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Improving the Energy Efficiency by Cooperative Transmission in Multi-Hop Wireless Ad-Hoc Networks

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IMPROVING THE ENERGY EFFICIENCY BY COOPERATIVE TRANSMISSION IN MULTI-HOP WIRELESS AD-HOC NETWORKS

by

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Abstract

IMPROVING THE ENERGY EFFICIENCY BY COOPERATIVE TRANSMISSION IN MULTI-HOP WIRELESS AD-HOC NETWORKS

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Cooperative transmission has been recently proposed as a promising technique to combat multi-path fading and increased link reliability. It represents a potential candidate to exploit the benefits of using multiple antennas system without requiring to implement multiple antennas per terminal. There has been extensive research investigating physical layer issues of such systems; however, higher layer protocols that exploit cooperative links in ad hoc networks are still emerging in cooperative ad hoc networks, and it is important to effectively use cooperation without affecting the performance of the network.

In this dissertation, we proposed a novel a characterization of the optimal multi-hop cooperative routing in ad hoc networks, and developed a metric for both evaluation. The key advantages of cooperative links are to minimize the number of hops while maintaining the QoS requirements and to minimize the end-to-end total power for a given rate. Also we showed that energy can be used more efficiently if we determine the joint optimal packet size and the optimal power allocation for both the source and the relay.

For multi-flow scenario, we have proposed a clique-based inter-flow interference abstraction, and used the linear programming formulation to study the capacity gain of ad-hoc cooperative network. It is observed that the network capacity in multi-hop multi-flow settings is severely affected by interference between links and this effect increases when the cooperative relaying is imposed.

Acknowledgment

I would like to express my deepest gratitude to my co-supervisor and supervisor, Dr. Alagan Anpalagan and Dr. Muhammad Jaseemuddin for their inspiration and support throughout the entire study period. They have been of great help, and give me constructive comments and ideas. Without their helps, this thesis would probably not have been carried out at all. I am very grateful for all the support that I have received. Also, I would thank all lab mates family and all other members of Ryerson University; they kindly and friendly behave for their pleasant company during the entire study period.

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DEDICATION

To my family

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List of Symbols and Abbreviations

ACK/NAK	Positive/Negative Acknowledgment
AF	Amplify and Forward
ANL	Average Network Life
AODV	Ad hoc On Demand Distance vector Routing
ARQ	Automatic Repeat Requist
AWGN	Additive White Gaussian Noise
BB	Branch and Bound
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CASNCP	Cooperation Along Shortest Non-cooperative Path
CC	Coded Cooperation
CD	Cooperative Diversity
CDMA	Code Division Multiple Access
CG	Conflict Graph
CSI	Channel State Information
CSMA	Carrier sense Multiple Access
CT	Cooperative Transmission
DF	Decode and Forward
DMT	Diversity Multiplexing tradeoff
DSR	Dynamic Source Routing
DSTC	Distributed Space Time Coding
DT	Direct Transmission
EC	Evolutionary Computation

ENBGCR	Edge Node Based Geographic Cooperative Routing
ERC	Equal Ratio Combining
FPL	Fixed Priority List
FRC	Fixed Ratio Combining
GPS	Global Position System
GR	Geographic Routing
GSC-MRS	Generalized Selection Combining-Multiple Relay Selection
HARQ	Hybrid Automatic Repeat Requist
ITRS	Incremental Transmission Relay Selection
MAC	Medium Access Control
MCF	Multi Commodity Flow
MFR	Most Forward within Radius
MIMO	Multi Input Multi Output
MRC	Maximal Ratio Combining
MRS	Multi Relay Selection
NLP	Nonlinear Programming
OC	Opportunistic Cooperation
OFDMA	Orthogonal Frequency Division Multiple Access
OORS	Outage Optimal Relay Selection
OPA	Optimal Power Allocation
OR	Opportunistic Relaying
OT-MRS	Output Threshold-Multiple Relay Selection
PARS	Power Aware Relay Selection
PHY	Physical Layer
QoS	Quality of Service

RTS/CTS	Ready To Send/Clear To Send
SC	Selective Combining
SENS	Switched and Examine Node Selection
SEP	Symbol Error Probability
SINR	Signal to Interference and Noise Ratio
SNCP	Shortest Non-cooperative Path
SNR	Signal to Noise Ratio
SNRC	Signal to Noise ratio Combining
SRS	Single Relay Selection
TDR	Threshold Digital Relaying
TRSC	Threshold based Relay Selection Cooperation
V-MIMO	Virtual Multi Input Multi Output

Chapter 1

Introduction

Wireless ad hoc networks such as home and sensor networks have become an important part of our daily life and are expected to provide multimedia services, which increases the demand for higher data rates, higher link reliability and longer battery life. The main feature of these types of networks is self-organization (distributed), and these features reduce the cost and effort for their configuration and maintenance. Ad hoc networks have a wide range of applications for both the military and the civilian world. It is used for enhancing military communication in the battlefield or in areas hit by natural catastrophes. People are also using these networks in cafes, restaurants, malls, universities, and public gatherings such as conferences [1].

In wireless communication systems including ad hoc networks, transmitted signals experience multi-path propagation. As a result, fading phenomenon is introduced when multiple paths destructively interfere. Therefore, there is a need for wireless communication protocols that mitigate the fading effect and improve the system performance. Spatial diversity is a very powerful technique to increase robustness against channel fading through multiple antenna system [2, 3], where each node in the network has multiple antennas. However, this technique is not feasible in some situations as discussed in the next section.

1.1 Motivation of Cooperative Transmission

Nodes in wireless ad-hoc networks are powered by small batteries which are sometimes difficult to replace, and may run out of energy quickly. At the same time, in wireless transmission the signal quality suffers severely from a bad channel due to effects such as fading caused by multi-path propagation; as a result, more energy will be wasted to re-transmit the same corrupted data. Thus, improving the wireless link quality leads to reducing the energy consumption per bit for end-to-end data transmission which becomes a major problem in wireless networks generally and specifically in ad-hoc networks. Therefore, techniques should be innovated to improve wireless channel quality and to meet the power requirements.

Spatial diversity by using multiple antennas array system (i.e., MIMO) is one of the most promising technologies to cope with these limitations and to reduce the effects of fading [2, 3]. However due to size, cost and the hardware constraints, the use of MIMO techniques in ad-hoc networks may not always be feasible especially in small devices. This problem has recently spawned interest to introduce a new method that mimics a MIMO system and achieves their gain at cost effective way. This method is broadly named as cooperative communication technique, in which nodes equipped with single antenna share their resources to facilitate each others' communication.

