type of allocation are depicted in Fig 3.16 and Fig 3.17 from data rate and fairness index perspective, respectively. For *EF* = 1.3, *FF* = 0.434 results in proportional fairness and for *EF* = 1.9, *FF* = 0.345 results in proportional fairness. These two cases are shown with dashed line in Fig 3.16 and Fig 3.17. The proposed *E-F* function is capable of providing efficiency-fairness trade-off for resource allocation by selecting appropriate value of parameters *E* and *F*.

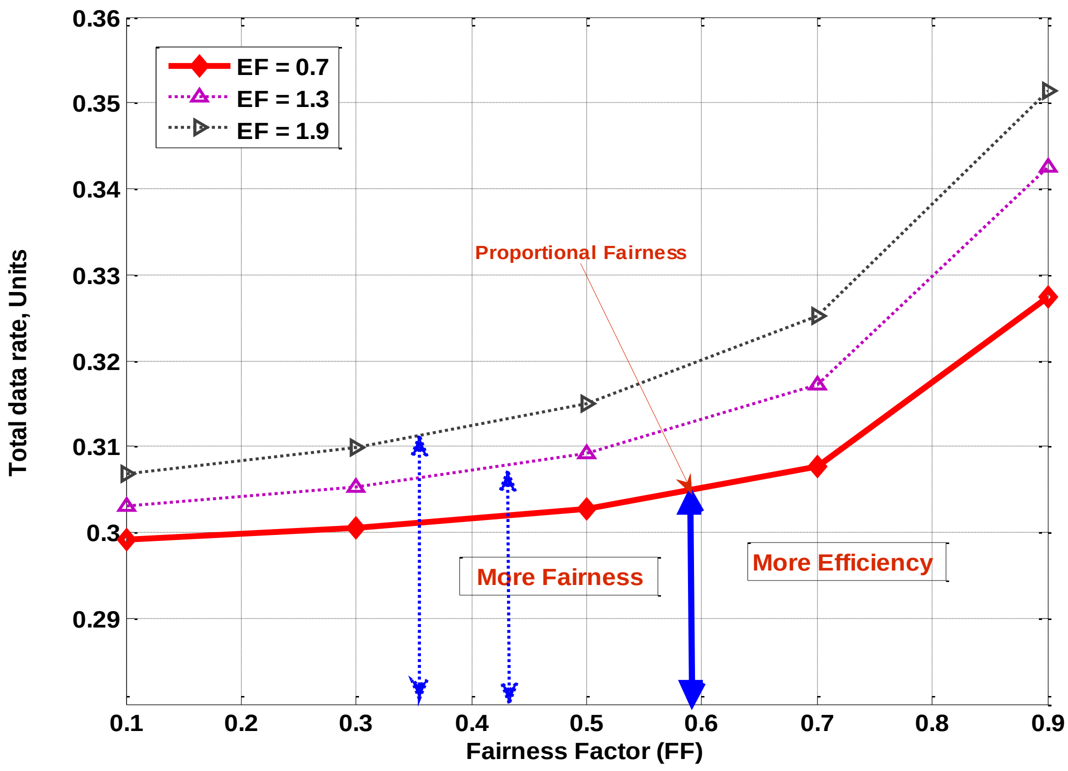


Fig 3.16 Total data rate as a function of FF: Regions of allocation

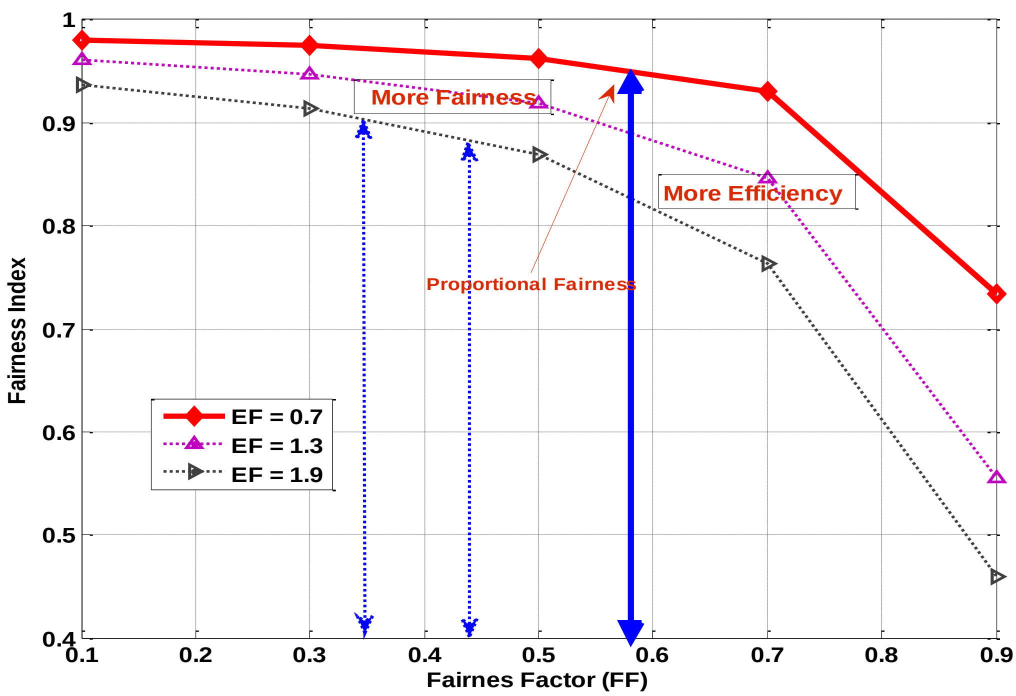


Fig 3.17 Fairness index as a function of FF: Regions of allocation

3.6 Comparison of Resource Allocation Approaches

Two approaches of resource allocation are presented in section 3.4 and one approach is discussed in section 3.3. The comparison of three approaches is presented in Table 3.10

Optimization problem A-I maximizes the efficiency without any consideration of fairness, which is indicated by 0.254 (≈*1/N*) fairness index and 0 price of fairness. Optimization problem A-II considers only fairness with 0.962 fairness index and 24.7% loss in total data rate. A-I and A-II do not possess any coefficient to do trade-off between efficiency and fairness. In A-III, one coefficient can be adjusted so the total data rate varies from 0.298 to 0.363 and fairness index varies from 0.988 to 0.443. Price of fairness indicates 4% to 27.1% penalty in total data rate. Two coefficients are adjusted in A-IV for achieving any desired fairness index with corresponding penalty of price of fairness.

Table 3.10 Comparison of approaches of section 3.3 and 3.4

	Utility (Table 3.2)					Resource constraint	E-F function
	A-I	A-II	A-III	A-IV	A-V		
Maximum total Data rate	0.379	0.304	0.363	0.379	0.363	0.353	0.351
Minimum total data rate	-	-	0.298	0.304	0.305	0.301	0.295
Maximum fairness index	-	0.962	0.988	0.958	0.954	0.963	0.994
Minimum fairness index	0.254	-	0.443	0.251	0.406	0.481	0.459
Maximum Price of fairness	-	0.247	0.271	0.244	0.242	0.258	0.284
Minimum price of fairness	0.000	-	0.044	0.000	0.043	0.074	0.078

The value of b = 1.1 and c = 0.9, lead to the similar result as A-I with 0.958 fairness index and zero price of fairness. A-V gives fairness index from 0.406 to 0.958 with the corresponding penalty of 4.3% to 24.2%. Two approaches of this section have minimum penalty of 7.4% and 7.8% compared to 4.3% and 4.4% of A-III and A-V. *E-F* function based approach reaches the highest among all fairness index of 0.994 with 28.4% loss in total data rate. It can be concluded from these results that the range of trade-off of utility based allocation is wider compared to remaining two approaches. It can be employed to yield desired compromise between efficiency and fairness. However, the selection of the coefficient needs additional efforts. Simplicity is the main attribute of resource constraint based approaches it involves optimization of data rate only. E-F function based approach is capable of giving excellent fairness index. Therefore, it can be employed in a network where fairness is essential.

In centrally controlled network, the controller chooses the value of coefficients by considering the loss in data rate and degree of fairness of services. In the following section, A-V utility function is explored further and is presented as a generic utility function which can satisfy many criteria of resource allocation like (a). Maximizing sum total data rate (b). Achieving proportional fairness (c). Reducing delay to minimum (d). Priority based allocation (e). Max-min fairness (f). Any desired trade-off between efficiency and fairness; by choosing only one coefficient.

3.7 Generic Utility Function Based Approach

A generic utility function which can readily be used to achieve different attributes of resource allocation is presented in this section. One utility function is used to achieve maximum data rate, proportional fairness, equal data rate, minimum delay and min-max fairness by simply changing one coefficient in a generic utility function. If it is decided to allocate the resources 'fairly', it gives rise to a crucial question of 'what do we mean by fair?' There are many approaches in the literature to define fairness like min-max fair, equal share fair, proportional fair, weighted proportional fair (Masato) (Borst) (Srikant). One thing common in all type of fairness based allocation is that it would lower the sum total data rate. In this section, we have evolved a single utility function which can allocate resources to achieve different criteria by setting proper value of the constant in utility function. Our utility function is capable of performing resource allocation for (a). Maximizing sum total data rate (b). Achieving proportional fairness (c). Reducing delay to minimum (d). Priority based allocation (e). Max-min fairness (f). Any desired trade-off between efficiency and fairness.

3.7.1 Generic Utility Function

A single function which can allocate resources to satisfy different criteria such as proportional fairness, minimum potential delay fairness and max-min fairness as well as maximum efficiency and equal data rate extremes of the resource allocation by selecting suitable value of L in (3.22) given below. No other utility function is capable of providing these many criteria of resource allocation (Masato) (Borst) (Srikant).

The proposed generic utility function is presented as

$$U_{Gi} = \omega_i * {R_i^C}^{(1-L)}/(1-L) \qquad L > 0, \quad L \neq 1 \tag{3.22}$$

where, ω is the weight or priority given to a particular source in case of weighted or priority based resource allocation and L is the coefficient to select the type of allocation. R_i^C is the data rate achieved by source *i* in cooperative mode.

3.7.2 Optimization Problem Formulation

In this sub-section, the problem formulation of generic utility function based resource allocation is presented. The resources under consideration are source power, relay power and bandwidth. Multiple sources seek help of single relay to communicate with common destination. Utility function depicted in (3.22) converts data rate achieved by the source in utility which indicates satisfaction achieved by the source after getting that data rate. R_i^C is the data rate of a source *i* with cooperation as calculated in (3.15).

The optimization problem is stated as

$$\max_{\{W_i P_i^S P_i^R\}} \sum_i \omega_i * R_i^{C^{(1-L)}}/(1-L) \qquad L > 0, \quad L \neq 1 \qquad \text{[D]}$$

$$subject\ to$$

$$\sum_i P_i^S \leq P_{max}^S, P_i^S > 0 \ \ldots (i)$$

$$\sum_i P_i^R \leq P_{max}^R\ P_i^R > 0 \ \ldots \ (ii)$$

$$\sum_i W_i \leq W_{max}, W_i > 0 \ \ldots (iii)$$

Constraints indicate that each node is assigned minimum non-zero resource and the sum of resources allocated to sources and relay are limited to the upper bound of maximum source power P_{max}^S, relay power P_{max}^R, bandwidth W_{max}.

3.7.3 Types of Fairness

3.7.3.1 Proportional fairness

Let $\{\widehat{X_i}\}$ be the resource allocation vector according to proportional fairness and $\{X_i\}$ be the vector of any other allocation. $\{\widehat{X_i}\}$ is proved to be proportional fair, if it satisfy the inequality (3.23).

$$\sum_i \frac{X_i - \widehat{X_i}}{X_i} \leq 0 \qquad (3.23)$$

This inequality states that if resource allocation deviates from proportional fair allocation $\{\widehat{X_i}\}$ to any other feasible allocation $\{X_i\}$, then the sum of the proportional changes in each user's share is less than or equal to 0. Proportional fairness can be attained when $L \rightarrow 1$. The function depicted in (3.22) becomes indeterminate for $L = 1$. To evaluate this function for $\rightarrow 1$, it is modified as (3.24) considering ω = 1,

$$U_G = (R_i^{C^{(1-L)}} - 1)/(1-L) \tag{3.24}$$

Functions depicted in (3.22) and (3.24) are going to apply for optimization. As far as optimization is concern, additive constant terms in objective functions do not affect optimal decisions.

Using L' Hospital's rule on (3.24)

$$\lim_{L\to 1}(R_i^{C^{(1-L)}} - 1)/(1-L) \ = \log(R_i^C) \tag{3.25}$$

For $L \to 1$, the utility function of (3.22) reduces to log utility function which is inherently proportional fair (Masato) (Borst) (Srikant) (Joe-Wong).

3.7.3.2 Weighted Proportional Fairness

In multi-user network, different users' class of service can be different. The service provider can earn higher revenue by allocating priority to such users by providing weighing factor or priority factor in the utility factor. For weighted proportional fairness, the inequality (3.23) can be modified as

$$\sum_i \omega_i \ \frac{X_i - \widehat{X_i}}{X_i} \leq 0 \tag{3.26}$$

where, ω_i is the weight or priority given to a particular user.

3.7.3.3 Max-Min Fairness

If an allocation attempts to maximize the minimum resource allocated in the network, it is referred to as max-min fairness. It gives maximum protection to the source who suffers from the weak channel. Once the allocation is done using Max-min approach, then it is not possible to increase the resources given to any source without decreasing the resource of the source whose data rate is minimum among all. In any set of allocation $\{X_i\}$ is proved to be max-min fair $\{X_i^*\}$, if it proves that "If $X_s > \; X_s^*$ for any source s in the network, then there exists another source p such that $X_p^* \leq X_s^*$ and $X_p < \; X_p^*$". When $\omega_i = 1$ and $L \rightarrow \infty$ in utility function (3.22), it corresponds to max-min fairness (Joe-Wong).

3.7.3.4 Minimum Delay Fairness

This criteria of fairness deals with the time in which the user can transmit the desired amount of data. Let the vector of data to be sent be $\{d_i\}$ and data rate achieved by the user be $\{R_i\}$. Then $\{d_i/R_i\}$ would be the vector of time taken by each user to complete the data transfer. The objective of resource allocation is to minimize the total delay. i.e.$min \; \sum_i \{d_i/R_i\}$, where $\sum_i R_i = \; R_i^C$. It is equivalent to $max - \; \sum_i \{d_i/R_i\}$. If data to be sent is normalized to 1, then it would be $max \; \left(-\sum_i \left\{1/R_i^C\right\}\right)$.

Let $\omega_i = 1$ and $L = 2$ in (3.22)

$$U_{Gi} = \; R_i^{C^{(1-2)}}/(1-2) = \; - \; 1/R_i^C \tag{3.27}$$

Replacing this utility in objective function [D] yields

$$\max_{\{W_i \, P_i^S \, P_i^R\}} \; \sum\nolimits_i - \; (1/R_i^C) \tag{3.28}$$

which is same as

$$\min_{\{W_i \, P_i^S \, P_i^R\}} \; \sum\nolimits_i (\, 1/R_i^C) \tag{3.29}$$

Particular source can be given priority to enable it to send data quickly than others. It is done by adding weighing factor ω_i. It is, then, referred to as weighted minimum delay fairness.

3.7.3.5 Desired Efficiency-Fairness Trade-off

Moreover, the same utility function can be applied to achieve efficiency, neglecting fairness by choosing $L \rightarrow 0$. As L increases from 0, efficiency starts reducing at the cost of fairness and fairness reaches proportional fairness when $L \rightarrow 1$. When $L = 2$, it becomes minimum delay fair and for higher L, reduction in efficiency becomes significant. Higher L gradually results in allocation such that the data rate of all the users become similar but the sum total data rate of the network goes down. In this way, our proposed utility function can cover the whole spectrum of efficiency-fairness trade-off including both the extremes- perfect efficiency and perfect fairness.

3.7.4 Performance Evaluation and Discussion

Same simulation model and assumptions as section 3.3 are applied for performance evaluation. Simulation is carried out to find total data rate, fairness index and price of fairness for all the cases of allocation.

Table 3.11 Types of resource allocation

L	**ω**	**Type of allocation**
L = 0	**ω=1**	Maximizing sum of data rates
	0 < ω <1	Priority based
0.1≤ L ≤ 0.9	**1**	Efficiency – Fairness trade-off
	0 < ω <1	Priority based Efficiency – Fairness trade-off
L → 1	**1**	Proportional fair
L = 2	**1**	Minimum delay
	0 < ω <1	Priority based minimum delay
L >2	**1**	Max-min

3.7.4.1 Case – I Maximizing Sum of Data Rates

When the value of L = 0 and ω = 1, the utility maximization reduces to maximization of the sum total data rate of the network. As source 4 faces the best channel, the destination assigns maximum resources to source 4 and other sources are deprived of the resources which is apparent from Fig 3.22, Fig. 3.23, and Fig. 3.24. Fig 3.18 shows the maximum data rate is achieved by source 4 with maximum resources assigned to it. Fig 3.19 shows the total data rate achieved by the network of four sources. It is evident that total data rate of the network is dominated by the data rate achieved by source 4 in this case. Fig 3.20 shows that fairness index of this case is 0.251 which is the lowest among all allocations.

3.7.4.2 Case – II Efficiency-Fairness Trade-off at L = 0.1

As L rises from 0, the objective function maximizes the sum of the utility of all the users. The value of L is small so still more resources are assigned to source 4 but the other sources are also given some portion of the resource which makes their data rate higher compared to case - I. As a consequence, total data rate reduces from 0.379 to 0.363 units, fairness index improves from 0.251 to 0.404 and the loss in efficiency, depicted by price of fairness becomes 0.043 (Fig 3.19, Fig. 3.20 and Fig. 3.21 respectively). It can be seen from Fig 3.22, Fig 3.23 and Fig 3.24 that still nearly 72-75% of the total resources are allocated to source 4 and remaining resources are shared among remaining three sources.

3.7.4.3 Case – III Efficiency-Fairness Trade-off at L = 0.5

To give more emphasis on fairness, the value of L is increased further. It can be seen from Fig 3.18 that the difference in the data rates achieved by source 4 and source 1 becomes smaller. This allocation results in further reduction in total data rate and hence increase in price of fairness but fairness index improves to 0.876 from 0.406. The price of fairness increases from 0.043 to 0.202. By keeping $0.1 < L < 1$, any trade-off between efficiency and fairness can be achieved.

3.7.4.4 Case – IV Proportional Fairness at L →1

As *L* approaches 1, the fairness achieved is referred to as proportional fairness. All the sources experience different channel condition. In this case, all the sources would get resources in proportion to their relative channel condition. The resources are allocated to all the source are such that the data rates achieved by each source maintain their mutual relation with each other. As per the definition of proportional fairness in (3.23), Table 3.12 proves that this allocation is proportional fair. Proportional fair allocation means the summation of difference in data rate achieved with any other allocation and proportional fair allocation divided by proportional allocation is less than or equal to 0. In Table.3.12, last row shows that as the allocation done with $L \rightarrow 1$ is proportional fair. In this allocation, fairness index reaches 0.963 with price of fairness 0.248.