The key idea of cooperative communications technique is to make a single antenna network nodes cooperatively transmit and receive data for each other and forming virtual antenna arrays. In other words, relays are assigned to help a source node to deliver its information to its destination node. In addition, in wireless networks, the transmitted signals can be overheard by some nodes which do nothing but wait for their own transmission during other nodes' transmission in the network.

Most of the previous works on cooperative transmissions have mainly focused at the physical layer and how to acquire the benefits of cooperative transmission based on information theory. Details for upper layer functions such as relay selections, resource allocation and routing have been rarely considered jointly [4–14]. To fully take the advantage of cooperative communication and to implement cooperative communication in real networks, details of cooperative transmission and how it works in upper layer must be addressed.

1.2 Objectives

Wireless multi hop networks are challenging in many ways especially when cooperative communication is considered. In this thesis, we focus on a subset of these challenges, i.e., those related to the routing function. In particular, we address the following in this dissertation.

1. There have been fewer [4–14] results on how the cooperative routing protocols compare with each other and with traditional (non-cooperative) routing. The first question we are looking to address is: Does cooperative routing perform better than the traditional routing, and what is the gain that could be achieved through cooperative transmission in wireless ad hoc multi hop networks? Our objective is to investigate different routing algorithms with different goals and conduct there performance evaluation studies under different sets of network conditions, including node density.

2. The second question for the study is, can the energy efficiency of the network be improved by optimizing the size of the data packet? Unlike the fixed packet transmission, where the size of packets is fixed regardless of the channel link states, the bigger the packet size in non-reliable links, the higher the packet loss, and thus the higher the loss of energy. Therefore, an energy efficient network requires a joint allocation of packet size and the transmitted power across all links. From this viewpoint, to use the energy of the network more efficiently, adaptive packet size network should be considered and jointly optimized with the transmitted power.

3. Although cooperative transmissions provide benefits of spatial diversity to the networks, they utilize more transmission medium than non-cooperative transmissions. Data must be sent by the source and the relay/relays; hence, the interference range for the cooperative link is greater than in the case of direct link. Therefore, more links will be in conflict and the achievable total network capacity is not well understood and should be studied. The third question considered in this study is, how to model interference in wireless cooperative multi hop networks and is the total network throughput affected in the presence of interference from simultaneous transmissions in the network when cooperative transmission is considered.

1.3 Thesis Contribution

Motivated by the above mentioned objectives and the potential gain achieved by using the cooperative transmission at physical layer (one hop), in this thesis, we study the benefits of using cooperative transmission in multi-hop ad hoc wireless networks at upper layers. The key contributions of this thesis can be summarized as follows:

First, we survey the relay selection algorithms proposed for wireless cooperative networks [15]. Several algorithms with different metrics have been proposed in the literature. We give a thorough overview of more elaborate metrics that address the additional challenges added to wireless network by considering cooperative transmission. In particular, we discuss different algorithms, their optimization goals, the type of information required as well as their advantages and drawbacks.

Second, we consider a cooperative transmission scheme in multi hop ad hoc network with only one flow. For this system, we propose and analyze two different routing schemes with two different objectives which are applicable for energy constrained networks such as ad hoc wireless network. First, based on the formulated cooperative transmission range extension factor, the source-destination best path is selected such that the number of hops involved in the path are minimized [16]. Then, a power efficient routing protocol is proposed that jointly selects the appropriate cooperative partner for each link based on the total energy required to transmit data to its neighbors and, the best end-to-end path between the source and the destination is the path with minimum total end-to-end power among all paths [17]. Based on the analysis of both algorithms, energy efficiency is improved by implementing the proposed strategies.

Then, we extend the previous work by investigating an adaptive packet size for cooperative link to improve the network energy efficiency [18]. We propose a new global optimal solution method for packet size based on the interval arithmetic to solve the formulated non-convex problem. The analysis mainly focuses on the optimum packet size and the optimal power allocation for the source and relay at different locations.

Finally, we extend the previous work to include multi flow scenario to investigate the total network throughput [19]. The problem is formulated as multi commodity flow problem and the optimal solution technique is obtained using an optimization tool that optimizes the total network throughput and selects the best path for each flow that maximizes the total throughput. We study the total network throughput and conflict performance analysis using conflict graph. Our objective is to study the effects of using cooperative transmission to the total network throughput in multiple flow scenario. Our result shows that, to gain the benefits of cooperative communication, it is better to implement it in multiple channel systems where the conflicted links are allocated with different channels.

1.4 Thesis Organization

The remainder of the thesis is organized as follows:

A literature survey of cooperative communications and a brief introduction to background subjects related to our work such as relaying techniques, relay selection algorithms, diversity combining techniques, conflict graphs, global optimization and interval arithmetic are presented in chapter 2. The main focus here is to provide an overview of the state-of-the-art relay selection schemes in cooperative ad hoc networks and presents a classification of these protocols according to the number of relays used in cooperative communication. We also present a comparison of these schemes and show the advantages and drawbacks of each scheme in terms of network efficiency, simplicity and power saving.

In chapter 3, two different routing protocols are proposed. First, we introduce the transmission range extension as a routing metric and propose a routing protocol based on geographic greedy routing. Then, the total transmitted power for the source and relay is analyzed and considered as our routing metric. Based on the new routing metric, an energy efficiency routing protocol is proposed. The performance of both proposed protocols are analytically evaluated and verified via simulations.

In chapter 4, the above work is extended to include the packet size jointly with the transmitted power to maximize the energy efficiency of the network. In this chapter, we propose to jointly optimize the packet size and the transmitted power and, propose an efficient algorithm to solve the problem globally. Again the analytical work is verified with simulation.

The previous works are extended to a network with multi flow scenario in chapter 5. In this chapter, we study the affects of using cooperative relaying to the total network capacity. We study the optimal total network capacity by formulating the problem as multi commodity flow MCF problem. The optimal solution is obtained using CPLEX [20] optimization software that optimizes the throughput and avoids the interference by selecting the best path to each flow.

The contribution of this dissertation is summarized in chapter 6. In addition, the future research directions relevant to the works in this thesis are discussed. Final remarks of the thesis are given at the end of chapter 6. The snap shot of the thesis work is shown in the Fig. 1.1.

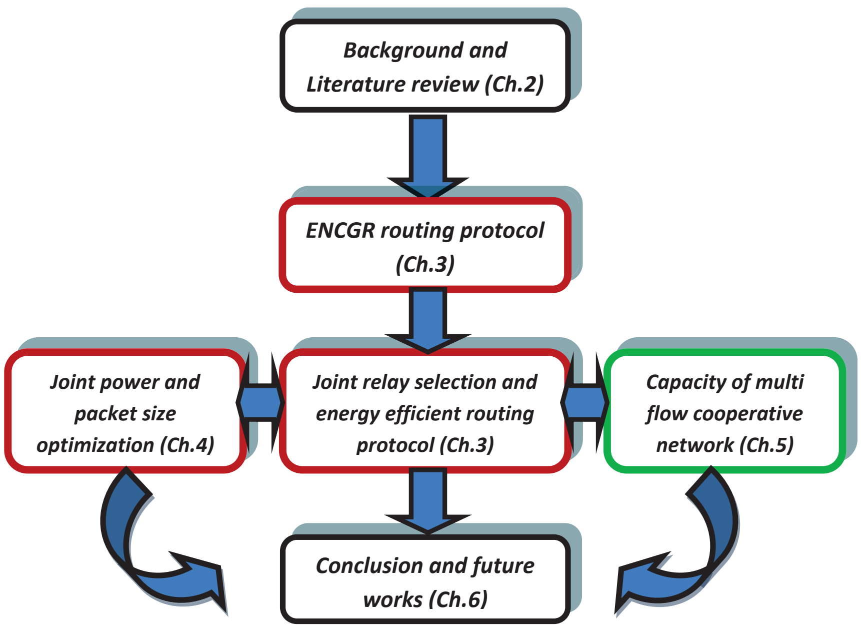


Figure 1.1: Thesis organization.

Chapter 2

Background and Related Work

This chapter presents the important literature relevant to the problems studied in this dissertation and provides background on the related issues and considerations. We divided this chapter into four main sections. Section 2.1 summarizes the significant characteristics of the cooperative transmission environment, describing cooperative transmission systems, the relevant protocols and combining techniques proposed for this purpose. Section 2.2 discuss of the resource management in cooperative networks such as power control, bandwidth allocation and relay selection. Section 2.3 provides detailed survey of distributed relay selection schemes that have been proposed in the literature and suitable for ad hoc wireless networks with traditional two-hop cooperative transmission. Finally section 2.4 describes the methodology used in this thesis to model and analyse the system.

2.1 Cooperative Transmission

Recently, a new form of distributed spatial diversity has been investigated in the literature that leverage cooperation between wireless terminals, which is called *cooperative communication*. These proposed schemes show performance improvement in wireless relay networks and can provide the benefits of diversity without requiring multiple antennas per terminal, by allowing surrounding terminals to collaborate, acting as a virtual MIMO antenna array.

Cooperative communication aims to achieve spatial diversity gain via the cooperation of user terminals in transmission without requiring multiple transceiver antennas on the same node. It employs one or more terminals as relays in the neighborhood of the transmitter and the receiver, which collaborate in the transmission and serve as a virtual MIMO antenna array. The basic idea of cooperative diversity network technology is that between the transmitter and receiver nodes, there can be another node, which can be used to provide diversity by forming a virtual multi-antenna system. Allowing cooperation in wireless communication engenders new problems such as resource allocation, relay selection and routing.

Figure 2.1 shows the evolution toward cooperative communication and how this scheme tries to exploit the benefits of traditional MIMO in different scenario. In the case of cooperative transmission shown in this example, the transmitter S transmits the message to the receiver and relay during the first phase, and the relay R retransmits the message for the receiver D during the second phase. The spatial diversity is achieved because the message from S to D (or R to D) is transmitted through two independent fading paths, $S - D$ and $R - D$ to the receiver.

2.1.1 Cooperative transmission systems

To date, various cooperative diversity systems have been proposed and analyzed in the literature. According to how relays react during the second phase, cooperative system proposed in the literature can be categorized in to different schemes. Some of these schemes will be discussed briefly in the following subsections. For additional information regarding the cooperative diversity system, interested reader could refer to [21–34].