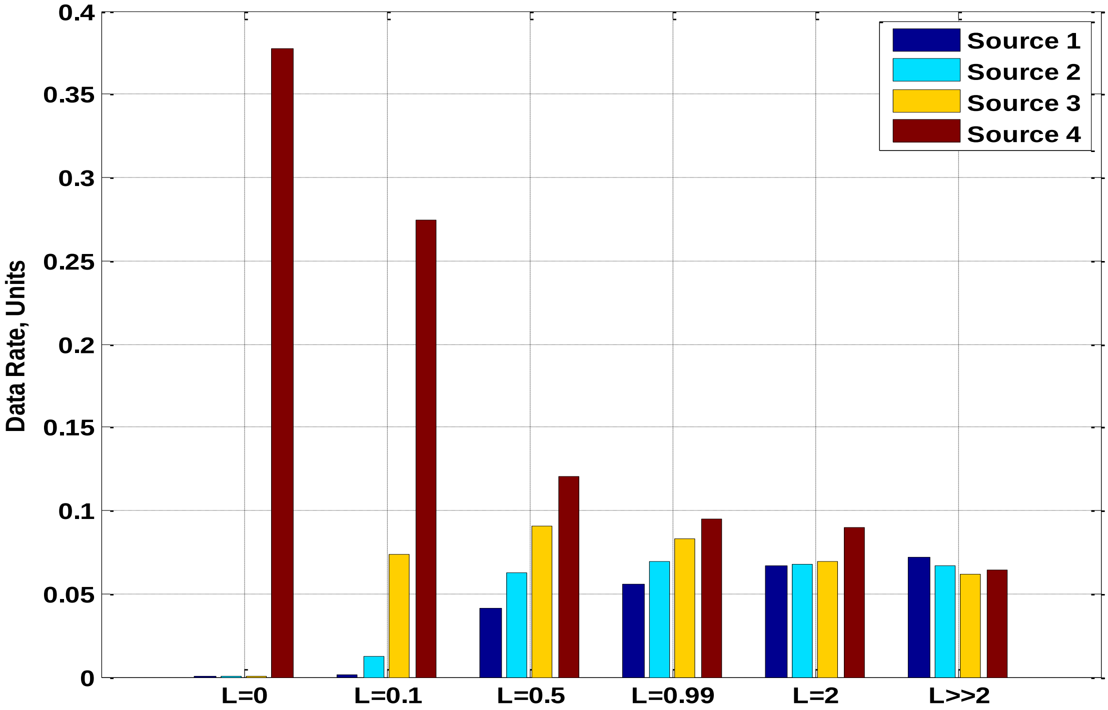


Fig 3.18 Data rate of each source under different cases

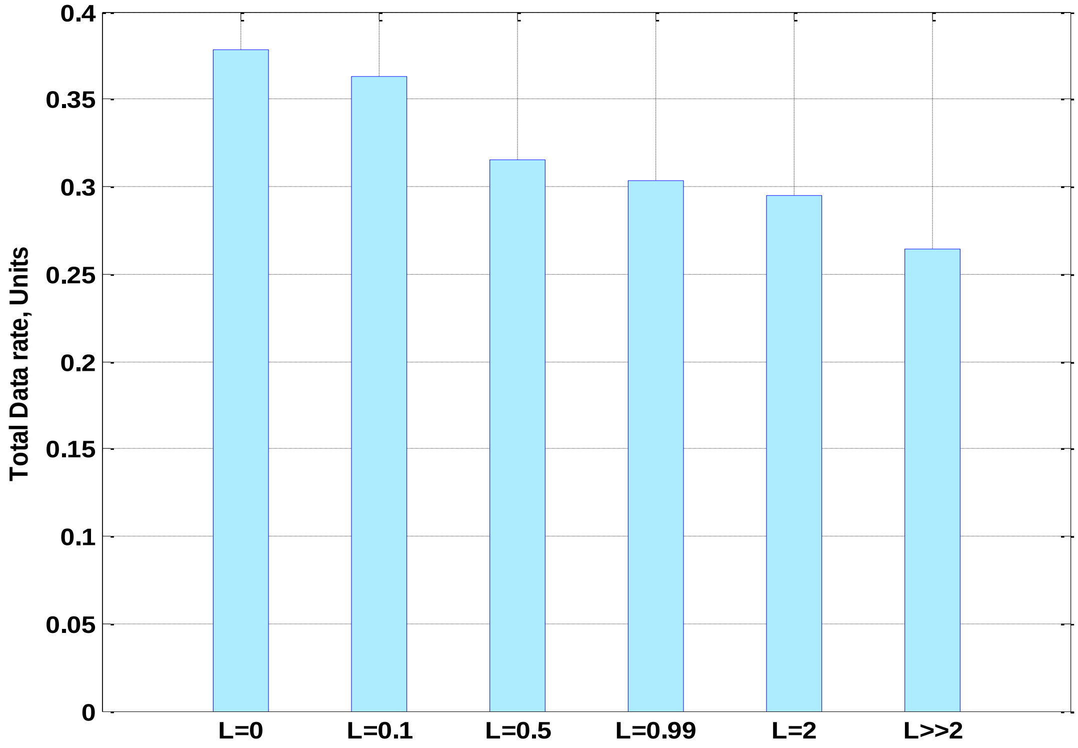


Fig 3.19 Total data rate under different cases

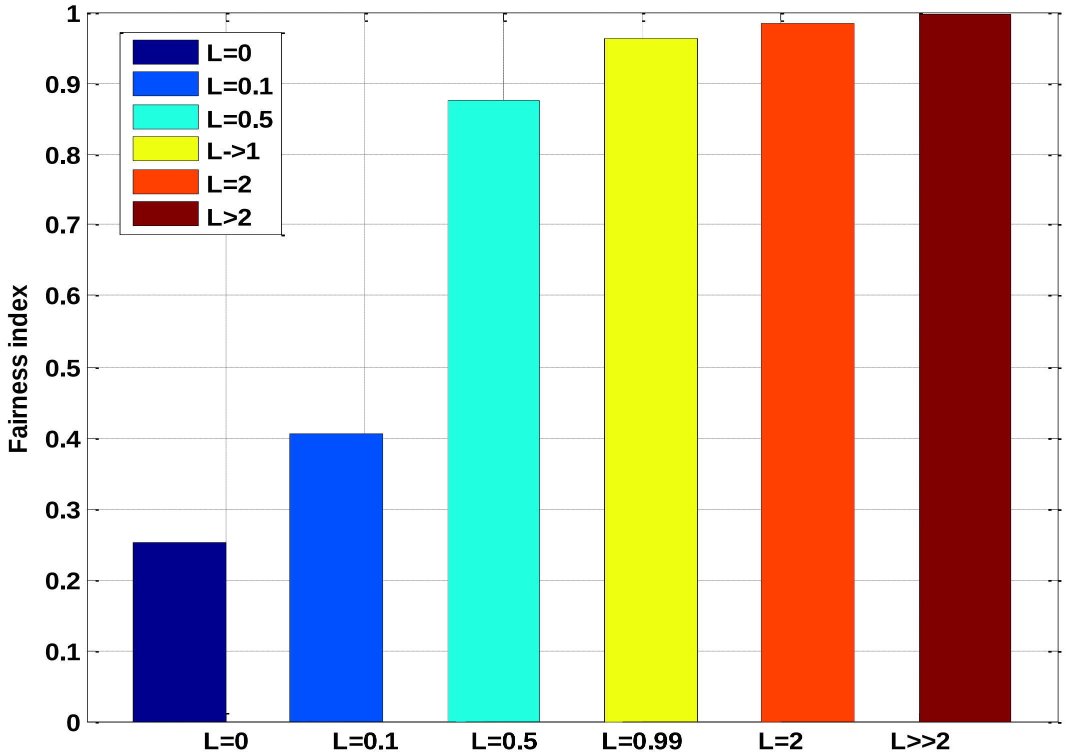


Fig 3.20 Fairness index under different cases

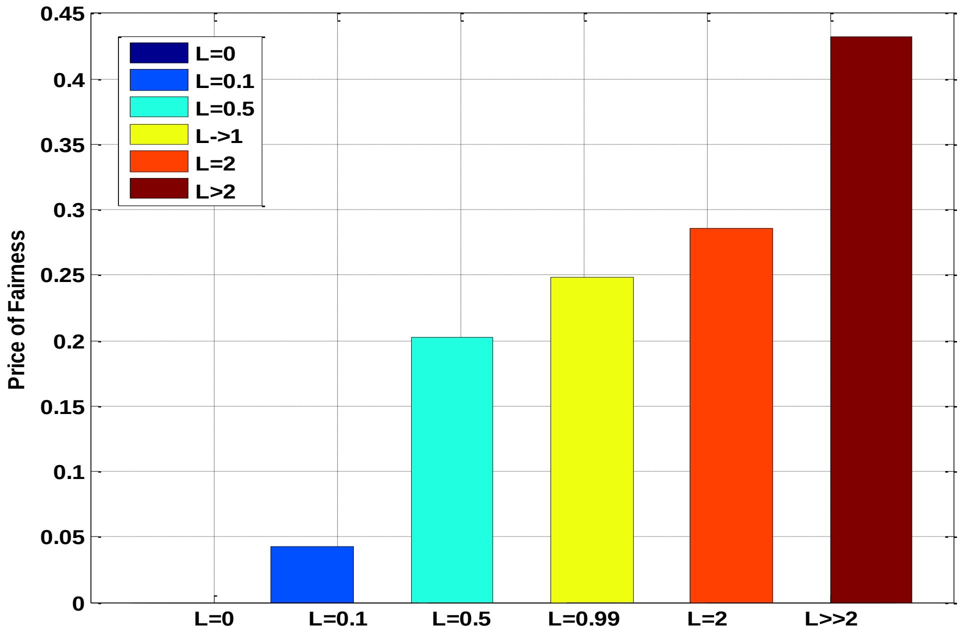


Fig 3.21 Price of fairness under different cases

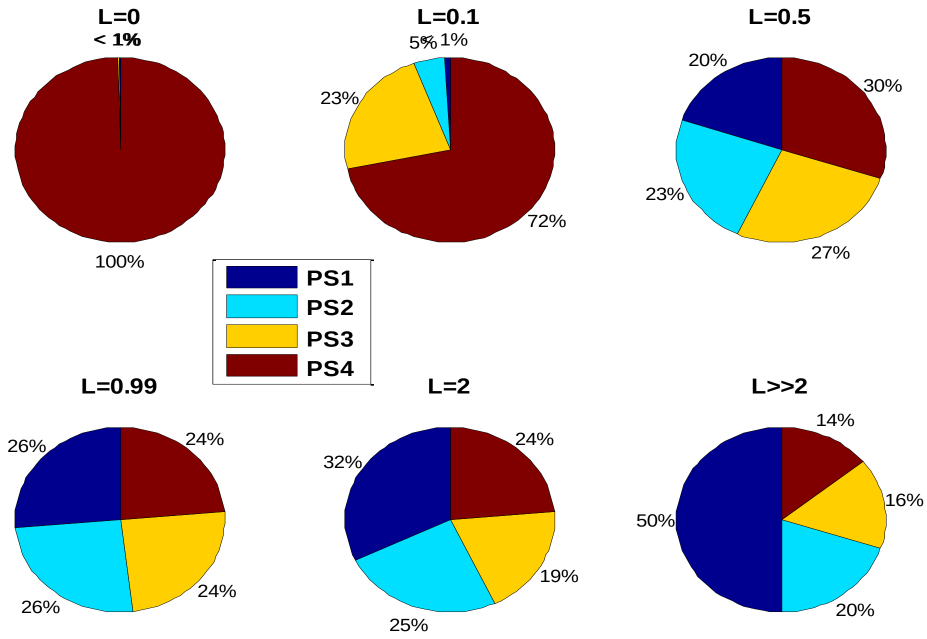


Fig 3.22 Allocation of source power to sources under different cases

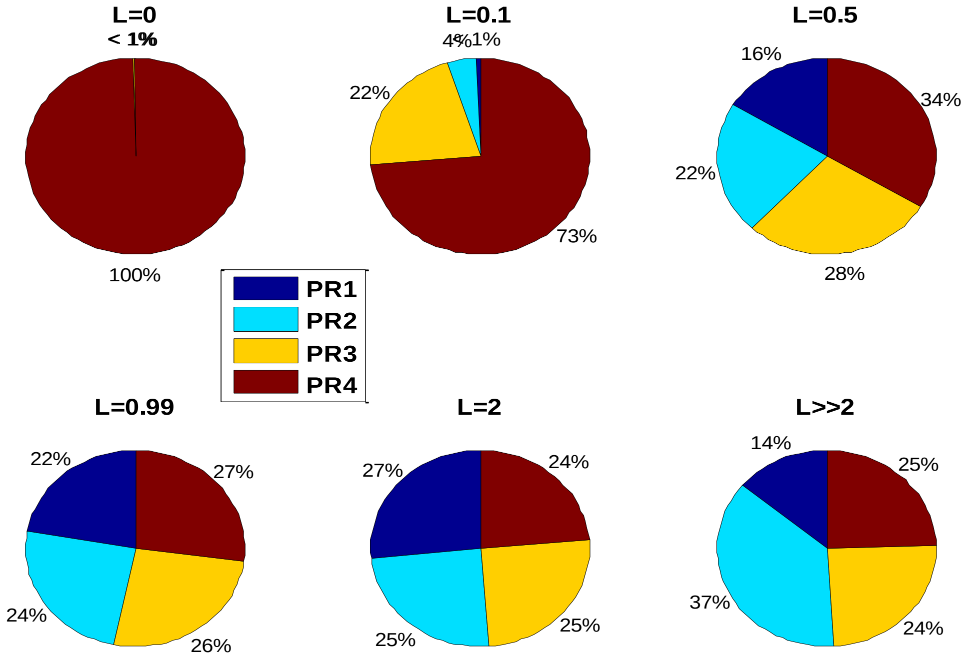


Fig 3.23 Allocation of relay power to sources under different cases

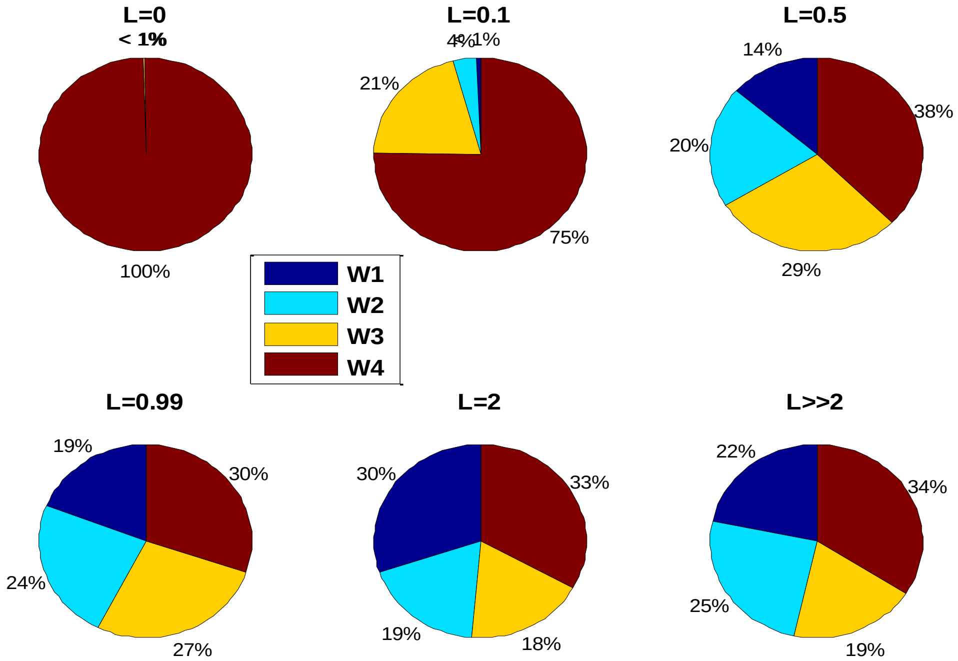


Fig 3.24 Allocation of bandwidth to sources under different cases

Table 3.12 Proof of proportional fairness

	$\frac{(R_{L=0}-R_{L\to1})}{R_{L\to1}}$	$\frac{(R_{L=0.1}-R_{L\to1})}{R_{L\to1}}$	$\frac{(R_{L=0.5}-R_{L\to1})}{R_{L\to1}}$	$\frac{(R_{L=2}-R_{L\to1})}{R_{L\to1}}$	$\frac{(R_{L=5}-R_{L\to1})}{R_{L\to1}}$
Source 1	-0.996	-0.970	-0.262	0.201	0.295
Source 2	-0.996	-0.817	-0.097	-0.021	-0.043
Source 3	-0.996	-0.110	0.096	-0.162	-0.261
Source 4	2.964	1.884	0.259	-0.054	-0.322
$\sum_{i=1,2,3,4}\frac{(R_{L=k}-R_{L\to1})}{R_{L\to1}} \le \mathbf{0}$? $\boldsymbol{k} \in \{\mathbf{0}, \mathbf{0.1}, \mathbf{0.5}, \mathbf{2}, \mathbf{5}\}$	**-0.024**	**-0.014**	**-0.004**	**-0.036**	**-0.332**

3.7.4.5 Case – V Minimum Potential Delay at L=2

For L = 2, the allocation tries to minimize the time taken to transmit the data of fixed size with minimum delay. The sources with poor channel are now assigned more resource compared to sources with good channel. Sources 1 and 2 are assigned more than 50% of the source power and relay power compared to 5-6% in case of L = 0.1. As a result, the fairness achieved by this technique is excellent 0.9831 but with heavy price of fairness of 0.286.

3.7.4.6 Case – VI Max-Min Fairness at L>>2

For L >> 2, (here L=5 is considered in simulation) data rate achieved by source 1 is maximum as compared to source 4. The source with poor channel is given more protection. The data rate achieved by all four sources become nearly equal, which is indicated by fairness index of 0.997 but price of fairness becomes 0.432, which indicates 43.2% loss in efficiency. In this allocation, the source with minimum data rate is given resources to maximize it data rate.

In above mention all the cases, weighing factor is assumed to be 1. All allocations can be priority based by adding weighing factor ω_i to each source in the network. Case – I to VI show that proposed generic utility function can be employed to achieve desired type of resource allocation in the cooperative network. The generic utility function can attain different goals of resource allocation like full efficiency, proportional fairness, max-min fairness, minimum delay fairness. It is also possible to achieve any desired efficiency-fairness trade-off using the same utility function. Simulation results show that fairness index from 0.251 to 0.997 can be achieved with price of fairness ranging from 0 to 0.432. The priority base allocation can also be done by the generic utility function be putting weighing factor in utility function of each source.

3.8 Conclusion

Resource allocation techniques for centrally control multi-source cooperative network are developed in this chapter. The service provider installs one or more relays to generate cooperative diversity in the network. The goal of the service provider is to maximize the revenue as well as to provide satisfactory services in the network. Utility based resource allocation maps data rate of the source in utility and allocate the resources to maximize sum of the utility. Utility functions suitable for data network are developed. Simulation results have shown that limited resource are allocated to achieve different goals of the resource allocation like full efficiency with 0.251 fairness index to 0.998 fairness index with 27% loss in data rate. Resource constraint approach put restriction of data rate and achieve the trade-off with the help of two parameters *A* and *B*. *B*=1 leads to equal resource allocation and hence fulfil the requirements of fairness, whereas *B*=2.5 leads to efficient allocation for smaller *A*. In E-F function based approach, three types of allocations are obtained, namely efficiency, fair and proportional fair. The condition $F = \frac{1}{1+E}$, leads to proportional fairness, $F < \frac{1}{1+E}$ leads to more fairness and $F > \frac{1}{1+E}$ leads to efficiency. Generic utility function developed in this chapter is proved to be capable of satisfying multiple criteria of resource allocation be selecting only one coefficient. Proportional fair technique of allocation is shown to allocate resource in proportion of their channel gains or demands. Max-min fair technique gives more protection to source with poor channel and allocates more resources, which results in fairness index of 0.997 but loss in efficiency becomes 43.2%.

Chapter 4

Multi-unit Auctioning Based Resource Allocation Technique for Semi-Distributed Cooperative Network

The approaches of resource allocation, discussed in chapter 3, are applicable to centrally controlled network like cellular network where the relays are installed by the service providers. The cooperation would be more attractive if nodes cooperate with each other without the need of specially installed relay. Multi-unit auctioning technique is presented in this chapter which encourages nodes, by offering compensation in terms of virtual currency, to become the relay. This technique eliminates the need of specially installed relays and reduces the computation burden of the central controller. Proposed multi-unit auction technique is based on revelation of demand curve parameters by the source nodes. Modelling of this technique is done and verified with the aid of extensive simulations. This technique is compared with conventional clock auctioning technique. It is also checked that the proposed technique also satisfies the theoretic properties of auction.

4.1 Auctioning Techniques for Resource Allocation

Auction is the game of incomplete information in which a buyer is unaware of the valuation of the goods by the other buyers (Fudenberg) (Osborne) (Vazirani). In this method, the information, in the form of bids, are sent from the potential buyers to seller, showing their willingness to pay. The outcome in terms of who will receive how much is determined solely on the basis of the received information (Zavlanos). Auction can be sealed bid or open bid (Krishna). In the sealed bid auction, the bid of a buyer is not known to the others. In open auction, all the potential buyers are aware of bids of all other buyers and accordingly they can modify their bids for the next cycle. In open bid auction, price can be ascending (or descending) in which the bid prices increase (or decrease) in step till all the units are sold. The sealed bid auction can be first price, in which the buyer willing to pay the maximum, wins and pay the highest. It can be second price, in which buyer willing to pay the maximum, wins and pay the second highest. Apart from these basic types, many variants of auctions are available in the literature (Krishna).