- Repetition based cooperative diversity

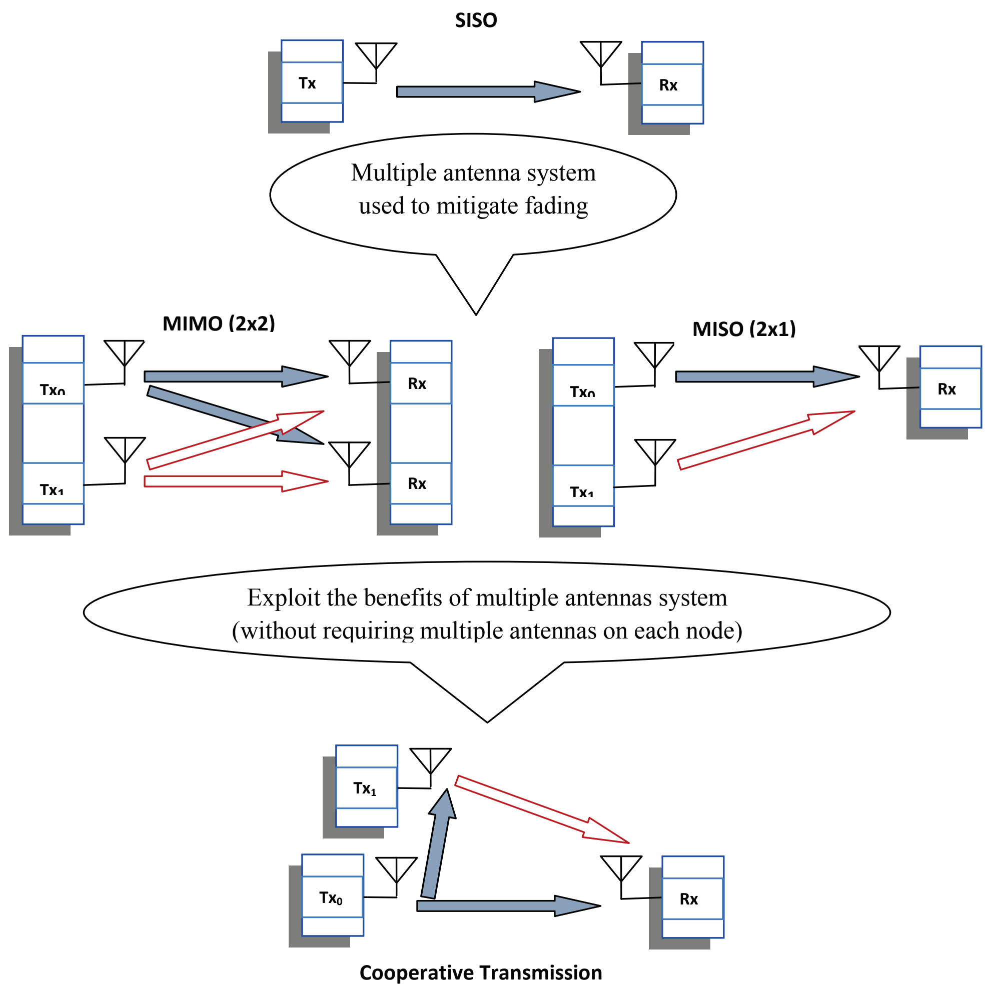


Figure 2.1: Evolution towards cooperative transmission.

This protocol proposed by Laneman et al. in [24] consists of two phases. In the first phase of this protocol, the source broadcasts to its destination and all potential relays. During the second phase, the other terminals relay to the destination, on orthogonal sub-channels. It is a very simple and low complex technique, and can offer full spatial diversity for multi-user cooperation to achieve diversity; but this simplicity and the achieved diversity gain comes at a price of decreasing bandwidth efficiency with the number of cooperating terminals, because each relay requires its own sub-channel for repetition.

- Distributed space time coding DSTC

  Laneman et al. in [24] proposed an alternative approach to improve bandwidth efficiency of the repetition based cooperative transmission mentioned above. This protocol operates in similar fashion to the repetition decode-and-forward cooperative diversity algorithm, except that during the second phase, distributed space time coding algorithm utilizes a space-time code to simultaneously transmit to the destination on the same sub-channel using a suitable space-time code, therefore enhances bandwidth efficiency

- Opportunistic cooperation (OC)

  This scheme was introduced by [28] that selects the best relay between source and destination based on instantaneous channel measurements. This scheme simplifies DSTC scheme in which a single relay is used to forward information toward the destination. The main advantages of opportunistic cooperation is that, it can be used to simplify a number of cooperative diversity protocols involving multiple relays (i.e., eliminate the need of DSTC) and this simplified protocol achieves the same diversity multiplexing trade off achieved in DSTC.

- Cooperative diversity for CDMA systems

  The CDMA-based decode-and-forward cooperative signalling was proposed by Sendonaris et al. in [21, 35, 36]. In this algorithm, each user has its own spreading code and each signalling period consists of three bit intervals. For example, in a network with two users, in the first and second intervals, each user transmits its own bits and detects the other user's second bit, and in the third interval, both users transmit a linear combination of their own second bit and their estimate of the partner's second bit, each multiplied by the appropriate spreading code. The transmit power for each interval is optimized according to the channel conditions.

- Cooperative based on channel coding CC

  Coded cooperation is proposed by Hunter in [32]. The basic idea behind coded cooperation is that each user tries to transmit incremental redundancy for its partner. Whenever that is not possible, the users automatically revert back to a non-cooperative mode. The key to the efficiency of coded cooperation is that all of these are managed automatically through code design (i.e., cooperative signalling is integrated with channel coding) and there is no need for feedback between users.

2.1.2 Cooperative transmission signalling

Generally, depending on how the received signals are processed at the relay before being forwarded to the receiver, cooperative transmission protocols can be grouped into two classes: amplify-and-forward (AF), and decode-and-forward (DF) methods. Both AF and DF algorithms consist of two transmission phases in a cooperative communication. A simplified demonstration and comparison of these two classes appears in Figure 2.2. In the first phase, a transmitter sends the information to its receiver and all neighbors receives the information as well due to the broadcast nature of wireless channel. During the second phase, potential or selected relays (two relays in this example) transmit the information to the receiver.

- Amplify and Forward (AF)

  In AF, the signal received by the relay/relays is amplified before it can be sent again in which the noise in the signal is amplified as well, which is the main downfall of this protocol. The destination will combine the information sent by the source and its partner and will make a final decision on the transmitted symbol. Amplify-and-forward is conceptually the simplest of the cooperative signalling methods.

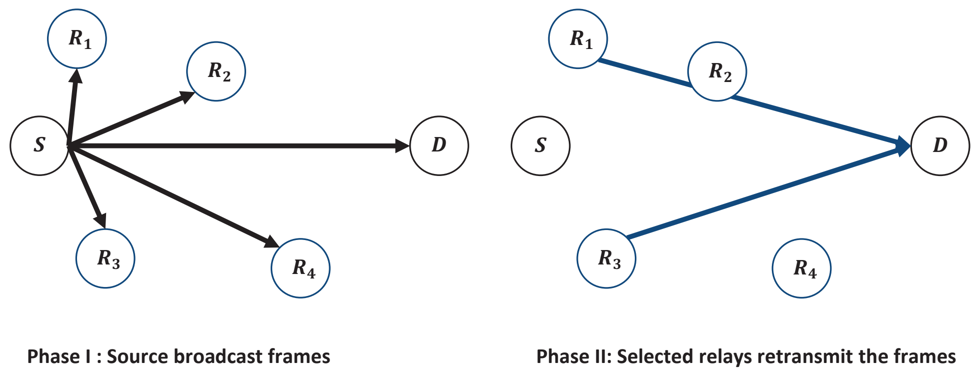


Figure 2.2: Two phases in cooperative transmission (two relays selected for cooperation)

- Decode and Forward (DF)

  Unlike AF protocol, DF completely suppresses the noise and there is no amplified noise in the transmitted signal. However, in DF, the received signal is first decoded and then re-encoded. The first work proposing a decode-and-forward protocol for user cooperation was by Sendonaris, Erkip, and Aazhang in [21, 36]

2.1.3 Diversity combining techniques

Diversity combing technique is needed at the destination to combine multi-branch signals to one improved signal. Generally, various diversity combining techniques can be distinguished [37]:

- Selection combing (SC)

  The SC selects the best signal among all the branches. It is very simple to implement and gives worse performance by ignoring other branches.

- Equal Ratio Combining (ERC)

  This is the easiest way to combine the signals, where all the received signals are just added up.

- Fixed Ratio Combining (FRC)

  In this method, all the branches are weighted with a constant ratio and summed as one signal. By using this method, we can achieve better performance than the previous method, but by giving the same weight to all branches, the weak signal may destroy the information carried by the strong signal.

- Signal to Noise Ratio Combining (SNRC)

  This method uses the same idea of the previous one (FRC), except that, this method uses SNR to weight the received signals. Using SNR that characterizes the quality of link leads to much better performance compared to former methods.

- Maximum Ratio Combining (MRC)

  Assuming that the channels' phase shift and attenuation are perfectly known at the receiver, the best performance can be achieved by using MRC [38]. The key idea of MRC method is that each input signal is multiplied by its corresponding conjugated channel gain. It means that the branches with strong signal are further amplified while weak signals are attenuated.

2.2 Resource Allocation in Cooperative Networks

Cooperative transmission technique based wireless network is proposed to improve the performance of wireless network in fading environment by taking the advantage of cooperation to mitigate fading. To fully exploit the benefits of relaying in wireless networks, efficient management of resources, such as power control, bandwidth allocation, and relay selection, etc is required. Recently, resource allocation in cooperative networks has attracted attention from the research community. Related work in this area can be categorized into two main categories based on how the algorithms are implemented: centralized and distributed mechanisms. Systems such as cellular networks in which users communicate with a central base station offer the possibility of centralized scheme. It means that a central base station collects and utilizes the required information to allocate the resources. Of course, centralized scheme for resource allocation requires excessive information exchange and overhead for most practical networks.

For example, in [39], the authors proposed a centralized resource allocation algorithm for relay selection and its strategy, power control, and bandwidth allocation in an Orthogonal Frequency-Division Multiple Access (OFDMA) based relay network. In their work, they propose a utility maximization framework that is capable of selecting the best relay, the best relay-strategy, and the best power, bandwidth and rate allocation in a cellular network with relays. Another example for centralized resource allocation is the work proposed by Shi et al in [40]. They have proposed a centralized optimal relay assignment scheme, for maximizing the minimum link capacity in a wireless network over orthogonal relay channels.

An alternative to the previous centralized solution is to allow each transmitter to adapt and allocate its resources autonomously. Systems such as ad-hoc networks which do not have centralized control require distributed schemes. In this category, each node individually determines and allocates its optimal resources according to the information exchange between nodes. The distributed schemes are usually sub-optimal, but it limits communication overhead and computation complexity comparing it with the centralized algorithm. In addition, the distributed algorithm is more applicable to networks such as ad-hoc networks. Some of the distributed allocation schemes proposed in the literatures, specifically relay selection and power allocation will be discussed in the next section.

2.3 Distributed Relay Selection Schemes

In a multi-user scenario, relay selection scheme determines how relays are assigned, in other words, how it is determined which users cooperate with each other, and how often relays are assigned. Optimal relay selection is vital for reaping the performance benefit of cooperative communication. It is at the same time a challenging task in regards to sharing of channel information in timely and distributed manner and making optimal selection of relay. A crucial challenge in the implementation of cooperative communication is how to assign source-relay pairs before cooperation begins.

The number of relay nodes to be selected to assist the source node in cooperative communication is crucial for the relay node selection algorithm. Determining whether the source communicating with the destination uses a single relay node or multiple relay nodes, relay selection schemes can be classified into two main categories. In general, we classify the distributed relay selection mechanisms based on the number of selected relays into two main categories as shown in Figure 2.3. Each category has its advantages and disadvantages. For example using a single relay as a cooperative node, the hardware at the receiver is simple and easy to implement. However, the performance of multiple-relay selection is fundamentally limited by the orthogonal partitioning of system resources, inefficient usage of power, or difficult synchronization among cooperative nodes which increases the complexity expenses. Relay selection techniques have been studied extensively in recent years [28, 41–47] and several selection criteria were proposed. As shown in Figure 2.3, we categorize distributed relay selection protocols in wireless cooperative networks into two main category. In this section, we will review some of these protocols for both categories.

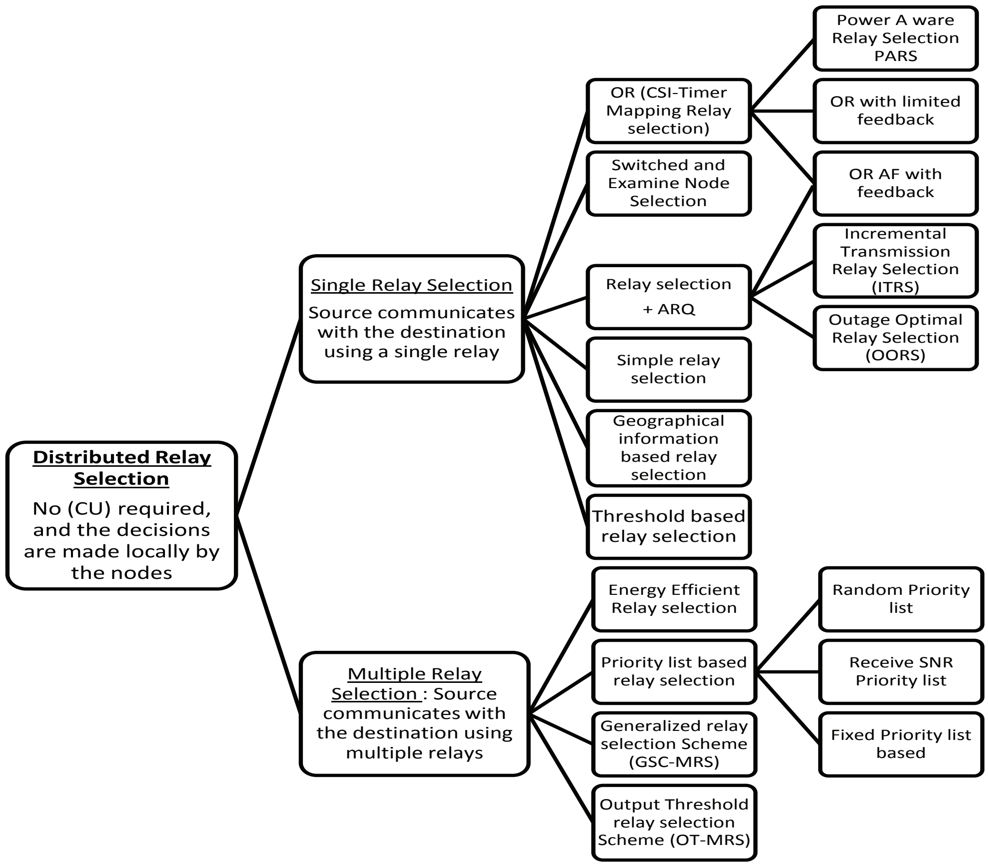


Figure 2.3: Categorization of distributed relay selection schemes developed for ad-hoc wireless network