Auctioning is employed for resource allocation by considering source nodes as a buyer and relay nodes as a seller of 'cooperation'. The sources are unaware of the price at which the relay would sell units of power and number of units of power available with the relay for sell. At the same time the relay is unaware of the demand of the power from one or more sources. The source would not like to pay more than the benefit which it gets from the cooperation. If relay demands too high price, source would not buy any power from it. On the other hand, if relay announces very low price, the source would buy all the units of power, which results in sub-optimal revenue for the relay. In (Baidas) (Mukherjee) (D. G. Yang) (D. X. Yang), ascending / descending auction has been considered in which negotiation takes place step by step between the source and the relay which results in large delay in establishing cooperation. This delay is not at all appropriate in case of time varying wireless channel.

In this chapter, the interaction between network nodes is modelled as a buyer-seller market employing a single round, multi-unit auctioning mechanism based on revelation of demand curve parameters. To reduce the time needed in negotiation process, the requirement of the source is represented as demand curve. When there are multiple buyers with different demands and multiple sellers with different supply, the allocation can be done using supply–demand curve based market clearing strategy. It has been demonstrated in (Sandholm, Market clearability) (Sandholm, Optimal clearing of supply/demand curves). It results in low complexity and less overheads; compared to clock-auction based techniques. The uniqueness of the wok presented in this chapter is that the interaction between the source and the relay is based on the source demand curve and available supply with relay. The objective of allocation is to maximize the revenue earned by the relay. The relay are given two options to charge the price: non-discriminatory (uniform) and discriminatory. This technique is semi-distributed in which the source finds the suitable partner (or relay) locally. The management of virtual currency is done by the central controller in order to avoid probable malfunctioning by the nodes. The central controller maintains the balance of virtual currency and informs each node from time to time. By employing this technique, the data rate of source nodes is increased and power is saved. This technique requires fewer overheads and results in less delay compared to clock-auctioning technique (Baidas) (Mukherjee).

4.2 System Model

There are M wireless nodes with a single antenna communicating with the common destination in the network. All the nodes are given equal virtual currency in the beginning to trade for getting cooperation from the nodes in the vicinity. Nodes can increase the balance of currency by cooperating with the needy nodes and spent it when they are in need. Access point maintains the balance of the virtual currency and informs all the nodes from time to time. The decision to cooperate is taken by the nodes but the accounting of currency is done by the central controller to avoid malpractices by the nodes. Out of M nodes, the node having good channel with the destination but does not have its own data to send, acts as a relay. The node having data to send but not having good channel with the destination, acts as a source. Amplify and forward relay protocol is assumed due to its simplicity. Each node is assumed to have channel state information between the relay and itself and destination and itself, respectively. Achievable maximum data rate by the source with the cooperation of one or more relays and phases required for establishment of cooperation are presented in following subsections.

4.2.1 Maximum Achievable Data Rate with Cooperation

For Amplify and forward protocol, the maximum achievable data rate with cooperation can be given by (3.15). If multiple relays are ready to help the source and if the source has sufficient virtual currency to make payment to multiple relays, then the source may choose the relays to help and take benefit of higher diversity order (Liu). In multiple relay scenario, (3.15) can be modified as

$$R_{iK}^{C} = \frac{1}{2} * \ log_2 \left(1 + \Gamma_{SD} + \sum_{j=1}^{K} \frac{\Gamma_{SRj}\Gamma_{RjD}}{\Gamma_{SRj}+\Gamma_{RjD}+1} \right) \tag{4.1}$$

(Notations carry the meaning as defined in Table 3.1)

where $j = \{1,2, \ldots, K\}$ number of relays cooperating to a source and R_{iK}^{C} is the data rate achieved by source *i* with *K* relays. One relay may help one or more sources by giving its power and in return, the relay charges certain revenue to the sources. The relay wants to allocate the power so that it can take maximum benefit of good channel condition and maximize its revenue.

4.2.2 Phases for Establishing Cooperation

To establish the successful cooperation, the nodes negotiate with each other. We have considered relay-centric scenario. Therefore, the nodes in need of cooperation i.e. source nodes send demand curve parameters to relay and relay makes decision about the price and units of power to be allocated to each source which can maximize relay revenue. Multi-unit auctioning mechanism involves following steps:

I. In the beginning of the block, the sources that cannot achieve their desired transmission rate, generate a demand function showing its maximum requirement of power from the relay and its ability to pay. (The analytical model of the same is developed in the next section)

II. The node that wants to act as relay receives the requests. It calculates the units of power and price per unit that can maximize its revenue and informs it to the corresponding sources
III. If the demand of the source is more than the spare resources available with the relay, it is rejected.
IV. Relay informs clearing price and units of power to sources which can maximize relay revenue.
V. Sources start communication cooperatively and get higher data rate as per (3.15).
VI. The allocation of power to the sources by the relay remains the same for the given block.
VII. At the beginning of new block, the cooperating nodes continue with the same power and price by sending a signal to each other. If anyone wants to leave or change the trade generates fresh demand and supply.

The mechanism to generate demand functions by the sources and choosing optimum allocation by the prospective relay is presented in the following section.

4.3. Multi-Unit Auctioning Mechanism

The source nodes buy power from relay to increase data rate. In return, source nodes have to pay price per unit of power to the relay node. The relay node utilizes its power to retransmit source nodes' signal. The trade becomes successful only when both the nodes are able to earn benefit out of it. Utility of source and relay are formulated in the following sub-section. As per the theory of auction, the successful auction must possess certain properties as described below.

4.3.1 Properties of Auction

Auction is the mechanism to do trade between the buyer and seller. An efficient design of auction mechanism must satisfy the following important properties:

A. Truthfulness: For all the buyers, the dominating strategy is to reveal its true valuation of the object while putting the bid.

B. Budget-Balance: Price paid to the seller is equal to or smaller than the price taken from the buyers in case of auction when the auction is done in the presence of an auctioneer.

C. Individual Rationality: Buyers and sellers, both can get benefit by participating in auction

D. System efficiency: The benefit obtained by all the participants is maximized as a result of allocation.

A validation check for these properties with regard to the proposed auction mechanism is carried out in section 4.3.5.

4.3.2 Utility of Source and Relay

Utility of the source and utility of the relay can be defined as the benefit gained by each one by participating in cooperation. The utility of the source *i* depends on two factors – increase in data rate due to cooperation and total revenue paid to the relay. The utility of the relay depends on unit price of power and total units of power sold to the sources. Consider *N* sources in need of cooperation from the potential relay. The benefit acquired by the source node $i, \ \forall \ i = \{1, 2, 3, \dots, N\}$ is expressed as a utility function, U_{S_i} and can be computed as

$$U_{S_i} = \mu * \left(R_i^C - R_i^{NC}\right) - (\Theta * \Pi_i) \tag{4.2}$$

where, R_i^C is the transmission rate achieved as a result of cooperation, R_i^{NC} is the transmission rate of the direct path, Θ is the price per unit of power charged by the relay and Π_i is the units of power purchased by the source *i*. μ is the scaling parameter for comparing increase in transmission rate with price (Wang).

The utility of the relay can be modelled as

$$U_R = \sum_{i=1}^{N} \Theta * \Pi_i \tag{4.3}$$

The source has to determine how much power it desires to purchase at a particular price. Moreover, the source is completely unaware about the utility of the other sources. Utility of the relay is the total revenue generated as a result of selling surplus units of power. The prime objective of the relay is to maximize its revenue.

In ascending price clock-auction (Baidas), as the relay gradually increases its price, the demand of the source goes down. The deal is struck at when the demand matches with the supply. The price at which the relay agrees to sell power is called market clearing in auction terminology. Determining market clearing price is a computationally complex task (Mukherjee) (D. G. Yang) (Baidas). The market clearability can be done in most efficient manner when the buyers/sellers project their demand/supply in the form of demand/supply curves (Sandholm, Market clearability) (Sandholm, Optimal clearing of supply/demand curves). The sources express their demand in the form of price-power demand curve. The demand curve can be step for fixed data rate users and linear or exponential for variable data rate users. In this work, linear curve for variable data rate user and step for fixed data rate users are assumed.

When large number of sources ask for the cooperation, it is not possible for the relay to fulfil the requirement of all of them completely. In that case, relay starts increasing the price which results in reduction of the demand. When demand and supply matches, the auctioning is accomplished. The delay incurred in the process of reaching an optimum solution is very large and increases communication overheads also. In time varying wireless channels with mobile nodes, the optimum allocation would no longer remains optimum. The practical approach is to implement a technique having fewer overheads, less delay and allocate the resources proportionally. In the following section, we have developed a technique to establish cooperation with proportional power allocation to sources, incurring less delay and having reduced overhead.

4.3.3 Determination of Power Allocation to Sources

When a source realize that it is not possible to achieve its targeted data rate on direct S-D link, it generates the demand of units of power necessary to reach the target. It also mention its capability of pay after considering the balance of virtual money possessed by it. Relay gets such information from many sources and determines the revenue maximizing allocation, considering availability of power. Modelling of this trade and evaluation of revenue maximizing allocation for is presented in following sub-sections.

4.3.3.1 Demand Curve of a Source

The source demands power from the relay for relaying its information. The demand of the source is high, if price per unit of power is small. As price per unit of power increases, the demand of source decreases. This is because as per (4.2), if source buys power at higher price, the benefit in data rate would be less compared to price paid. Hence, source wants to avoid this situation. The demand of the source is represented as linear demand curve.

$$\Pi_i = -\alpha_i * \Theta + \beta_i \tag{4.4}$$

where α_i is the slope of the line and β_i is the maximum units of power source wants to utilize if price is minimum. The demand curve shows the price as a function of units of power $\Theta(\Pi)$. If demand of the source is cleared at price Θ per unit of power, the source receives Π units of power at price Θ per unit of power. The utility of the relay is the revenue earned i.e. $\Pi * \Theta(\Pi)$. Negative sign of the curve indicates that demand decreases with increase in the price.

In the beginning, each source calculates α_i as,

$$\alpha_i = R_i^{tar}/(R_i^{tar} - R_i^{NC}) \tag{4.5}$$

where R_i^{tar} is the maximum targeted rate the source wants to achieve and R_i^{NC} is the rate achieved by the source i in non-cooperative mode. We define a parameter β_i for source i which represents the estimate of the additional units of the power required from relay to achieve the targeted rate under the cooperative mode. It can be estimated as,

$$\beta_i = P_{max}^{req} \quad (4.6)$$

where P_{max}^{req} is the maximum units of power required from relay.

The relay can charge from the source either the non-discriminatory price or the discriminatory price. In non-discriminatory price, the relay would assign different units of power to different sources at the same price per unit of power. In discriminatory price, the relay charges different price per unit of power to different sources. In the following sub section, we have presented the optimization problem with an objective to maximize the relay revenue for both the pricing techniques. The comparison of pricing techniques is presented in simulation results. We have also analysed the applicability of these pricing technique based on the demand of the sources.

4.3.3.2 Maximizing relay revenue with non-discriminatory price

Each interested source, $i,\ i = \{1,2,..N\}$ sends only two parameters α_i and β_i to the relay. The relay calculates the aggregate demand from the individual demands as,

$$\Pi_{aggre} = \sum_{i=1}^{N}(-\alpha_i * \Theta + \beta_i) \quad (4.7)$$

Utility of the relay is the total revenue of the relay, Ω, which can be computed from (4.3) and (4.7) as,

$$\Omega = \sum_{i=1}^{N}(-\alpha_i * \Theta^2 + \beta_i * \Theta) \quad (4.8)$$

The objective of the relay is to maximize its revenue R. The optimization problem for relay revenue can be formulated as A1.

$$max\,\Omega \ = max \sum \Pi_{\mathrm{i}} * \ \Theta \qquad [A1]$$

subject to

$(i)\quad \Pi_i = -\alpha_i * \Theta + \beta_i$

$(ii)\ \sum \Pi_i \leq \Pi_{max}$

where Π_{max} is the maximum power available with relay for cooperation.

The condition for maximum revenue can be established by differentiating (4.8) with respect to Θ, it yields

$$\Theta_{\mathrm{max}} = \ \sum \beta_i / 2 \sum \alpha_i \qquad (4.9)$$

and

$$\Pi_{aggre} = \sum \beta_i / 2 \qquad (4.10)$$

The amount of maximum revenue can be found by putting the value of Θ in (4.8) as

$$\Omega_{max} = \ \sum {\beta_i}^2 / 4 * \sum \alpha_i \qquad (4.11)$$

It can be seen from (4.11) that relay calculates clearing price to yield maximum revenue from parameters α_i and β_i of the sources.

4.3.3.3 Maximizing Relay Revenue with Discriminatory Pricing

In discriminatory pricing technique, the relay charges each source differently based on the urgency of source to buy power. Let Θ_{i} be the price per unit power charge by relay source *i*.

The optimization problem for relay revenue can be formulated for discriminatory price as,

$$max\,\Omega = max \sum \Pi_i * \Theta_i \qquad [A2]$$

subject to

$(i)\ \Pi_i = -\sum \alpha_i * \Theta_i + \sum \beta_i$

(ii) $\sum \Pi_i \leq \Pi_{max}$

The above problem can be rewritten as $min - \sum \Pi_i * \Theta_i$. It is two variable optimization problem and can be solved using Lagrangian multipliers [subh1] [subh2]. Applying Lagrangian multipliers to objective function A2 yields

$$\min\left((\Pi_i{}^2/\sum \alpha_i) + (\sum \beta_i \Pi_i/\sum \alpha_i)\right) + \Lambda\,(\Pi_{max} - \sum \Pi_i) \qquad (4.12)$$

where, Λ is the Lagrangian multiplier. Solving (4.12) gives

$$\Lambda = \frac{2 * \Pi_{max} + \sum \beta_i}{\sum \alpha_i}$$

Substituting the value of Λ, optimum price and quantity for each source can be obtained as

$$\Theta_i = -\,(\beta_i/2) + (\alpha_i/2) * ((2 * \Pi_{max} + \sum \beta_i)/\sum \alpha_i) \qquad (4.13)$$

and

$$\Pi_i = (\beta_i/2 * \alpha_i) + \frac{1}{2} * ((2 * \Pi_{max} + \sum \beta_i)/\sum \alpha_i) \qquad (4.14)$$

The relay, in this method allocates power by keeping the demand from all the sources in mind. i.e. source with higher demand will be charged more and vice-versa. One important characteristic of discriminatory pricing is that it gives degree of fairness among sources. The power is allocated to all the sources so that the difference in the maximum and minimum data rate achievable by the sources reduces.

4.3.3.4 Power allocation for fixed data rate users

There are certain applications which require fixed data rate. In such cases, the source's demand curve becomes step i.e., it either wants full or none. With the limited resources, the relay chooses source/s which can maximize its revenue and the request from other sources are rejected. This optimization problem for revenue maximization for fixed data rate can be formulated as

$$max \sum \Theta_{\mathrm{i}} * x_{\mathrm{i}} \tag{A3}$$

subject to

$(i)\ \ \sum \Pi_{\mathrm{i}} * x_i \leq \Pi_{max}$
$(ii)\ x_i \in \{0,1\}$

In the above problem $x_i = 1$ indicates that the source *i* is selected and assigned the power fully as per its demand and $x_i = 0$ indicates that the relay has denied the demand of source *i*.

4.3.4 Algorithm for Multi-unit Auctioning Process

In this proposed mechanism, the source is the buyer and the relay is the seller of power for re-transmission. Both the nodes prefer to maximize their benefit. Source node likes to maximize the data rate and reach its target and relay node wants to maximize the revenue. The step by step procedure for establishing successful cooperation is as follows:

i. Source *i* generates a tuple (α_i, β_i) where α_i and β_i are calculated from (4.5-4.6).
ii. On receiving α_i and β_i from all the participating sources, relay generates aggregate demand curve based on (4.7).
iii. The relay calculates price and units of power to maximize its revenue from (4.9-4.10) for non-discriminatory price and for discriminatory price from (4.13-4.14).
iv. Relay chooses the appropriate pricing technique based on maximum revenue.

v. Relay selects sources which contribute to maximize relay revenue.

vi. Selected sources confirm allocation by sending signal to the relay and the destination.

vii. In the beginning of new block (or frame), if demand changes, the whole process is repeated otherwise sources and relay follow the same allocation.

4.3.5 Validation Check for Auction Properties

The auction mechanism is required to satisfy certain properties as described in 4.3.1. The proposed auction mechanism fulfils those properties in the following manner.

A. Truthfulness: In the proposed technique, each source has to reveal its requirement and its ability to pay truly. The smaller value of slope of the curve indicates higher requirement of the power by the source. The relay allocates more power to it and the source has to pay more. Conveying smaller value of slope to get more power by the source may result in negative utility as per (4.2). Also, the source is unaware of the competition so the source has to reveal its true valuation for getting relay cooperation.

B. Budget-Balance: This technique is without the aid of any centralized auctioneer so the price paid by the sources directly goes to the relay i.e. price paid by the buyer is the same as the price asked by the seller. So it is budget balanced.

C. Individual Rationality: Here, source decides the amount of power which can result in positive utility and relay decides price and units of power which can maximize its utility. Both the nodes are rational decision makers and makes decision to increase their individual utilities.

D. System efficiency: This is the relay centric auction in which relay maximizes its revenue by allocating units of power to the sources in need. However, the sources are not able to get all the units of power as required from one relay. The process for exactly equalizing demand and supply units of power is time consuming and computationally complex. Looking at the time varying nature of the wireless channel and variable data rate application of the sources, it is a practical approach to allocate the power as quickly as possible with minimum overheads and complexity. The sources can definitely increase the transmission rate with the help of one relay. The same technique can be further modified to model multi source-multi relay scenario in which the sources would be able to get the desired number of units as per its requirements.

4.4 Performance Evaluation and Discussion

The performance of the proposed technique is checked with the help of extensive simulations. Data rates of individual sources with both type of pricing technique are found out and compared. Revenue maximizing allocation and power allocation under both the pricing schemes are also computed. Amount of power saved by source nodes are calculated to demonstrate the benefit of cooperation.

4.4.1 Simulation Environment

The wireless nodes communicating with a common access point are distributed randomly in the given area. Three sources S1, S2 and S3 and one relay R communicating with access point D are considered as shown in Fig 4.1. All the three sources are at equal distance from the destination. The distance between each source and the relay is also assumed to be same. The target data rate of the source are 0.22, 0.25 and 0.28 units, respectively. For the sake of simplicity, path loss channel model with path loss exponent 3 is considered for simulation. This technique is also applicable for random channel model. The negotiation occurs between sources and relay at the beginning of new block. If channel does not change rapidly, the same negotiation can be continued for longer duration of time. Otherwise, at the beginning of each new block, the negotiation can be changed.

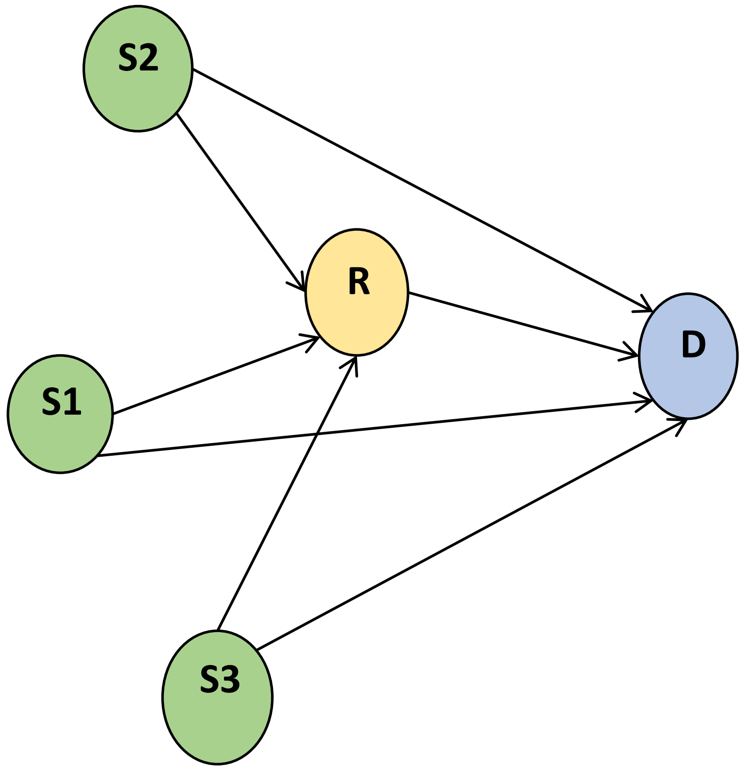


Fig 4.1 Simulation model

For the sake of simplicity, the channel coefficients are assumed to be dependent on distances between the nodes. The power transmitted by all the sources P_{s_j} = 1 units, $\forall$j = {1, 2, 3}.