2.3.1 Single relay selection schemes (SRS)

Several works on relay selection have shown the importance of selecting only one node to be used as a cooperative relay, since this minimizes the overhead due to orthogonal channels and also reduces the complexity of the selection process. The schemes that are generally classified under this category are detailed next:

- CSI-Timer Mapping Relay Selection (OR)

  In [28], Bletsas et al. concluded that it is difficult to design a space-time-code that allows for an arbitrary number of relays and identified this to be an open area of research. They proposed opportunistic relaying (OR) scheme, which is a distributed relay selection scheme that does not require global topology information in selecting a single relay. The OR scheme allows conventional coding scheme for communication. It assumes that: each potential relay i can overhear the RTS/CTS sequence between transmitter and receiver indicating the start of a transmission, a potential relay can overhear all the others, and all potential relays deduce the channel quality (g_{Si}, g_{iD}) from the strength of the received RTS/CTS sequence and derive a time-out from it. The time-out serves as a back off through that the station with the earliest time-out becomes the cooperating relay. The back-off results in a decentralized scheme based on instantaneous channel measurements only. The authors show that the achievable diversity in OR scheme is on the order of the number of cooperating terminals even though only one relay transmits [28]. Assuming that the potential relays may be hidden from each other, transmitter and receiver must announce the winner of the time-out period, therefore inducing additional signalling overhead. Bletsas et al., proposed their relay selection scheme as an alternative to space-time-codes for multiple users. It simplifies the multi-user scenario by reducing it to the well-known three terminal cases with the instantaneous channel quality being the deciding factor. However, they do not consider the specifics of coded cooperation in which further criteria are relevant for relay selection. The channel estimates (g_{Si}, g_{iD}) based on the received signal strength of both the packets that indicate the quality of the inter-node channel (g_{Si}) and the relay's uplink channel (g_{iD}). The following two policies have been proposed to define the parameter h_i for the same purpose of selecting the best end-to-end link between transmitter and receiver [28].

Policy I: the minimum of (g_{Si}, g_{iD}) is selected.

$$h_i = \min\{(|g_{Si}|)^2, (|g_{iD}|)^2\} \tag{2.1}$$

Policy II: the harmonic means of the two links is used.

$$h_i = \frac{2}{\frac{1}{|g_{Si}|^2} + \frac{1}{|g_{iD}|^2}} = \frac{2\,|g_{Si}|^2\,|g_{iD}|^2}{|g_{Si}|^2 + |g_{iD}|^2} \tag{2.2}$$

The initial timer value for relay i is set to be the proportional inversion of h_i, according to the following equation $v_i = \frac{\lambda}{h_i}$, where λ is a constant and has the units of time. The "best" relay has its timer reduced to zero first. When the timer of a potential relay expires, it first senses the medium. If it cannot detect a signal, e.g., using clear channel assessment, it broadcasts a flag packet to announce its help (i.e., signal its presence that becomes the cooperating relay). Hearing the flag packet, all the potential nodes stop their timers and back off. Since all nodes must sense the channel before making an announcement, only one node can win the contention assuming the announcement is of sufficient duration. If potential relays may be hidden from each other, transmitter and receiver must announce the winner of the time-out period through a control packet, thereby causes additional signalling overhead. The analysis of diversity-multiplexing trade-off (DMT) was presented for opportunistic relaying which is exactly the same as in (conventional) cooperative diversity that uses more complex space-time coded protocols.

- Power-Aware Relay Selection (PARS)

In wireless networks, e.g. ad hoc network, where the nodes are equipped with limited battery power, power conservation becomes an important factor in designing relay selection protocols in order to increase lifetime of a node. The OR scheme does not consider the issue of power conservation in relay selection. In [42], the authors propose the power-aware relay selection strategies (PARS) to maximize the network life time by minimizing the overall transmit power using the optimal power allocation (OPA) scheme. The OPA finds the minimum total power needed for the cooperative transmission of the transmitter and the potential relay. The main idea of PARS can be explained in two parts:

Part I - Optimal Power Allocation (OPA): Each potential relay performs the OPA algorithm on the basis of channel measurements to minimize the total transmit power at the given transmission rate. As a result of OPA, each relay can get the optimal transmit power for both the transmitter and each relay i (P_S^C, P_i^C). The optimal solution that is applicable for both AF and DF cooperation schemes is obtained using Lagrange multiplier method.

Part II - Relay Selection: The PARS employs both the minimum total transmit power of each pair of the transmitter and relay obtained from OPA (P_S^C, P_i^C) and the residual power level of the transmitter and each potential relay (P_{rS}, P_{ri}) in its relay selection scheme. Three criteria are proposed to select the best relay in [42]. The selected relay i^* and the initial values of the timer at the transmitter v_S, and each possible relay v_i for different criteria are shown in the following.

- Criteria I: Minimizing the total transmit power

$$i^* = \arg\min_i \{P_S^C + P_i^C\} \tag{2.3}$$

$$v_i = \lambda_1 \cdot (P_S^C + P_i^C) \tag{2.4}$$

$$v_S = \lambda_1 \cdot P_S^C \tag{2.5}$$

- Criteria II: Maximizing the minimum absolute residual power values

$$i^* = \arg\max_i \min\{P_{rS}^C - P_S^C, P_{ri}^C - P_i^C\} \tag{2.6}$$

$$v_i = \frac{\lambda_2}{\min\{P_{rS}^C - P_S^C, P_{ri}^C - P_i^C\}} \tag{2.7}$$

$$v_S = \frac{\lambda_2}{P_{rS}^D - P_S^D} \tag{2.8}$$

– Criteria III: Maximizing the minimum ratio of the residual power

$$i^* = \arg\min_i \max\left\{\frac{P_S^C}{P_{rS}^C}, \frac{P_i^C}{P_{ri}^C}\right\} \tag{2.9}$$

$$v_i = \lambda_3 \cdot \max\left\{\frac{P_S^C}{P_{rS}^C}, \frac{P_i^C}{P_{ri}^C}\right\} \tag{2.10}$$

$$v_S = \lambda_3 \frac{P_S^D}{P_{rS}^D} \tag{2.11}$$

where $\lambda_1, \lambda_2, \lambda_3$ are constants which have the units of sec/watt, sec.watt, and sec respectively. The authors simulated and compared their results with the OR scheme proposed in [28] in terms of the average network life (ANL) time. They found that the optimal power allocation and relay selection of PARS extends the network lifetime by about 100% [42] as compared to OR.