4.4.2 Analysis of Power Allocation Based on Aggregate Demand Curve

Three sources S1, S2 and S3 have different targeted transmission rates. Being not able to achieve it on their own with maximum power limitation, they calculate their demand function and broadcast it to get help from neighbouring node. The interested relay node R gets such request from one or more than one source. It calculates units of power to be allocated and price per unit of power which can maximize its revenue for that aggregate demand. The sources whose demand is too high, would be denied cooperation. The plot in Fig 4.2 shows demand of each source, aggregate demand curve and revenue maximizing allocation by the relay.

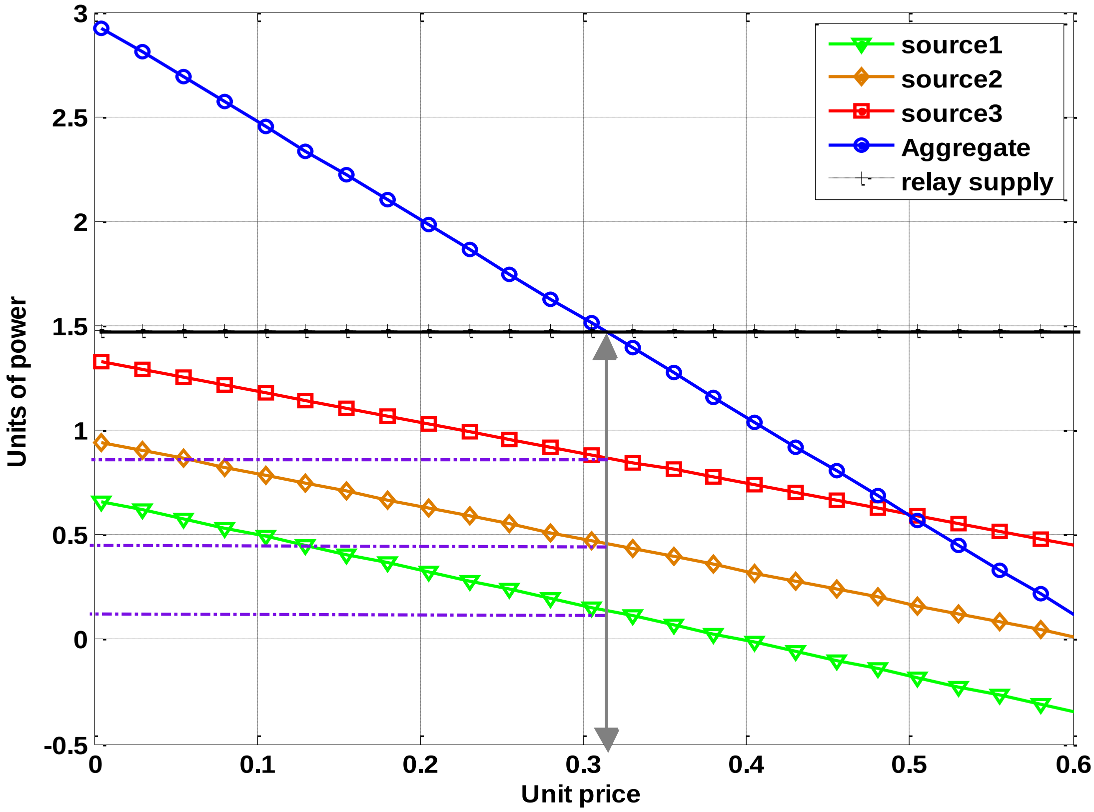


Fig 4.2 Revenue maximizing allocation for non-discriminatory pricing

Source 1 demands for 0.66 units of power, source 2 wants 0.94 units of power and source 3 demands 1.325 units of power from relay to reach their target data rate, if the price from the relay is minimum. As the price increases, the demand of the source reduces. The slope of the demand curve is determined by the difference between the target data rate and data rate of direct source to destination link as per (4.5). Sources broadcast the slope of demand curve, α_i and maximum units of power required at minimum price β_i. Relay considers the demands which can be served by it. Using (4.7), the relay calculates aggregate demand and determine non-discriminatory revenue maximizing allocation with the help of optimization problem [A1].

It also calculates revenue maximizing allocation with discriminatory price with the help of optimization problem [A2]. Fig 4.2 shows that the relay allocates 1.47 units of power at 0.32 per unit of power. At the point of revenue maximization, relay offers 0.14 units of power to source 1, 0.46 units of power to source 2 and 0.87 units of power to source 3. The objective of relay in not to allocate power to satisfy the aggregate demand of sources completely but the relay wants to maximize its revenue from the cooperation. Relay has another option to use optimization problem [A2] to determine different price and units of power for different sources, depending upon their individual and relative demand. Fig 4.3 shows units of power and price per unit of power for each source as per (4.13) and (4.14). In this case, source 1 would get 0.34 units of power at the price of 0.19 per unit of power, source 2 would get 0.47 units at the price of 0.30 per unit and source 3 would get 0.67 units of power at 0.45 per unit of power. As the need of source 3 is more, relay charges more per unit of power and allocates less units of power. Source with less demand would get power at less price and the moderate demand source gets nearly same power in both the cases. One source with very high demand prevents other sources from getting sufficient help of the relay in non-discriminatory pricing scheme. In discriminatory pricing scheme, relay takes benefit of demand curve of the source with the highest demand, which indicates that the source is ready to pay high price. Therefore, the relay allocates fewer units of power at higher price to it as per the demand curve. In this case, the source with the lowest demand would also get significant power at lesser price than the non-discriminatory case.

4.4.3 Evaluation of Utility of source and relay

Sum of the utility of the all the source and the relay as mentioned in (4.2, 4.3) show that the utility of the relay can be maximized by determining the price per unit of the power and maximum units of power to be allocated for sources. Utility of source and relay as a function of price for non-discriminatory pricing scheme is depicted in Fig 4.3. The utility of the source is minimum at the point where the utility of the relay is maximum. It is because the technique discussed here is relay centric, where sources compete to get cooperation of relay. It is also possible to devise source centric technique where multiple relays compete to cooperate with the source and earn virtual currency. In that case, the utility of the source would be maximum and relay would be minimum at the point of trade.

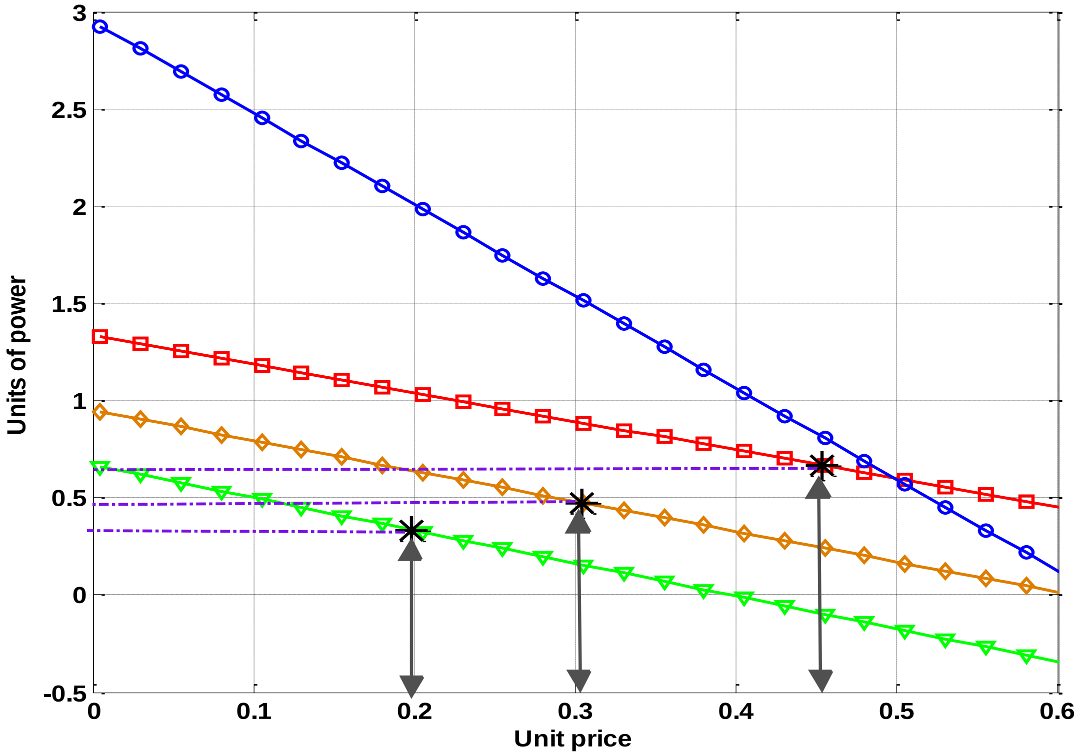


Fig 4.3 Revenue maximizing allocation for discriminatory pricing

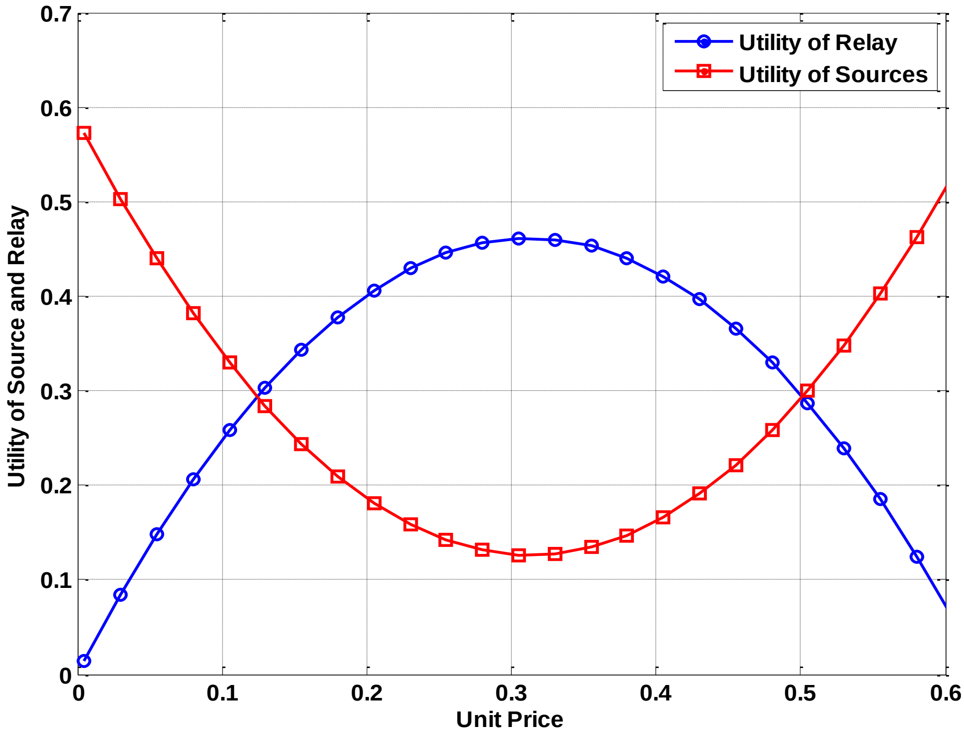


Fig 4.4 Price per unit vs. Utility of source and relay

4.4.4 Analysis of Source Data Rate in Cooperation

The data rate achieved by the sources in direct transmission is not sufficient so sources choose relay and buy power from the relay. Relay allocates power to re-transmits sources' signal as per non-discriminatory or discriminatory pricing schemes. In each case, sources would get different relay power and hence get different data rate. The data rate achieved by the sources without cooperation, their target data rate and data rate with non-discriminatory price and discriminatory price are shown in Fig 4.4. Percentage increase in data rate due to cooperation in both pricing schemes is depicted in Fig 4.5. It is evident from Fig 4.5 that all the sources are able to increase the achievable data rate with the help of the relay. As per our assumption, the target data rate of source 1 is the lowest and that of source 3 is the highest. As all the sources are assumed at the same distance from the destination and the relay; and the power available with each source is the same, the no-cooperation data rate of all the sources are the same.

All the sources can achieve higher data rate then no-cooperation data rate in both pricing schemes. Percentage increase in data rate of all the three sources are shown in Fig 4.6. The sources get 0.09 units data rate in no-cooperation mode. The data rate is increased to 0.13, 0.19 and 0.24 units in the case of non-discriminatory pricing for the source 1, source 2 and source 3, respectively. In case of discriminatory pricing scheme, the sources get 0.17, 0.19 and 0.22 units, respectively. The data rate of source 1 increases by 30.2 % and 47.2% with non-discriminatory and discriminatory pricing schemes, respectively. Source 2 is able to increase the data rate by 53.2% in non-discriminatory and 53.7% in discriminatory pricing scheme. Source 3 gets maximum resource to increase its data rate by 63.1% in case of non-discriminatory and 59.3% in discriminatory pricing scheme. The source with higher demand as source 3 gets more benefit in non-discriminatory scheme whereas the source with lower demand benefited more in discriminatory pricing scheme. Source2 with intermediate demand is indifferent between any of the two pricing schemes.

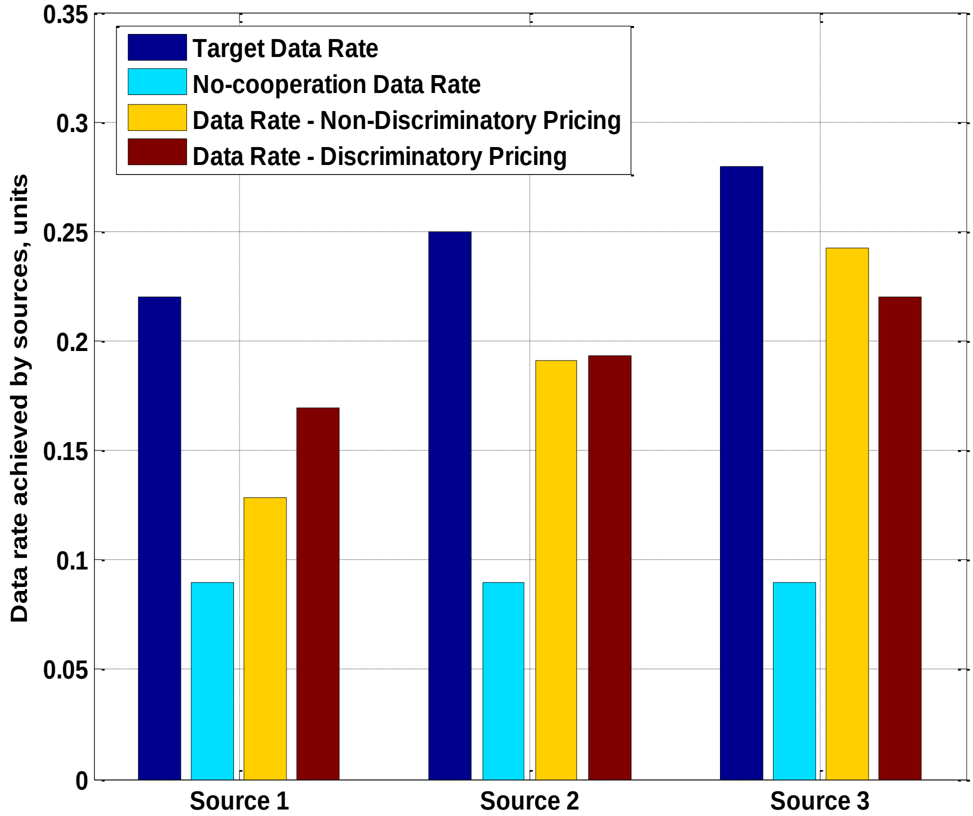


Fig 4.5 Comparison of data rates

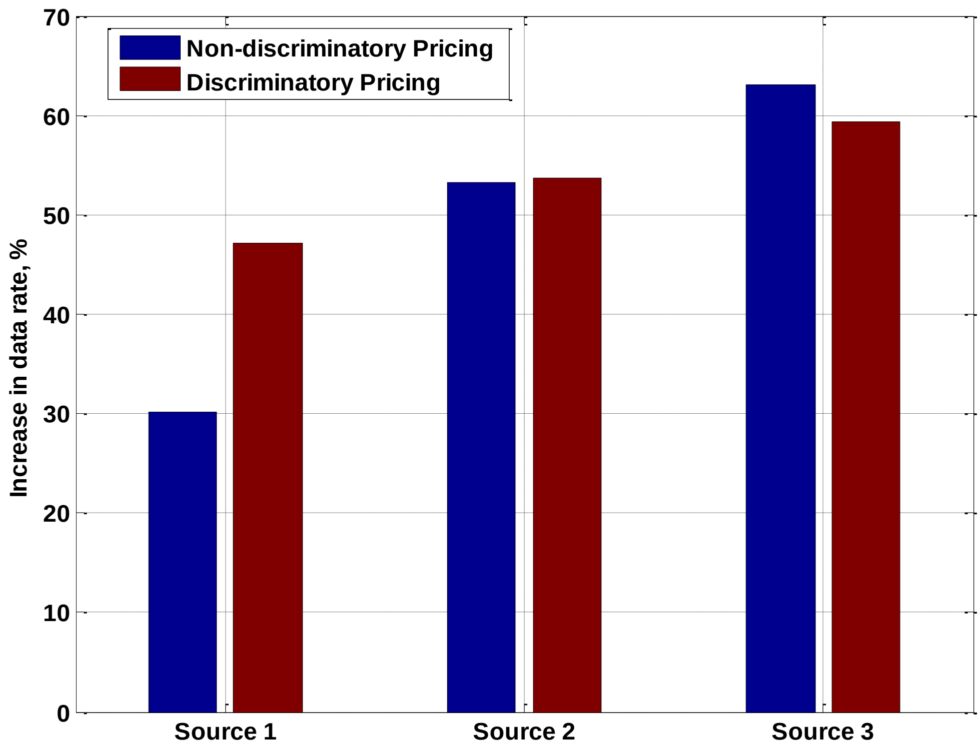


Fig 4.6 Increase in data rate with cooperation, %

Fig 4.5 and 4.6 show that sources get higher data rate with cooperation in the range of 30.2% to 63.1%.

4.4.5 Comparison of Non-Discriminatory Price and Discriminatory Price Allocation

In Fig 4.2, the relay allocates different units of power to the sources by charging all the sources at equal price. But the relay can earn more revenue by allocating different units at different price to the sources. Fig 4.3 shows allocation of different power at different price to the sources. Fig 4.7 and Fig 4.8 show units of power allocated to each source and corresponding price per unit of power charged by user under non-discriminatory pricing and discriminatory pricing schemes, respectively.

Source 1, 2 and 3 get 0.14, 0.46 and 0.87 units of power in non-discriminatory pricing scheme, respectively. All the sources gets power at the same price of 0.31 in this case. In case of discriminatory pricing scheme, relay gives more units to nearer user with less price and allocates less power to farther user at more price. As a result, source 1, 2 and 3 get 0.34, 0.47 and 0.67 units at a price per unit power of 0.19, 0.30 and 0.45 respectively. The sources would get power and price per unit depending on the competition among the sources. The revenue earned by relay is shown in Fig 4.9. Relay earns more revenue from source1 by allocating more units at less price and source3 by allocating less units at more price to sell the units of power to maximize revenue. The relay earns 11% more total revenue in discriminatory pricing. The relay has to decide whether to go for discriminatory or non-discriminatory pricing scheme. However, the relay’s decision of discriminatory price may not be in favour of sources with higher demand as it would get less power with more price. The willingness of sources for the type of pricing scheme and choice pricing scheme by the relay depend on urgency of cooperation to sources and monopoly of the relay. If there exists more relay, the relay may switch to uniform price to attract source with high demand.