- Switched-and-Examine Node Selection (SENS)

The OR scheme [28], and its extension PARS that is based on OR [42], as discussed previously, provide multiplexing and diversity trade-off as DSTC. However, the OR and PARS can lead to collision when the timer of two or more relay nodes expire at the same time that results in failing the process. Also, they find the best relay node for each transmission that increases the complexity, since channel state information (CSI) of all participating links are required in the relay selection. Further, all available relay nodes must maintain the listening mode during the RTS and CTS packet transmission in OR, which increases their power consumption. In [41] and [43], the authors propose an algorithm using the idea of the switched diversity with post selection.

The main idea of this algorithm is to reduce the load of the channel estimation is described as follows. First, the channel between the transmitter and an arbitrarily selected relay node, which is denoted as $g_{S,1}$, is estimated at participating relay node. If the channel gain of the chosen hop is acceptable at the relay node because it is greater than the threshold (i.e., $g_{S,1} \geq g_T$), the relay node requests the CSI to the receiver. If the estimated channel gain at the receiver is higher than the target threshold (i.e. $g_{1,D} \geq g_T$), the given relay is chosen as a relay and thus have SNR as $\Gamma_1 = g_{S,1}$ and $\Gamma_2 = g_{1,D}$ at the relay and the receiver respectively. If the first relay node is not selected due to the channel gain $g_{S,1}$ trailing the threshold, the selection procedure loops through the list of nodes to find a relay node whose transmitter-relay channel gain exceeds the threshold. Finally, if the loop terminates without choosing a node, then the last L node in the list is chosen as the relay node without comparing its channel gain with the target threshold of g_T.

In this scheme, the relay nodes do not need to maintain listening mode all the time, rather only the node under investigation whose channel gain is compared with the threshold needs to be in the listening mode at any given time. Thus the power consumption of the relay nodes are reduced. By setting a suitable threshold SNR at both a relay node and the receiver, the proposed scheme achieves the same performance of the outage and BER as achieved in OR [28] with less channel estimation load.

- OR with Limited Feedback

  The CSI for both transmitter-relay and relay-receiver channels are required for relay selection, for example in OR scheme. As the number of users increases, the exchange of state information also increases, which requires CSMA on the relay-receiver link in OR that complicates the analysis. Ali and Nosratinia in [44] present a modified OR scheme that requires limited feedback while achieving the same multiplexing and diversity trade-off as in DSTC. The mode of operation of this protocol consists of two phases; in the first phase, the transmitter transmits the message while both the relay and the receiver try to decode it. They indicate success or failure to the receiver via one bit of data. In the second phase, the receiver selects the best relay based on the relay-receiver channel measurement and indicates its decision with one bit feedback per relay.

The analysis show that by limited exchange of information in the network, this protocol can achieve the same diversity-multiplexing trade-off achieved by space-time coded protocol, and the amount of information exchanged required is $\frac{2M-1}{M}$ per relay which is extensively smaller than the amount of side information required to be fed back in other protocols such as OR.

- Simple Relay Selection

Multiple flows which are avoided in the previous work is considered in [47]. In this work the authors consider a network that contains a set of $\mathcal{M}$ of m nodes. Each node $S \in \mathcal{M}$ has data to transmit to its own receiver $D(S) \notin \mathcal{M}$, and acts as a relay for other nodes in $\mathcal{M}$. the proposed algorithm works as follows.

In the first phase all nodes use orthogonal channels to transmit information to their respective receivers, and each node decodes the information from the other $m-1$ sources. Each node determines if it has decoded the information correctly. If node S_j has decoded the information from the transmitter S_i correctly, it declares itself as a member of the decoding set $\mathcal{D}(S_i)$ of nodes eligible to be a relay for node S_i. Such a decoding set $\mathcal{D}(S_i)$, is formed for each transmitting node $S_i \in M$.

During the second phase, the receiver of each transmitter S_i, picks the relay with the highest instantaneous relay-receiver channel power from its decoding set $\mathcal{D}(S_i)$

according to (2.12), and each relay forwards the information for the transmitter $r(S_i)$.

$$r(S_i) = \arg \max_{r_k \in \mathcal{D}(S_i)} \{|g_{r_k}|^2\}; \tag{2.12}$$

$$\text{where }, k = 1 \ldots |\mathcal{D}(S_i)|$$

Through analysis of outage probability and simulation, it is shown that this protocol achieves full diversity order and significantly outperforms DSTC in all networks with more than three potential relays.

- Geographical Information based Relaying Selection

In [48] a simple geographic-based relay selection protocol for wireless sensor networks is proposed, in which the best relay can be efficiently determined by using the geographical information among nodes. The proposed relay selection protocol is designed for minimum symbol error probability (SEP) at the destination. The protocol is proposed for a simplified cluster based relay network in which network nodes are grouped into cooperative clusters, data are transmitted between clusters using cooperative communication.

In the single-hop relay selection model each source node in the cluster has M relays (r_i, $i = 1, 2 \ldots M$) to select for transmitting the data to the destination in the next cluster. Multi-hop transmission is realized by concatenation of single cluster-to-cluster hops. Assuming the distance information is perfectly known at each node, the goal is to select the best relay to maximize the cooperation gain and, hence minimize the SEP at the destination. The proposed algorithm works as follows. First, each relay i acquires the distances between it self and source $d_{S,i}$, and destination $d_{i,D}$ to calculate its own selection metric ($\Delta_i = A^2 \cdot d_{S,i}^{\beta} + B \cdot d_{i,D}^{\beta}$), then send it to the source. Next, the source chooses the best relay (i.e. the one with the minimum metric) by the following.

$$i^* = \arg \min_{i \in \{1,2,\ldots,M\}} \{\Delta_i\}; \tag{2.13}$$

where, Δ_i is the selection metric, which indicates the SEP performance at the destination. The smaller the metrics, the better the resulting SEP performance, A and B are two parameters based on modulation scheme used [48], $d_{S,i}$ and $d_{i,D}$ are the distances between source-relay and relay-destination respectively, β is the path loss exponent. Then the source broadcasts a message to others to indicate which relay is going to cooperate with it.