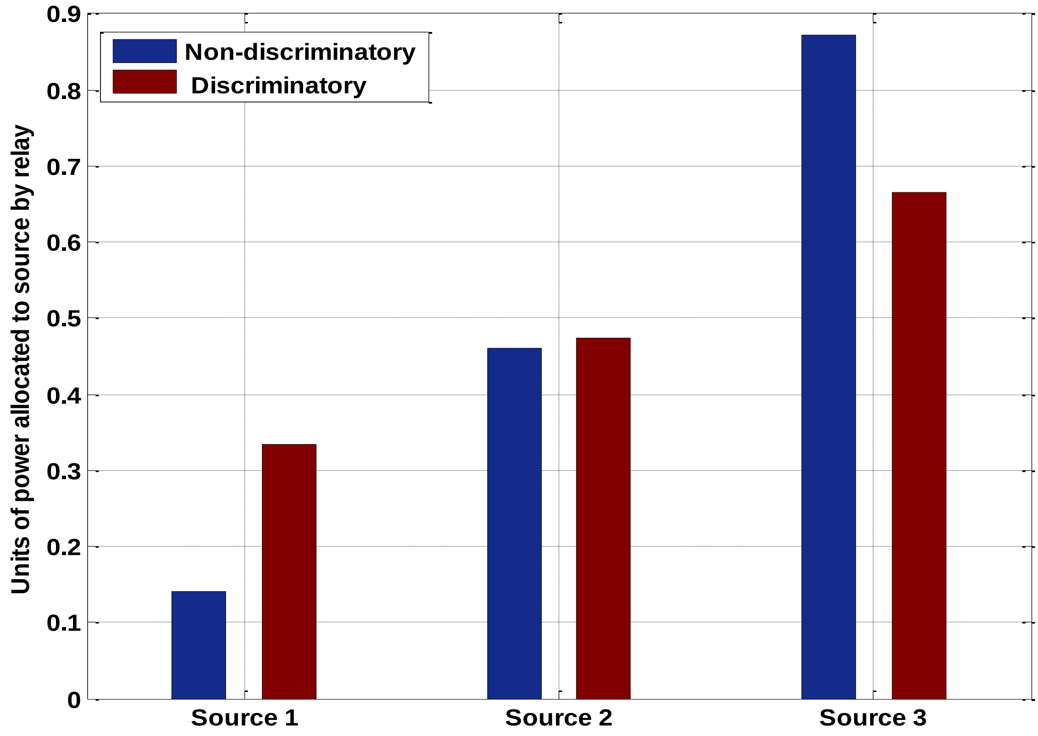


Fig 4.7 Power allocated under non-discriminatory and discriminatory schemes

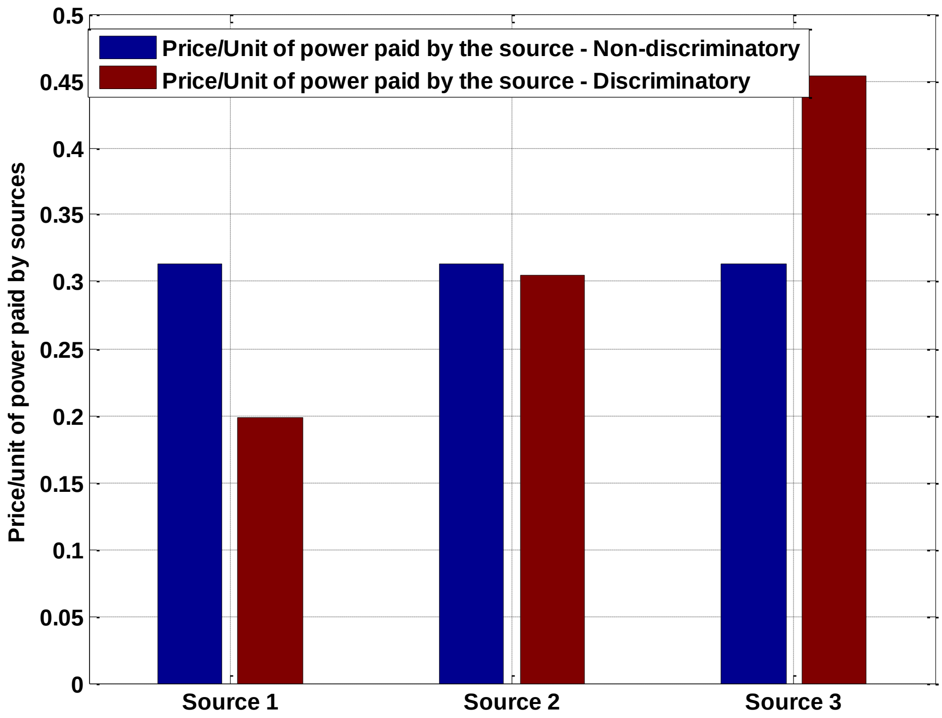


Fig 4.8 Price / unit of power paid by the each source

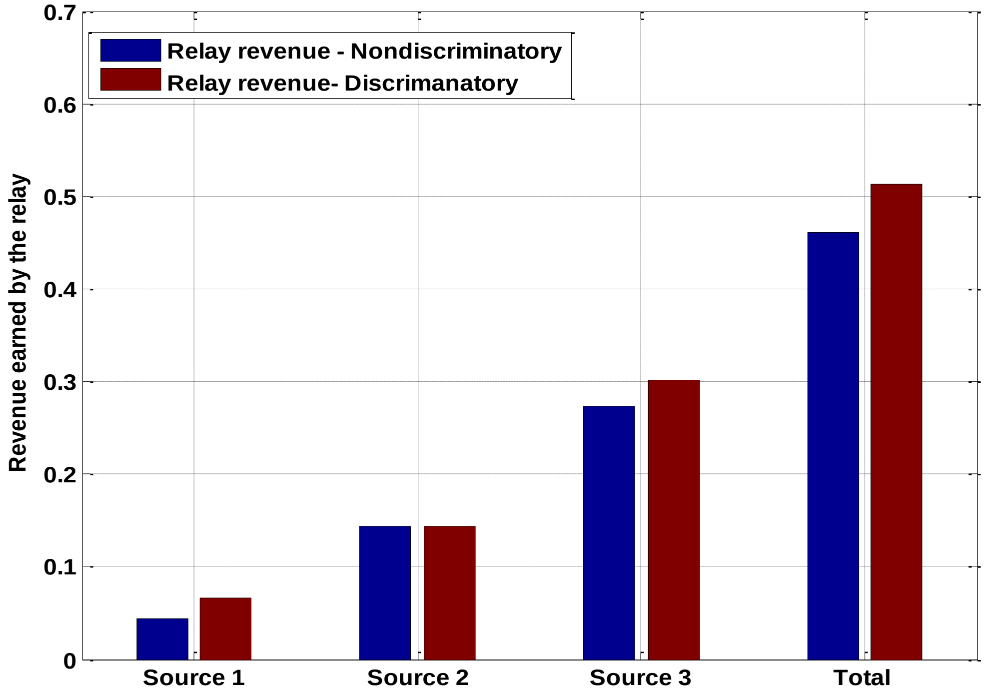


Fig 4.9 Revenue earned by the relay

4.4.6 Analysis of Source Power Saving

The cooperation between the sources and the relay results in saving of the power. It is assumed that all the sources have limited power of 1 unit. The sources try to achieve their target data rate with the help of relay. The relay allocates power to each of them to maximize own revenue. The amount of power allocated by the relay for retransmitting the source signal would result in higher data rate compared to no-cooperation data rate. Total power spent in cooperative mode is source power of 1 unit plus relay power. If relay does not cooperate with source and source attempts to achieve the data rate same as its cooperative data rate on its own, it has to spent more power. The source has two choices: either to transmit more power or to buy help of the relay. If source chooses the second option, it can save power. The saving of the power by the source extends its battery life and reduces interference in the network. Table 4.1 shows the saving of power with the units of the power assigned in non-discriminatory pricing scheme and discriminatory pricing scheme.

Table 4.1 Power saving in case of cooperative communication

Source	Power required to achieve data rate with Non-Discriminatory Pricing, Units			Power required to achieve data rate with Discriminatory Pricing, Units		
	Non-cooperation	Cooperation	Saving with cooperation %	Non-cooperation	Cooperation	Saving with cooperation %
1	1.46	1.14	21.9%	1.95	1.33	31.8%
2	2.22	1.46	34.2%	2.25	1.47	34.7%
3	2.22	1.87	15.8%	2.25	1.87	16.9%

In the case of non-discriminatory pricing, the relay allocates 0.14 units to source 1, 0.46 units to source 2 and 0.87 units to source 3. Therefore, total power spent in cooperation is 1.14 units, 1.46 units and 1.87 units by source 1, source2 and source 3, respectively. With that the sources achieve 0.13, 0.19 and 0.24 units, respectively. The sources have to spend power 1.46 units, 2.22 units and 2.22 units, respectively to achieve the same data rate in non-cooperation mode. As a result, source 1, source 2 and source 3 are able to save 21.9%, 34.2% and 15.8% of the power. Similarly, with the discriminatory price, the sources achieve data rate of 0.17, 0.19 and 0.22 units for which they need 1.95 unit, 2.25 unit ad 2.25 unit of power in non-cooperation mode. In cooperation mode, the sources get cooperation of 0.33 unit, 0.47 unit and 0.87 unit from the relay. As a result, source 1, source 2 and source 3 successfully save 31.8%, 34.7% and 16.9% of power.

4.4.7 Analysis of Effect of Node Mobility on Resource Allocation

In the mobile environment, the location of node and hence the distance between the nodes changes frequently. This in turn affects the channel and thereby the aggregate demand and power allocation. To demonstrate the effect of mobility on the power allocation and revenue clearly, two sources with equal target data rate are considered. One source is located at the normalized distance of 25 units from the destination. Another source is assumed to move 22 units to 28 units from the destination. The distance between the relay and both the sources are assumed to be constant. Fig 4.10 shows the aggregate demand curve and revenue maximizing allocation for different positions of the moving source. As one of the source moves away, its demand for relay power to achieve target increases thereby reduces the slope of the aggregate demand curve. When the demand of one source is high, relay could maximize its revenue by allocating 1.08 units of power at 0.37 unit price per unit of power. On the other hand, when that source comes closer, relay could maximize the revenue by allocating 0.79 units of power at 0.22 unit price per unit of power.

As far as, revenue maximization is concerned, relay tries to choose discriminatory pricing. Discriminatory pricing ensures that even when both the sources having same target data rate and same distances with relay, relay would not get less revenue than that with non-discriminatory pricing scheme. If the relay has monopoly, it would charge as per discriminatory pricing. In the scenario, when more relays are ready to help the sources, a relay can attract sources by choosing non-discriminatory pricing scheme.

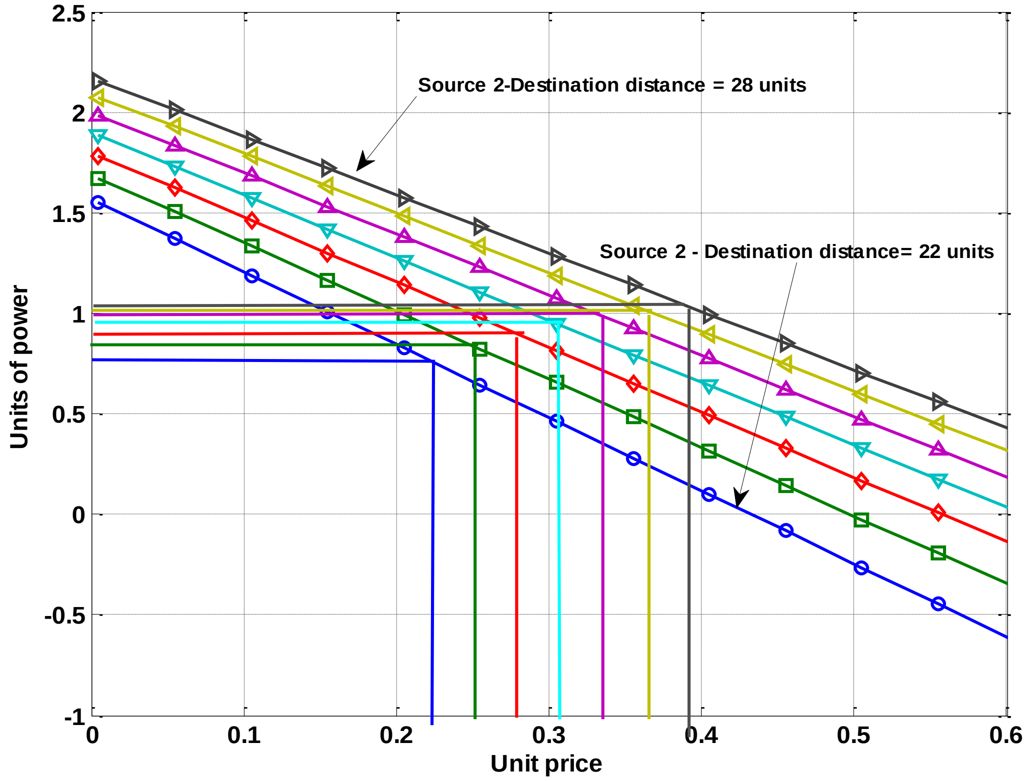


Fig 4.10 Revenue maximizing allocation with one source moving

4.4.8 Comparison of Computational Complexity

The computational complexity of the proposed technique is less compared to classical ascending or descending clock auction (Wang). In clock auction technique, the sources send their bids to demand number of units of power. If the units demanded by all the sources are more than available power with relay, relay increases the price. In next iteration, the sources generate their new demand at the increased price and again relay checks for available units and revenue generated. If the units demanded by the sources are less than the available units of power with relay, the relay decrease the price in order to increase the demand of the sources. The price is increased or decreased in steps. The time taken to click the deal between the sources and the relay depends upon the difference between the available power with the relay and demand of the sources and the step size in which the price increases or decreases. In order to maximize the revenue, the computational complexity required in clock auction is of the order of $O(N) * I(\varphi)$ where, N is the total number of nodes and $I(\varphi)$ is the number of iteration as a function of step size (φ). In proposed technique, the relay does not try to sell all the units of power. The efforts of selling all the units of power incurs delay due to rounds of negotiations. The demand of the source changes continuously due to time varying wireless channel and mobility. Power available with the relay also reduces as it spends power to cooperate with sources. In such situation, the proposed technique, relay allocates power in single shot and the sources improves the data rate compared to no-cooperation mode. The sources cannot reach the target data rate with the help of only one relay. However, the sources may buy power from more than one relay to reach the target data rate. The computational complexity of this sub-optimal negotiation process is of the order of $O(1)$. Thus, substantial reduction in computational complexity is achieved in the proposed technique.

4.5 Conclusion

Semi distributed multi-unit auctioning technique based cooperation stimulation has been presented in this chapter. The objective of power allocation is to maximize the revenue earned by the relay in form of the virtual currency and thereby encourages it to stick to cooperation. The node which acts as relay maximizes its revenue by allocating units of power to sources for retransmitting their signal. From the implementation point of view, sources in need of cooperation are required to compute and convey only two parameters α_i and β_i to relay, based on which relay decides the units of power to be allocated to sources and corresponding prices. The transaction of virtual currency and updating of accounts of the nodes is the only task done by the central controller. Two pricing schemes have been considered – Non-discriminatory and discriminatory. Simulation results shows an increase in source data rate compared to direct transmission in the range of 30.2 % to 63.1% in case of non-discriminatory pricing scheme and 47.2% to 59.3% in discriminatory pricing scheme. Non-discriminatory scheme assigns power in proportion of the demand of the source whereas discriminatory pricing scheme assigns power to minimize the difference between the maximum and minimum achievable data rate by the sources. For the system model considered for simulation, the relay could earn 11% more revenue in case of discriminatory pricing scheme. The sources are able to save 15.8% to 34.2% power in case of non-discriminatory and 16.9% to 34.7% power in case of discriminatory pricing scheme. There would be no difference in revenue if two sources having the same channel condition demand the same power from the relay. The computational complexity of this technique is of the *O (1)* and is substantially low as compared to that of clock auctioning technique. The allocation approach presented in this chapter can be easily applied to fixed data rate users where relay helps only some sources whose demand can be fulfilled completely. The remaining sources are denied the cooperation.

Chapter 5

Power-Bandwidth Exchange Based Resource Allocation for Distributed Cooperative Network

Pricing approach for resource allocation and cooperation encouragement has been presented in the previous chapter. Another powerful approach to bind nodes in cooperation is to make pair of nodes having complementary resource and allow them to exchange their resource to enhance performance of both. This mechanism is applicable in self-organizing adaptive network, where nodes are capable to estimate amount of exchange for cooperation and reassign its resources to others. In order to make the cooperation completely independent and distributed process, resource exchange mechanism is proposed in this chapter.

5.1 Resource Exchange for Cooperation

The essence of cooperative communication lies in the mechanism in which the nodes cooperate with each other without any external force. A scenario can be assumed where the nodes evaluate their own shortcoming and find out partner having complementary need in the vicinity. Both the nodes interact with each other and determine the amount of resource to be exchanged. This type of exchange is beneficial to both of them and therefore, they would remain in cooperation as long as they find benefit. This mechanism demands decision making capability and adaptability in the nodes. Wireless nodes in the advanced network possess higher processing power. They can be programmed to take decision to manage the resources to achieve better performance and save resources. Such nodes form a pair having complementary resource and share the resource owned by them with their partner. Thus, they remain in cooperation without the need of any outside stimulation like pricing, credit or reputation. Success of this cooperation scheme depends on target performance metrics, channel gains between each node pairs, power availability, and bandwidth and/or time slot availability in the network. The proposed framework takes into account all these parameters for successful resource exchange based cooperation. For forming successful cooperative pair, nodes need to negotiate with each other and decide amount of resource to be exchanged within the limit of availability of resource.

The exchange of resource can be bandwidth and / or time slot with power (Simeone) (Toroujeni) (D. R. Zhang) (Jayaweera) (Xu) or bandwidth with bandwidth (C. H. Zhang). With the emergence of advanced wireless communication networks like cognitive radio, device to device (d2d) communication and heterogeneous network, it is expected that the wireless node would communicate even when the node is unlicensed or out of the coverage of parent network. In this scenario, exchange of bandwidth and/or time slot with retransmission power (relaying) seems more practical. However, the concept of exchange of bandwidth with bandwidth or power with power is also possible. In this chapter, the exchange of bandwidth/time division with relaying power is undertaken. A node in need of extra bandwidth puts forward the offer of relaying power to retransmit information of other node in exchange of bandwidth. In this mechanism, nodes themselves would take decision about optimum resources to be employed in cooperative mode to meet individual targets. Nodes require to know only the local channel state information and make quick decision about feasibility of cooperation in their vicinity.

The success of this mechanism lies in finding the suitable partner, in the vicinity, with suitable interdependent need of resource. Our objective is to design distributed, low overhead resource exchange mechanism to search suitable partner and determine the amount of resource to be exchanged. A simplified and one-shot negotiation procedure is developed in this chapter where nodes can reach a deal of resource exchange quickly and accurately. Proposed framework stimulates and binds the nodes in cooperation, saves energy, increases data rate and hence proves to be resource efficient.

Futuristic wireless network consisting of variety of nodes, engaged in delay tolerant applications is considered in this proposal. Nodes make the pair in their vicinity to exchange bandwidth with relaying power. This exchange results in improved coverage, enhanced data rates and power saving of the nodes in the network. Proposed mechanism is suitable for d2d communication, ad hoc network and cognitive radio network where nodes are delegated the power to make decisions about routing, data handling, resource management, packet forwarding etc.

5.2 System Model

A futuristic wireless network consisting of $i,\ i \in \{1, 2,..,M\}$ self-organizing nodes ready to share bandwidth/time acting as source nodes and $j, j \in \{1,2,\ldots,N\}$ self-organizing nodes ready to become relay is considered. The destinations of source nodes and relay nodes are assumed to be different. The nodes are capable of making the decision of cooperation, degree of cooperation and resource optimization by sensing the channel locally. The network nodes are considered to employ Amplify and Forward (AF) protocol of cooperative communication. However, the mechanism is applicable to Decode and Forward (DF) protocol as well.

Fig 5.1 represents a typical scenario of *i* source nodes communicating with their destination *Ds* and *j* relay nodes want to communicate with their destination *Dr*. *Ds* and *Dr* can be the same node. Source nodes want to achieve data rate R_{si}^{tar} with *W* units of bandwidth allocated to them.

With limited power and bad channel condition, it is not possible to achieve target data rate on its own. Hence, source nodes seek cooperation of relay to retransmit and take benefit of diversity combining at the destination, *Ds*. Relay nodes, having their target data rate R_{rj}^{tar}, can be unlicensed nodes of cognitive radio or nodes out of coverage from parent network or nodes involved in d2d communication. Such nodes are in need of spectrum to carry on their own communication with destination *Dr*. Such nodes would be involved in exchange with offer of power to retransmit in exchange of a fraction of bandwidth.

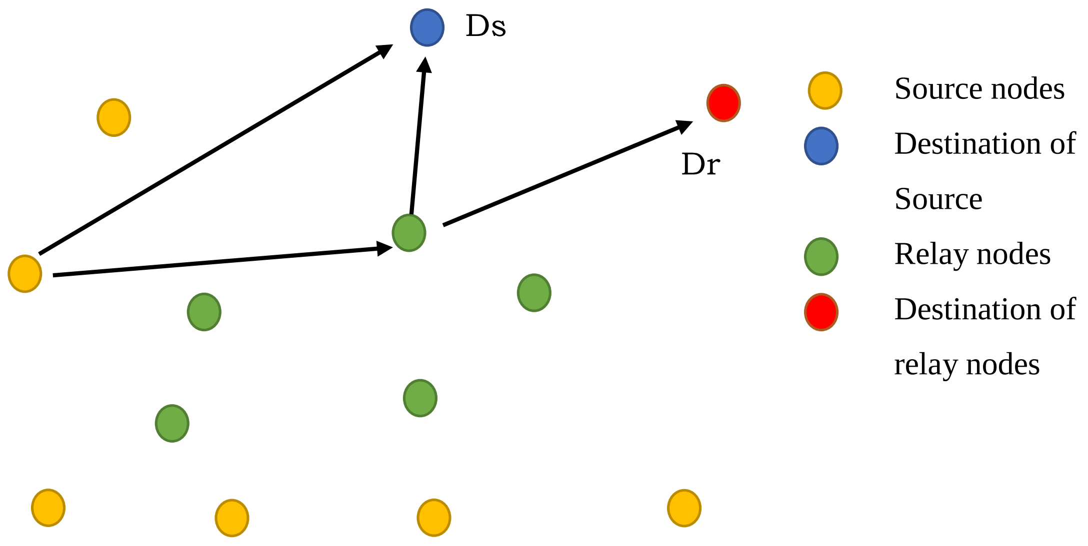


Fig 5.1 System Model for M sources and N relays

Table 5.1 Notations

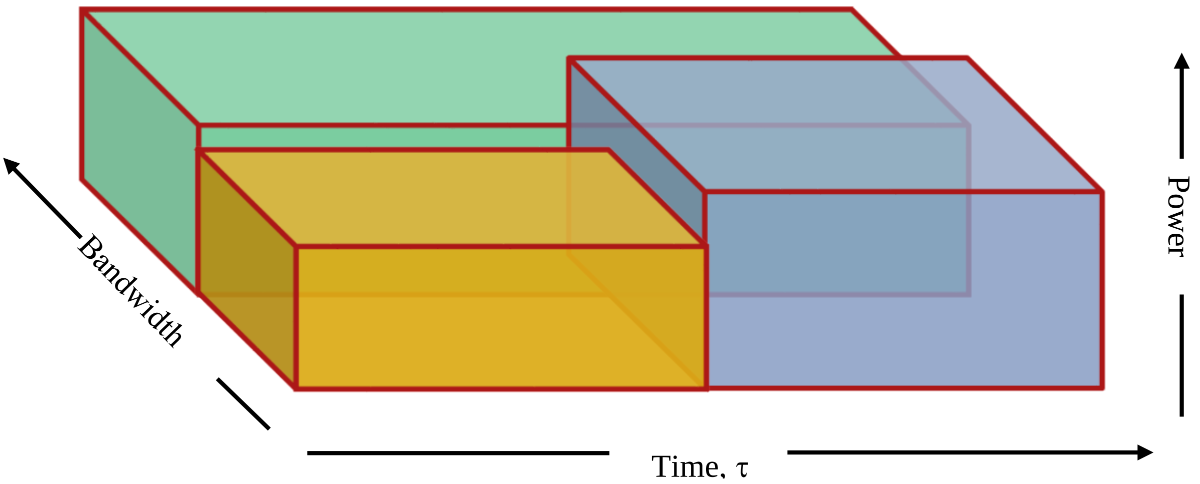
Notation	Meaning
$\boldsymbol{R_{si}^{NC}}$	Data rate achieved by source i without cooperation
$\boldsymbol{R_{si}^{tar}}$	Target data rate of source i with resource exchange
$\boldsymbol{R_{si}^{C}}$	Data rate achieved by source i with cooperation
$\boldsymbol{R_{rj}^{NC}}$	Data rate achieved by relay j without cooperation
$\boldsymbol{R_{rj}^{tar}}$	Target data rate of relay j with resource exchange
$\boldsymbol{R_{rj}^{C}}$	Data rate achieved by relay j with cooperation
$\boldsymbol{h_i^{SDs}}$	Channel gain of source-destination of source link of source i
$\boldsymbol{h_{ij}^{SR}}$	Channel gain of source-relay link of source i
$\boldsymbol{h_j^{RDs}}$	Channel gain of relay-destination of source link
$\boldsymbol{h_j^{RDr}}$	Channel gain of relay-destination of relay link
$\boldsymbol{\Gamma_i^{SDs}}$	Signal to noise ratio of source-destination of source link of source i
$\boldsymbol{\Gamma_i^{SR}}$	Signal to noise ratio of source-relay link of source i
$\boldsymbol{\Gamma_i^{RDs}}$	Signal to noise ratio of relay-destination of source link of source i
$\boldsymbol{\Gamma_j^{RDr}}$	Signal to noise ratio of relay-destination of relay link of relay j
$\boldsymbol{\Gamma_i^{AF}}$	Signal to noise ratio of S-R-DS two hop AF cooperative link
$\boldsymbol{\Gamma_i^{DF}}$	Signal to noise ratio of S-R-DS two hop DF cooperative link
$\boldsymbol{P_{Si}}$	Power transmitted by source i
$\boldsymbol{P_{si}^{NC}}$	Power required by source i to reach target without cooperation
$\boldsymbol{P_{Rj}^{total}}$	Power available with relay j
$\boldsymbol{P_{RS_{ji}}}$	Relay power used for re-transmission of source signal
$\boldsymbol{P_{RR_{jj}}}$	Relay power used for own transmission
$\boldsymbol{W_{si}}^{\boldsymbol{total}}$	Bandwidth available with source i
$\boldsymbol{W_{si}}$	Bandwidth used by source i for own transmission
$\boldsymbol{W_{rj}}$	Bandwidth allocated to relay j in exchange of cooperation
$\boldsymbol{W_{si}^{min}}$	Minimum bandwidth needed by the source i for given $P_{RS_{ji}}$
$\boldsymbol{n_R, n_D}$	Additive White Gaussian Noise at relay and destination with variance σ_R^2 and σ_D^2, respectively
$\boldsymbol{\tau}$	Time slot allocated to source for its transmission
$\boldsymbol{\beta}$	Fraction of time τ during which source transmits in phase I $(0 < \beta < 1)$
$\boldsymbol{\alpha}$	Fraction of power P_{Rj}^{total} used for re-transmission of source signal
$\boldsymbol{\gamma}$	Path loss exponent (=3)
$\boldsymbol{N_0}$	Average noise power
$\boldsymbol{\psi}$	Energy saving of source

5.3 Bandwidth-Power Exchange Mechanism

Source i is allocated bandwidth W units for time slot of τ unit. Source i realizes that $R_{si}^{NC} < R_{si}^{tar}$. The source is unable to achieve target data rate of R_{si}^{tar} without cooperation. On the other side, a node j is deprived of bandwidth and wants to achieve data rate of R_{rj}^{tar}. The procedure of determining suitable partner is initiated by either source or relay, as discussed in section 5.5. The source offers bandwidth W_{rj} ($< {W_{si}}^{total}$) to the relay as an incentive for retransmitting information of the source. Source decides to transmit in W_{si} ($= {W_{si}}^{total} - W_{rj}$) bandwidth.

The bandwidth W_{si} is divided in two parts in time slot of duration, τ as shown in Fig 5.2. In $(1-\beta)$ fraction of time slot, the source transmits its own signal. The relay receives it, amplifies, and forwards it in remaining β fraction of the time slot τ *($0 < \beta < 1$).* The source transmits only on W_{si} bandwidth for $(1-\beta)$ fraction of the time slot. The relay transmits own signal on bandwidth W_{rj} for the entire time slot and the signal of the source on bandwidth W_{si} for β fraction of the time slot. In this way, the relay allocate transmission power for relaying source's signal in exchange of the bandwidth.

In proposed exchange mechanism, a relay is ensured a fraction of bandwidth for full duration of time slot, which in turn, ensures target data rate to the relay. Source can save significant amount of energy in proposed technique by transmitting in fraction of the bandwidth for fraction of the time only. One source and one relay are involved in exchange so both the nodes get significant amount of benefit in terms of data rate and energy saving for source node and spectrum for transmission for relay node. Moreover, this technique needs less overheads as it requires only the local channel state information. A mathematical modelling of the proposed resource exchange scheme is presented in following subsection.



Source transmits in W_{si} $(=W_{si}{}^{total} - W_{rj})$ in time $(\beta * \tau)$ with power P_{Si}

Source transmits in W_{si} $(=W_{si}{}^{total} - W_{rj})$ in time $(1-\beta) * \tau$ with power $P_{RS_{ji}} = (\alpha * P_{Rj}^{total})$

Source i assigns bandwidth W_{rj} to relay for entire time, τ. Relay j transmits own information at power $P_{RR_{jj}}$

Fig 5.2 Bandwidth-power exchange mechanism

5.3.1 Data Rate of Source with and without Cooperation

Source i has bandwidth $W_{si}{}^{total}$ unit available for time τ and power P_{Si}. It wants to achieve the data rate of R_{si}^{tar} units. Maximum data rate that source i can achieve at a given instant depends on signal to noise ratio of the given source *S* - destination of source *Ds (S-Ds)* link. Achievable data rate without cooperation can be given as

$$R_{si}^{NC} = W_{si}{}^{total} * \log 2 \,(1 + \Gamma_i^{SDs}) \tag{5.1}$$

where, Γ_i^{SDs} is signal to noise ratio $(= \frac{P_{Si}\, h_i^{SDs}}{N_0})$ and h_i^{SDs} is the channel gain of *S-Ds* link.

If data rate without cooperation, $R_{si}^{NC} < R_{si}^{tar}$, source decides to cooperate with relay by sparing W_{rj} bandwidth, a fraction of total bandwidth $W_{si}{}^{total}$, and use it to attract suitable relay. After sparing W_{rj}, the bandwidth available with the source for its own transmission is $W_{si} = W_{si}{}^{total}$ - W_{rj} . The source finds the relay and determines the amount of resource to be exchanged. Detail mechanisms for resource exchange are presented in following sub-sections. The cooperative transmission is carried out in two phases:

(1) In phase I of time duration ($\beta * \tau$), source transmits in bandwidth W_{si} with power P_{Si}.

(2) In phase II of time duration 1-($\beta * \tau$), relay re-transmits the amplified version of the signal in W_{si} bandwidth using power $P_{RS_{ji}}$.

The relay transmits own signal on W_{rj} bandwidth, which is spared by the source as an incentive, at power of $P_{RR_{jj}}$. Destination of source receives the signal from source in phase I and from the relay in phase II and combines them using Maximal ratio combining (MRC). For simplifying the process at the relay, the time slot is divided in two equal parts by setting β = 0.5. However, any other value of β can be considered when relay applies decoding and re-encoding the signal at different rate. Signal to noise ratio of two hop channel through relay can be given as,

$$\Gamma_i^{AF} = \frac{1}{N_0}\left(\frac{P_{Si}\left|h_i^{SR}\right|^2 * P_{RS_{ji}}\left|h_j^{RDs}\right|^2}{P_{Si}\left|h_i^{SR}\right|^2 + P_{RS_{ji}}\left|h_j^{RDs}\right|^2 + N_0}\right) \tag{5.2}$$

Data rate achieved by Amplify and Forward protocol at relay and MRC at destination can be given as,

$$R_{si}^{C} = 0.5 * W_{si} * \log 2 \left(1 + \Gamma_i^{SDs} + \Gamma_i^{AF}\right) \tag{5.3}$$

In (5.3), 0.5 indicates that source and relay transmit for equal half of the time slot by setting β = 0.5. The value of $P_{RS_{ji}}$ in (5.2) and W_{si} in (5.3) are determined by source and the relay during the cooperation establishment process so that $R_{si}^{C} \geq R_{si}^{tar}$.

5.3.2 Determination of Bandwidth W_{rj} and W_{si}

The source and relay nodes are interested in achieving the data rate more than or equal to R_{si}^{tar} and R_{rj}^{tar}, respectively. Both the nodes would participate in cooperation, if the bandwidth offered by the source and re-transmission power offered by the relay are sufficient for the nodes to achieve their targets. Division of bandwidth between source and relay is within the constraint of maximum available bandwidth of ${W_{si}}^{total}$ of the source. Similarly, the relay spares power for retransmitting source's signal, $P_{RS_{ji}}$ and power for own transmission, $P_{RR_{jj}}$. Sum of these both cannot be more than available total power P_{Rj}^{total}.

Minimum bandwidth required by the source, W_{si}^{min} to reach target can be given by substituting $R_{si}^{C} = R_{si}^{tar}$ in (5.3) and re-arranging,

$$W_{si}^{min} = \frac{2 * R_{si}^{tar}}{\log 2\left[1 + \frac{P_{Si}\left|h_i^{SDs}\right|^2}{N_0} + \frac{1}{N_0} * \left(\frac{P_{Si}\left|h_i^{SR}\right|^2 * P_{RS_{ji}}\left|h_j^{RDs}\right|^2}{P_{Si}\left|h_i^{SR}\right|^2 + P_{RS_{ji}}\left|h_j^{RDs}\right|^2 + N_0}\right)\right]} \tag{5.4}$$

In determination of minimum bandwidth in (5.4), source requires the knowledge of power with which relay would retransmit, $P_{RS_{ji}}$ and channel gains. Source offers remaining bandwidth, W_{rj} $(= {W_{si}}^{total} - W_{si})$ to relay. Relay uses this bandwidth for entire duration τ and transmits own signal with power P_{RR_j}. Relay calculates the maximum data rate achieved with this bandwidth based on its power budget.

$$R_{rj}^{C} = W_{rj} * log_2\left[1 + \frac{P_{RR_j}\left|h_j^{RDr}\right|^2}{N_0}\right] \tag{5.5}$$

As long as data rate with cooperation $R_{rj}^{C} \geq R_{rj}^{tar}$, cooperative transmission continues. Due to change in channel gains or reduction in available power or increase in target data rate, if cooperation data rate reduces below target data rate, cooperation seizes. The source node *i* and relay node *j* have to redistribute bandwidth and power to sustain cooperation. In the process of redistribution, if none of the combinations of bandwidth-power exchange seems feasible, the nodes have two options: (1) to continue cooperation with data rate less than target, and (2) to initiate the procedure for searching for partner.

5.3.3 Relay Power Budget and Source Power Saving

Relay has limited power P_{Rj}^{total} available with it. It uses power $P_{RR_{jj}}$ for its own transmission for τ duration and power $P_{RS_{ji}}$ to cooperate with source during τ/2 duration as shown in (5.4) and (5.5). Let relay spare α fraction of power P_{Rj}^{total} for source and use remaining (1- α) fraction for itself, *i.e.*

$$P_{RS_{ji}} = \alpha * P_{Rj}^{total} \text{ and } P_{RR_{jj}} = (1-\alpha) * P_{Rj}^{total} \qquad 0 < \alpha < 1 \qquad (5.6)$$

From (5.4), (5.5) and (5.6), it can be seen that possibility of cooperation between a pair of nodes depends on target data rate of both the nodes, available resources with both the nodes and channel gains between the nodes. These parameters are used to find matching partner.

Another motivation for the source node is to save the power by opting for cooperation. If the source *i* tries to achieve target data rate R_{si}^{tar} directly, it requires power P_{si}^{NC}. If power available with source is $P_{Si} < P_{si}^{NC}$, source opts for the cooperation of relay. Power required by the source in direct transmission to achieve the target can be given by re-arranging (5.1) as

$$P_{si}^{NC} = \frac{N_0}{|h_i^{SDs}|^2} * \left([2^{\left(R_{si}^{tar} / W_{si}{}^{total}\right)}] - 1 \right) \qquad (5.7)$$

In case $P_{Si} > P_{si}^{NC}$, then also source can choose cooperation mode to save energy. This exchange mechanism would result in saving of the energy for the source node. In direct transmission, the source node would spent power P_{si}^{NC} in ${W_{si}}^{total}$ units of the bandwidth for time duration τ, whereas in cooperative mode, it spend P_{Si} power in W_{si} units of bandwidth ($W_{si} < {W_{si}}^{total}$) for τ /2 duration only. Energy saving in cooperative mode compared to direct transmission can be given as

$$\psi = \left(P_{si}^{NC} * {W_{si}}^{total} * \tau\right) - (P_{Si} * W_{si} * \tau /2) \quad (5.8)$$

It is, therefore, in benefit of source to go for cooperation to save energy, if suitable relay is available in the vicinity.

5.4 Performance Evaluation and Discussion

Extensive simulation are carried out to evaluate the performance of the proposed mechanism. Amount of resource to be exchanged to fulfil the requirements of target data rate of source and relay is determined. The performance is tested over the random channel variations also to prove that the cooperation of this type is long lasting. Energy saved by the source node is calculated to emphasis on the benefit of cooperation.

5.4.1 Simulation Environment

To demonstrate the resource exchange mechanism, a four node network is considered as shown in Fig 5.3. Node *S* establishing the link with its destination *Ds* finds it difficult to reach target data rate using its available power. There is a node R, without any bandwidth resource, wants to communicate with its destination *Dr*. Such nodes make pair with each other using the procedure, discussed in section 5.5. The node with spectrum behaves as source node and node without bandwidth acts as relay to retransmit source node's signal in exchange of a fraction of bandwidth.

The distance between source S and relay R is 100 units, relay R and destination of source Ds is 100 units, source S and destination of source Ds is 200 units and relay R and destination of relay Dr is 150 units. For the sake of simplicity, path loss channel model with exponent 3 is assumed in which channel gain is inversely proportional to the distance between the nods. The relay is assumed to employ AF protocol. Source power P_S and relay power P_R^{total} are 2 units and 5 units respectively. Bandwidth available with Source is 10 units. Simulation model is presented in Fig 5.3.

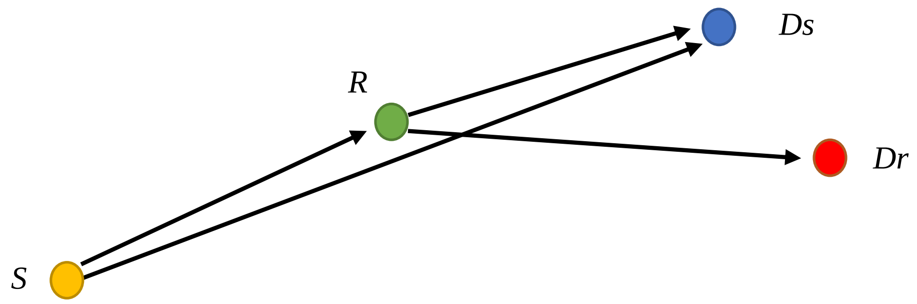


Fig 5.3 Simulation Model

5.4.1 Relay's Demand Curves for Different Target Data Rate of Source

The degree of cooperation depends on the resource available with nodes and their target data rates. If the source wants to achieve higher target of data rate and it has less power of its own, it wants relay to cooperate with more power. In turn, the relay wants large portion of bandwidth to remain in cooperation. Therefore, both the nodes have to reach to a compromise where both can achieve their individual target within the limitation of their resources. Fig 5.4 shows the exchange of relaying power P_{RS} with fraction of bandwidth W_r as a function of target data rate R_s^{tar} of the source. Source calculates minimum bandwidth required for own transmission W_s^{min} for a given value of P_{RS} using (5.4), and offer remaining bandwidth, W_r to relay as an incentive.

When source target data rate is 1bit/unit, source would offer bandwidth from 5.2 to 7.3 units in exchange of relay power from 1 to 4.5 units. When source target is 2 bits/unit, source keeps more bandwidth with it and offers bandwidth from 0.2 to 4.7 units in exchange of relay power from 1 to 4.5 units, respectively. Source offers more bandwidth if exchange of more power is reciprocated. The dark curve shows the demand of the relay for achieving its target data rate of 1 bit/unit. Intersection of the dark curve with the set of curves of source's offer indicates the possible resource exchange for cooperation for the given target data rate of the source and the relay.

5.4.2 Relay's Demand Curve for Different Target Data Rate of Relay

Similar situation from relay's perspective is demonstrated in Fig 5.5. When target data rate of relay is 0.7 bit/unit, it demands bandwidth form 1 to 6.5 in exchange of relaying power from 1 to 4.5. The demand of relay changes from 1.9 to 11.9 in exchange of relaying power from 1 to 4.5 for target data rate of 1.2 bits/unit. If relay's demand exceeds available resource with source, cooperation would not be possible. This issue is to be taken care while establishing the cooperation during negotiation process. The dark curve shows source's offer to relay and the intersection point is the possible resource exchange for successful cooperation.

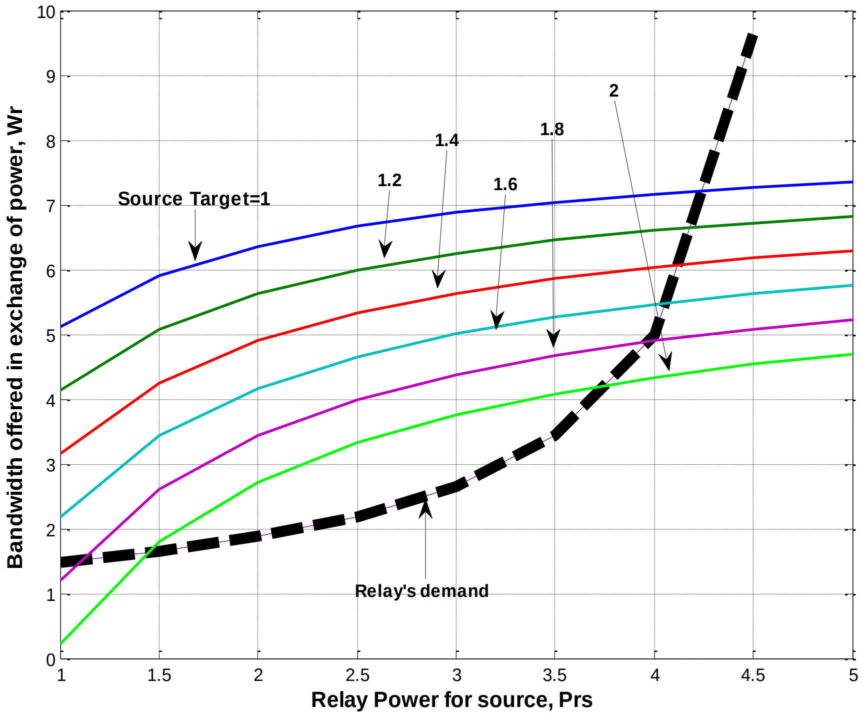


Fig 5.4 Relay power against bandwidth with relay target fixed at 1 bit / unit

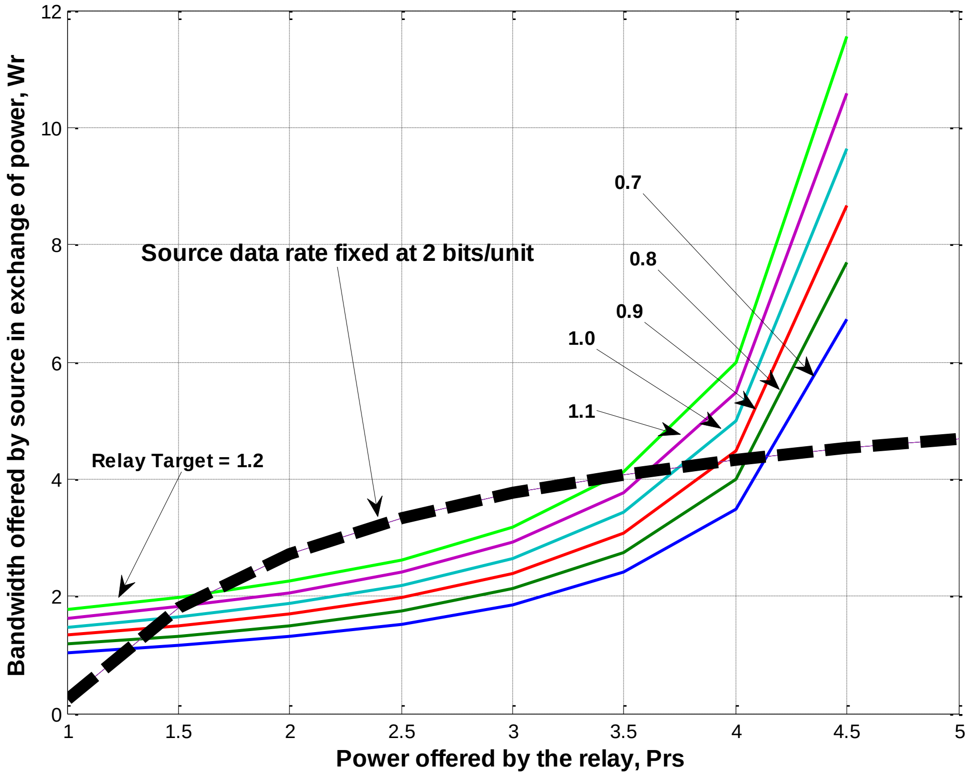


Fig 5.5 Offer of relay power for bandwidth for source target fixed at 2 bits/unit

5.4.3 Analysis of Range of Equilibrium of Resource Exchange

Relay offers $\alpha, (0 < \alpha < 1)$ portion of its power P_R^{total} to retransmit source's signal as mentioned in (5.6). The range of α for successful cooperation is depicted in Fig 5.5 for different values of relay target data rate. Without cooperation, the source is in position of achieving data rate of 1.7 bit/unit of bandwidth using own power P_S and bandwidth $W_S{}^{total}$ in direct transmission. It wants to get 2 bits/unit of bandwidth. Therefore, search for suitable relay to offer a fraction of bandwidth to engage it in cooperative re-transmission.

In turn, the relay promises to use $P_{RS} = \alpha * P_R^{total}$ for source signal re-transmission. Fig 5.6 shows data rate achieved by the source, when relay spares different portion of power in exchange of bandwidth. For example, if relay offers small amount of relaying power by setting α = 0.1 for source signal re-transmission and demands more bandwidth, source would not be able to achieve target data rate. Source can achieve the target for the range of α from 0.4 to 0.7, even if relay target changes from 0.8 to 1.2. This range of α provides stable cooperation.

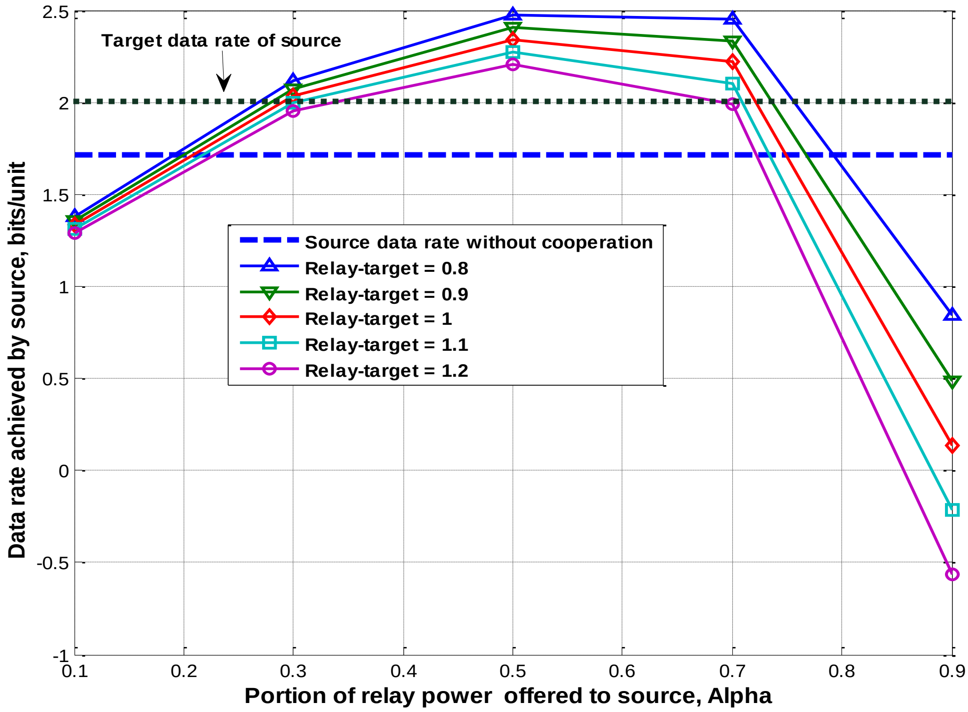


Fig 5.6 Range of equilibrium of resource exchange

5.4.4 Analysis of Energy Saving for Source

For the source node, the cooperation would result in saving of the energy as shown in (5.7) and (5.8). Suppose, the source node is not power constrained. To achieve target, it has to transmit more power per unit in W units of bandwidth for full time slot. In cooperative mode, it transmit less power for Ws < W units of bandwidth and for half of the slot (considering β = 0.5) as shown in Fig 5.2

By participating in cooperation, it could save energy to prolong its lifetime without recharging the battery. Fig 5.7 shows the power spent by the source in direct transmission mode and cooperative mode with respect to available source power, P_S for different degree of cooperation from the relay node. In direct transmission mode, the energy spend by the source linearly varies with available source power from 1 to 2 units. When relay node helps by sparing 0.2 portion of its power ($\alpha = 0.2$), energy consumed in cooperative mode varies from 8 units to 10 units as available source power varies from 1 unit to 2 unit.

For α = 0.8, source spends energy from 4.6 to 5.8 units as source power varies from 1 unit to 2 units. Source spends less energy of its own if α is large. This is because when α is small, relay cooperates with less power so it would get less bandwidth in exchange and source would be transmitting in large bandwidth so energy spent by the source is more compared with the case of large α. Therefore, the energy saving by the source varies between 21% to 54% for P_S =1 and 51.7% to 71.5% for P_S = 2.

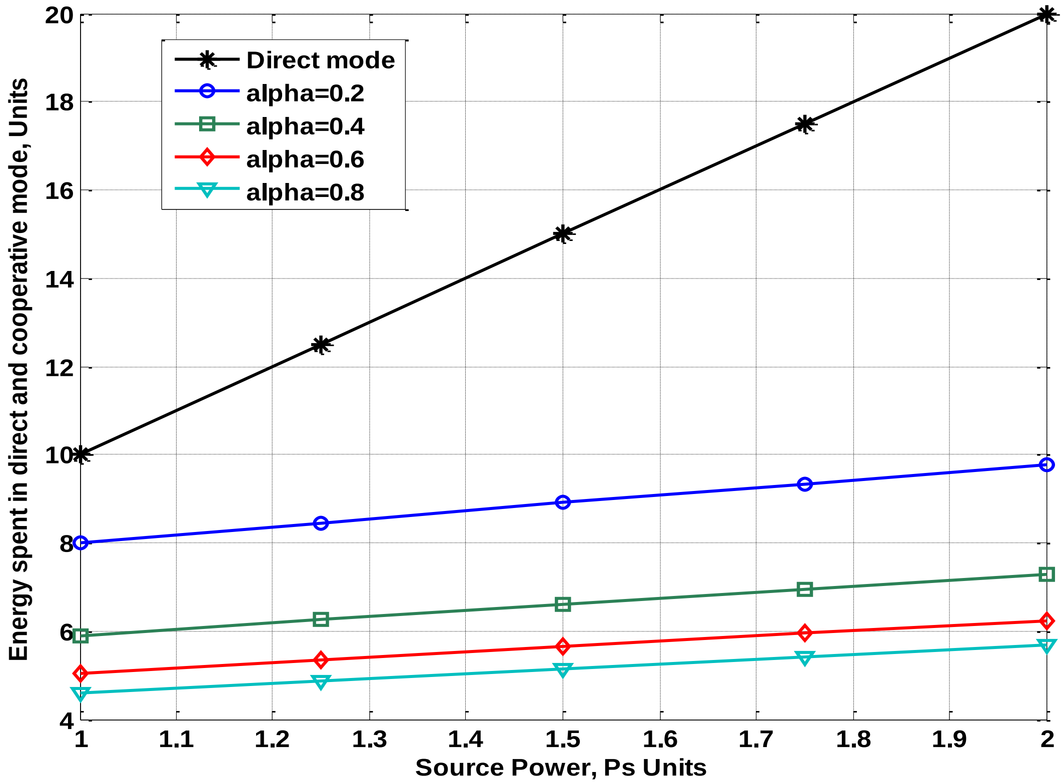


Fig 5.7 Energy spent by source node in direct mode and cooperative mode

5.4.5 Stable Cooperation in Case of Channel Variations

Exchange of resources for mutual gain depends on channel gain of inter-node links. When nodes are mobile, the change in their location causes channel gain to change. In this exchange mechanism, nodes stick to cooperative behaviour under the condition of mobility. For including the effect of mobility, channel model is modified. In path loss model, channel gain depends only on the distance as

$$\Gamma^{mn} \propto \left(\frac{d_0}{d_{mn}}\right)^{\gamma}, m \in \{S, R\} \quad n \in \{R, Ds, Dr\} \tag{5.9}$$

where, d_{mn} is distance between *m* and *n*.

To realize the effect of mobility, the model of (5.9) is modified as

$$\Gamma^{mn} \propto \left(\frac{d_0}{d_{mn}+\theta}\right)^{\gamma}, m \in \{S, R\} \quad n \in \{R, Ds, Dr\} \tag{5.10}$$

where, θ is random variable with zero mean and variance 10. The distance is assumed to be varied approximately +/- 10 units over the mean distance. Fig 5.8 and Fig 5.9 show the benefit of cooperation to source node in terms of higher data rate and energy saving considering the mobility of both the nodes for 100 random channel realizations. Even though the nodes are steady, wireless channel may face variation in channel gains. To realize the effect of time varying channel in path loss model, Rayleigh random variable with zero mean and different value of variances are added to channel gains between each node. Fig 5.10 and Fig 5.11 show the sustainability of cooperation even in time varying channel.

In Fig 5.8 and Fig 5.10, the dots show the direct data rate of source without cooperation. It is apparent that cooperation yields higher data rates compared to direct data rate even if the channel undergoes random variations for the value of α between 0.4 and 0.7. Exchange of relay power and source bandwidth is able to withstand channel variations and ensures long lasting cooperation. When channel is favourable, the source continue cooperative mode and save energy. Fig 5.9 and Fig 5.11 demonstrate the energy saving by the source under random channel variations based on (5.7) and (5.8) Energy saving is positive for the value of α between 0.4 and 0.7 in both the cases channel variations.

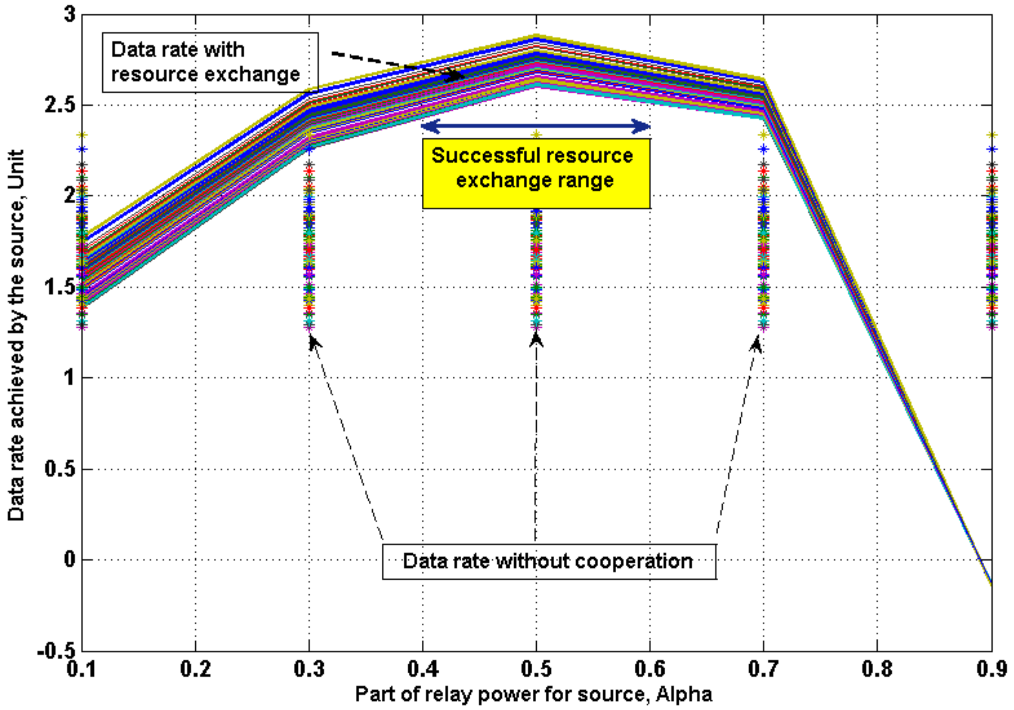


Fig 5.8 Source data rate with random variation in channel due to node movement

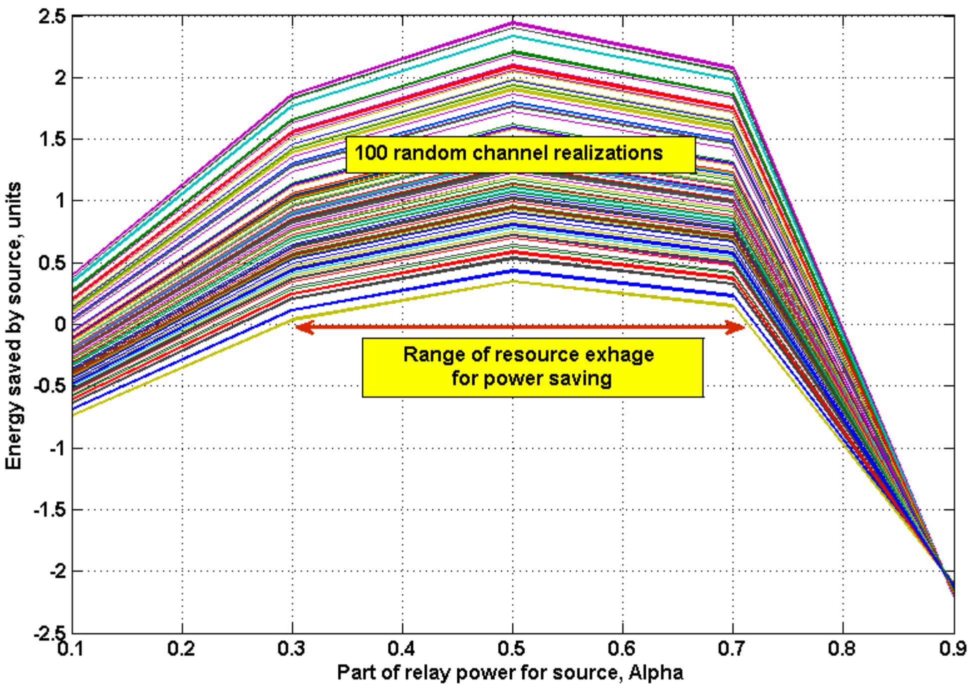


Fig 5.9 Source energy saving with random variation in channel due to node movement

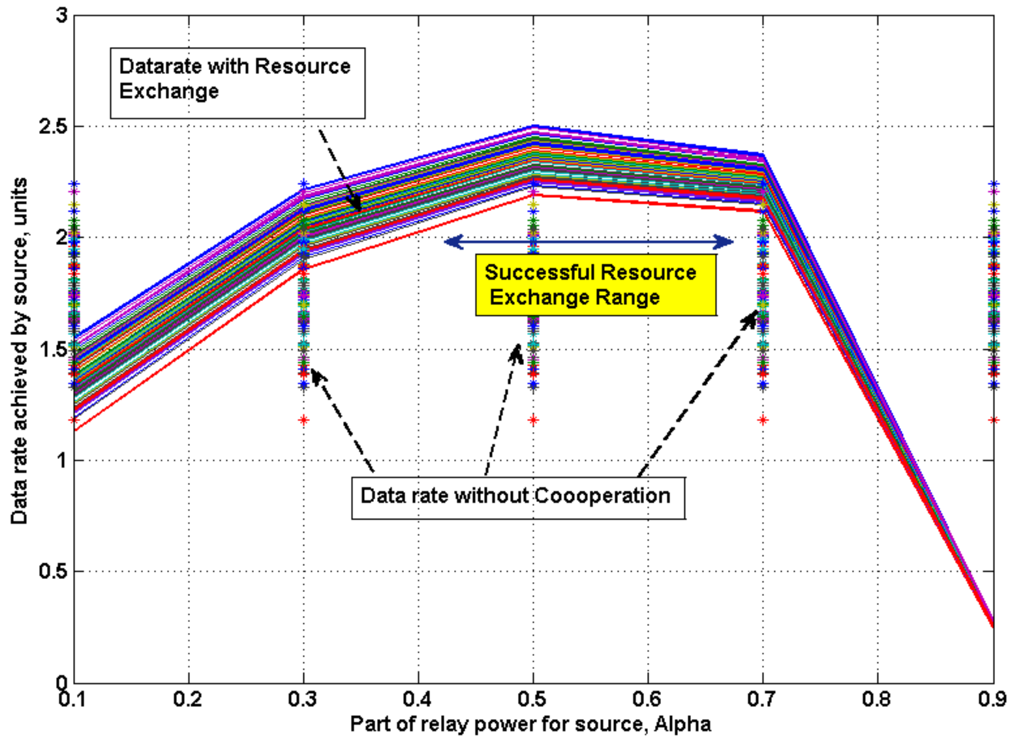


Fig 5.10 Source data rate achieved with random channel variations

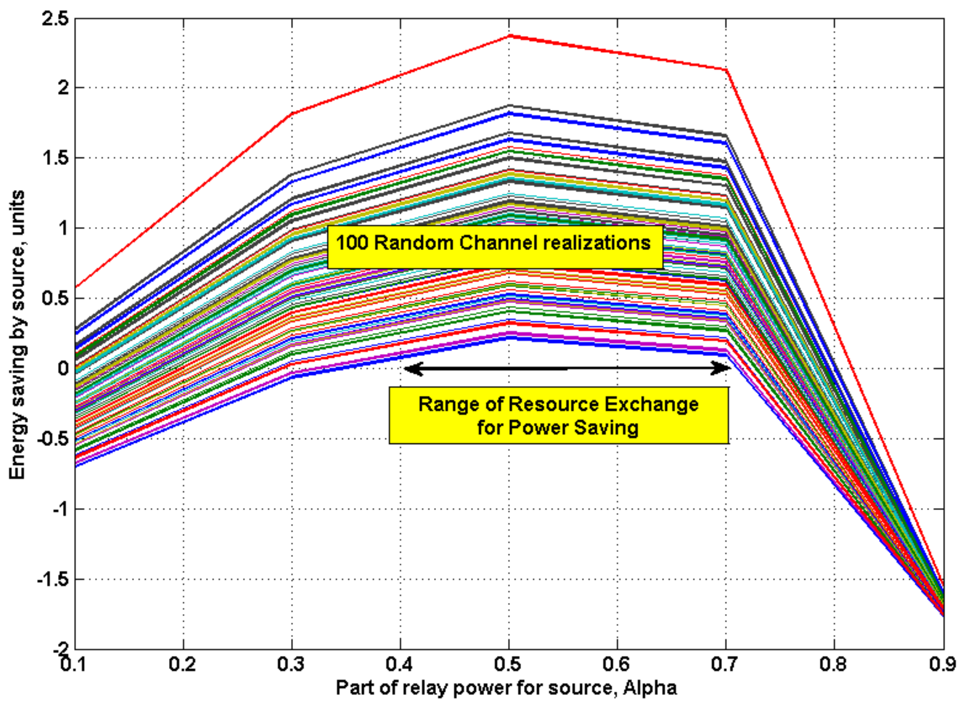


Fig 5.11 Source energy saving with random channel variation

In Fig 5.8 and Fig 5.10, the dots show the direct data rate of source without cooperation. It is apparent that cooperation yields higher data rates compared to direct data rate even if the channel undergoes random variations for the value of α between 0.4 and 0.7. Exchange of relay power and source bandwidth is able to withstand channel variations and ensures long lasting cooperation. When channel is favourable, the source continue cooperative mode and save energy. Fig 5.9 and Fig 5.11 demonstrate the energy saving by the source under random channel variations based on (5.7) and (5.8). Energy saving is positive for the value of α between 0.4 and 0.7 in both the cases of channel variations.

For ensuring long lasting cooperation and mutual benefit, matching of suitable source and relay is essential. In the next sub-section, iteration based conventional approach is discussed. A One-shot and accurate approach is also presented to make the match making process fast and low overhead.

5.4.5 Comparison with Other Exchange Techniques

Power-Bandwidth resource exchange techniques are found in (Simeone), (Toroujeni) and (D. R. Zhang). In Table 5.2, a comparison of the proposed exchange mechanism is done with these references. The mechanism in (Simeone), needs full channel state information. Moreover, many relays share the bandwidth of source for fraction of time. As a result, the relays cannot achieve higher data rate. In (Toroujeni), relay gets bandwidth for only fraction of time slot. The mechanism mentioned in (D. R. Zhang), source allocates a part of bandwidth to relay, in addition of the bandwidth possessed by the relay. Practically, it needs extra efforts to transmit in two different bands simultaneously. The proposed mechanism allocates a part of bandwidth for entire duration to the relay. It enables relay to utilize that part of the bandwidth as per its desire. The source restricts its transmission for fraction of the bandwidth for a fraction of time, which enable the source to save energy, in addition of getting higher data rate, by continuing resource exchange.

Table 5.2 Exchange mechanisms in literature

	Source transmission	Relay transmission	Limitation
(Simeone)	Whole bandwidth is used for fraction of time slot.	Remaining fraction of time slot is distributed among relays.	Full channel state information is required. Relay cannot achieve high data rate.
(Toroujeni)	Whole bandwidth is used for fraction of time slot.	For remaining time, the spectrum is shared between relay's own transmission and source re-transmission	Relay gets spectrum only for fraction of time slot
(D. R. Zhang)	Fraction of bandwidth is used for entire time slot.	Relay gets extra spectrum in addition to its own spectrum	Difficulty to transmit in two different spectrum at a given time
Proposed	Fraction of bandwidth for fraction of time slot	Fraction of bandwidth for entire time slot	---

5.5 Source-Relay Negotiation Procedure

In self-configuring, distributed, multi-node scenario, the node searches for the suitable partner in the vicinity. Equilibrium of resource exchange depends on channel gains, available resource and target data rates of both the nodes. For discussing the negotiation procedure, the presence and readiness of the tentative partner are assumed. The node having bandwidth resource dominates the negotiation procedure by taking the initiative. The node acting as a source node proposes a fraction of the bandwidth to get relaying power offers from the relay nodes. The iterative procedure for step-by-step negotiation of resource exchange is presented in Fig 5.12. Source initiates by offering small fraction, say 0.1 of bandwidth.

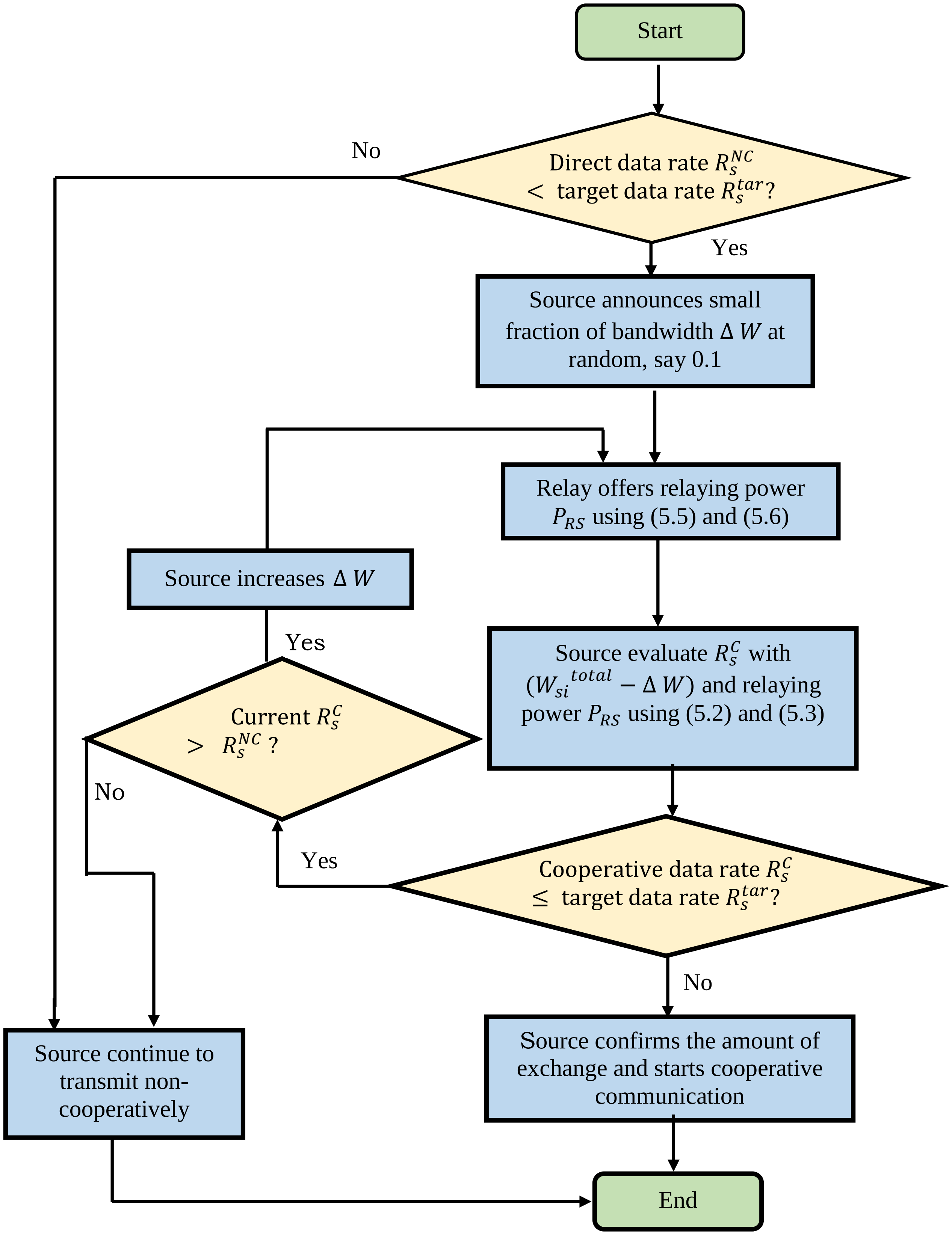


Fig 5.12 Iterative negotiation procedure

Relay calculates the amount of power that can be spared at that bandwidth using (5.5) and (5.6). Source confirms quantity of resources exchanged, if it is acceptable to it. Otherwise, source offers more bandwidth to get more relaying power. Offering of larger fraction of bandwidth would not result in increased data rate as depicted in Fig 5.5. Then, source prefers to communicate non-cooperatively. The iterative negotiation procedure depicted in Fig 5.12 is time consuming and requires more overheads. A one-shot, accurate, and low overhead negotiation procedure is presented in Fig 5.13. In this approach, the node interested to become relay initiates the procedure by revealing its parameters in terms of 3-tuple $(R_r^{tar}, h^{rDr}, P_R^{total})$. In this negotiation procedure, the relay reveals its parameters in terms of a tuple $(R_r^{tar}, h^{rDr}, P_R^{total})$ at the beginning of frame or at regular interval of time. To get the exchange deal done with the source, the relay has to reveal its true parameters. Otherwise, the relay would not get benefit of cooperation. For example, if the relay declares high target data rate R_r^{tar} in order to get more bandwidth from the source, the source would demand high relaying power in return. If the relay demands higher than the requirements, it may not be selected by any source. After receiving relay parameters, the source calculates P_{RS} considering possible values of W_r. P_{RS} can be calculated by re-arranging (5.5) and applying power budget as $P_R^{total} \geq P_{RR} + P_{RS}$.

$$P_{RS} = P_R^{total} - \frac{N_0}{|h^{RDr}|^2} * \left(2^{\left(\frac{R_r^{tar}}{W_r}\right)} - 1\right) \tag{5.11}$$

Source calculates required minimum of bandwidth W_{si} by inserting P_{RS} calculated in (5.11) in (5.4). Source also checks if available bandwidth is sufficient or not to cater the own requirement and relay's requirements as ${W_s}^{total} \geq W_s + W_r$. There may be more than one value of (W_r, P_{RS}) to ensure mutual benefit in cooperation. Then source has to select any one value of (W_r, P_{RS}). Suppose cooperation is possible for two values of $W_r - W_{r1}$ and W_{r2} such that $W_{r1} < W_{r2}$. The source may offer smaller bandwidth for keeping large portion for itself or offer larger bandwidth to get more relaying power and save own energy. The source confirms amount of exchanged resources and cooperative phase begins. This technique requires very less overhead to reach mutually acceptable deal. Also, it reaches the final deal in single shot. Both the node, need only local channel state information and simple computation. These features make the technique suitable for distributed network.

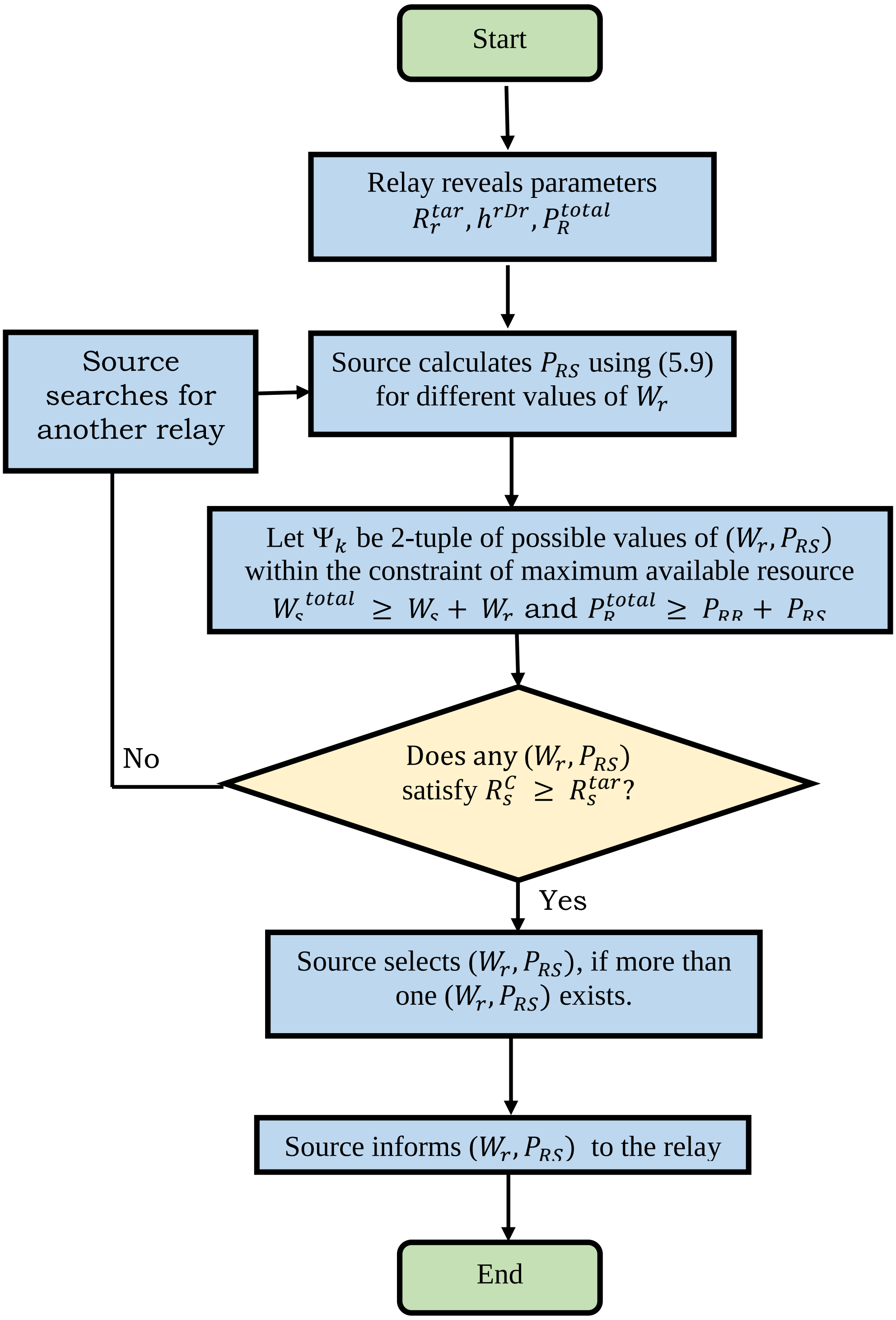


Fig 5.13 One-shot negotiation procedure

5.6 Conclusion

Cooperation stimulation and resource optimization framework for successful and long lasting cooperation has been presented in this chapter. The framework proposed here has proved that the nodes involved in cooperation by exchanging complementary resources can earn benefit and hence, tried to remain in cooperation. Source having sufficient bandwidth but less power cooperates with relay having sufficient power but no bandwidth and both of them have achieved their target data rates, which was impossible to achieve individually. When source target data rate is 1bit/unit, source offers bandwidth from 5.2 to 7.3 units in exchange of relay power from 1 to 4.5 units. When source target is 2 bits/unit, source keeps more bandwidth with it and offers bandwidth from 0.2 to 4.7 units in exchange of relay power from 1 to 4.5 units. Source can achieve the target for the range of α from 0.4 to 0.7, even if relay target changes from 0.8 to 1.2. It is demonstrated that source could save 21% to 71.5% energy by restricting transmission to only in a part of its bandwidth and relay was able to achieve its target by getting the part of source's spectrum. Robustness of this framework has been tested on 100 random channel variation and it has been found that cooperation with the same node remains unchanged and source has gained 13.4% to 46.7% more data rate compared to direct transmission. At the end, one-shot and accurate negotiation procedure has been discussed. It requires the three parameters from relay to establish cooperation. It also enforces relay to reveal the true parameters to enjoy mutual benefits.

Chapter 6

Conclusion and Future Scope

Resource allocation techniques for cooperative wireless network have been developed, analysed and evaluated in this thesis. These techniques have been developed for three types of wireless network- centrally controlled, semi-distributed and self-organizing network. In centrally controlled network, the technique of resource allocation has been shown to encourage service provider to install relay nodes to create virtual spatial diversity. Three approaches have been developed in chapter 3 to allocate source power, relay power, and bandwidth jointly to achieve different goals of resource allocation. Utility function based approach has shown capabilities to allocate the resources to yield fairness index on the full scale of $1/n$ to 1, where n is the number of sources. Resource constraint based approach achieves the trade-off between efficiency and fairness by putting restrictions on minimum and maximum amount of resources given to any one source. An E-F function has been evolved to achieve desired degree of fairness in resource allocation. A generic utility function has been presented which can allocate resources for (a). Maximizing sum total data rate (b). Achieving proportional fairness (c). Reducing delay to minimum (d). Priority based allocation (e). Max-min fairness (f). any desired trade-off between efficiency and fairness.

Multi-unit auctioning based low overhead resource allocation technique has been presented in chapter 4 for semi-distributed network. Technique based on linear demand curve reduces computational complexity of negotiation and makes the process of determination of relay power allocation faster. Both type of nodes have been shown to earn benefit – relay node in terms of virtual currency and source node in terms of higher data rate and power saving. Sources in need of cooperation are required to compute and convey only two parameters to relay, based on which relay determines revenue maximizing allocation of the units of power. Two pricing schemes have been considered – Non-discriminatory and discriminatory. Simulation results shows an increase in source data rate compared to direct transmission in the range of 30.2 % to 63.1% in case of non-discriminatory pricing scheme and 47.2% to 59.3% in discriminatory pricing scheme. Non-discriminatory scheme assigns power in proportion of the demand of the source whereas discriminatory pricing scheme assigns power to minimize the difference between the maximum and minimum achievable data rate by the sources. The sources are able to save 15.8% to 34.2% power in case of non-discriminatory and 16.9% to 34.7% power in case of discriminatory pricing scheme. The computational complexity of this technique is of the *O (1)* and is substantially low as compared to that of clock auctioning technique.

Cooperation stimulation and resource optimization framework for successful and long lasting cooperation has been presented in chapter 5. Source having sufficient bandwidth but less power cooperates with relay having sufficient power but no bandwidth and both of them have achieved their target data rates, which was impossible to achieve individually. When source target data rate is 1bit/unit, source offers bandwidth from 5.2 to 7.3 units in exchange of relay power from 1 to 4.5 units. When source target is 2 bits/unit, source keeps more bandwidth with it and offers bandwidth from 0.2 to 4.7 units in exchange of relay power from 1 to 4.5 units. Source can achieve the target for the range of α from 0.4 to 0.7, even if relay target changes from 0.8 to 1.2. It is demonstrated that source could save 21% to 71.5% energy by restricting transmission to only in a part of its bandwidth and relay was able to achieve its target by getting the part of source's spectrum. Robustness of this framework has been tested on 100 random channel variation and it has been found that cooperation with the same node remains unchanged and source has gained 13.4% to 46.7% more data rate compared to direct transmission. At the end, one-shot and accurate negotiation procedure has been discussed.

Future scope of work

The work presented in this thesis has shown the impact of resource allocation on the performance of the cooperative network. Looking at the ever increasing demand of data rate and limited available spectrum, alternative approaches must be considered for the forthcoming generation of wireless communications. The approaches presented in this thesis can be further expanded for designing of protocols and scheduling of cooperative communication. In pricing mechanism of chapter 4, the management of virtual currency is assumed to be done by the central controller. The process of currency transfer can be made reliable with tamper proof hardware design. This point can be further investigated to make pricing scheme suitable distributed network. Hardware realization and prototype development can be explored for actual implementation of the proposed schemes. Cooperation in cognitive radio network and device to device (d2d) communication are the areas of the application of the proposed mechanisms and approaches in this thesis.

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