Simulation results demonstrate the proposed relay selection protocol can efficiently improve the system performance and outperform the random relay selection protocol in terms of symbol error probability.

- Threshold-Based Relay Selection for Detect-and-Forward (TRSC)

A relay selection protocol proposed on [49] focuses on the detect-and-forward (or demodulate-and-forward) cooperative relaying protocols. Unlike decode-and-forward relaying, in detect-and-forward relaying the relaying does not rely on any error correction or detection codes which means that these protocols are efficient in terms of energy consumption. However, The main disadvantage of this scheme is error propagation, where the relays can forward erroneous information, these errors propagate to the destination causing end-to-end detection errors.

The proposed protocol based on the idea of threshold digital relaying (TDR), where a relay forwards the received data only when its received SNR is above a threshold value, as a result error propagation can be mitigated. The use of a threshold in [49] was to determine relays that are reliable in the sense that a higher SNR translates into higher probability of correct decoding. The relay selection is performed based on the equivalent e2e bit error rate (BER) of each relay channel. The proposed Threshold based Relay Selection Cooperation (TRSC) protocol works as follows.

- In the first phase, the transmitter broadcasts its information toward the receiver; where relays are also listening to the wireless medium and receiving the signal. Then each relay i decides independently whether its detection is reliable by comparing its received SNR , to a threshold value γ_{thr}. (i.e., relay i is considered as a reliable relay if $\gamma_i \geq \gamma_{thr}$
- In the second phase, the reliable relays send a short message to the receiver which allows the receiver to estimate the channel gains (g_{iD}) between itself and each reliable relay i. Then the receiver picks the relay with the highest channel gain, and feedback with a short message conveying which relay is selected for retransmission.

A simple threshold function is proposed and under this proposed threshold, it is shown that the network can achieves full diversity order $(M + 1)$ where M is the number of relays in the network. BER for the TRSC with the proposed threshold function and optimal threshold values determined through numerical optimization are compared with similar protocols such as relay selection based on the equivalent instantaneous BER (RSC-inst), and relay selection based on the equivalent average BER (RSC-ave). The results show that TRSC performs comparable to RSC-inst with no instantaneous $S - r$ SNR knowledge at the destination.

In addition to the previous mentioned works, there have been some work that combines relay selection scheme with ARQ utilizing feedback from the receiver to determine whether user cooperation is necessary. It was shown that using this scheme we can improve the spectral efficiency of the network when compared to the no-feedback relaying case, simply because relay retransmission is used only when it is needed. In the sequel some of these works will be presented [50–52].

- Opportunistic AF Relaying with Feedback

  In [50], the authors combined ARQ with opportunistic relaying to achieve a remarkable performance gain. Similar to [28], a system where each node sets a timer inversely proportional to its channel gain was considered. Upon its timeout, the node with the strongest channel gain first broadcasts its own channel information (using flag message) to its peer nodes. Unlike [28], the selected relay will not transmit the received message until it receives a single-bit feedback from the receiver, indicating that the message has not been decoded correctly during the first phase. The main idea of the proposed scheme is to avoid the waste introduced by using no-feedback opportunistic protocol in terms of the channel degrees-of-freedom, when the receiver receives the message directly from the transmitter successfully.

  Comparing the proposed algorithm with no-feedback opportunistic protocol proposed in [28], Opportunistic AF Relaying with Feedback provides substantial gains in terms of diversity order. This gain can be further enhanced by using additional rounds of feedback.

- Incremental Transmission Relay Selection (ITRS)

  Tannious and Nosratinia [51], consider DAF relaying and proposed an incremental transmission relay selection (ITRS) protocol where the transmitter itself is also considered in the selection procedure and an additional gain is obtained. In this protocol, the limited feedback has dual use: it selects the best relay, thus improving diversity, and also enables retransmission (HARQ), thus improving spectral efficiency. ITRS protocol works as follows: the transmitter broadcasts the message during the first phase. If the receiver cannot decode, it will identify and pick the best available node from among successful relays and the transmitter for retransmission during the second phase after performing a limited-feedback handshake with the transmitter and successful relays. The (DMT) of ITRS was analyzed and improvement over existing methods for half-duplex DAF relays including DSTC and opportunistic relaying [28] was observed.

- Outage-Optimal Relay Selection (OORS)

  In [52], the authors propose a relay selection scheme combined with feedback and adaptive forwarding (i.e., using AF or DF protocol) in cooperative communication systems, this scheme called "Outage-Optimal Relay Selection (OORS)". In this scheme, the feedback is utilized from the receiver to determine whether user cooperation is necessary. If it is necessary, a decision threshold is introduced and each relay independently evaluates its eligibility for cooperation. All eligible nodes form a cooperative set S_C, from which the receiver selects the node that can provide the maximum instantaneous mutual information as the cooperative node. The selected one will adaptively forward the received message with AF or DF protocol, depending on whether it has decoded this message correctly. If the cooperative set is null, the transmitter node will be selected for retransmission. Simulation results demonstrate that the proposed scheme outperforms a variety of existing relay selection schemes in terms of outage performance including opportunistic relaying with feedback [50] and incremental transmission relay selection (ITRS) [51].

2.3.2 Multiple relay selection schemes (MRS)

Although single relay selection schemes (where the destination combines only the best indirect link with the direct link) have higher bandwidth efficiencies (i.e., increase the spectral efficiency) and energy saving comparing to all-participate relaying scheme, these schemes do not fully exploit the available degrees of spatial diversity and suffer a performance loss in terms of the error rate and the outage probability. To achieve better trade-off between error performance and spectral efficiency and to save more energy, multiple relay selection could be considered. Some of these schemas are detailed as follows:

- Energy-Efficient Relay Selection

  In [46], the energy efficiency of cooperative communication based on a simple relay selection strategy is investigated. Since cooperative beam forming is used at the transmitter (cooperative beam-forming has been proposed to save energy in transmitting data from the relay to the receiver [46]), multiple relays may be selected as the final relay set.

  The scheme works as follows: the transmitter broadcasts its message with fixed power P_S, at fixed rate R bits/symbol (assuming that no direct transmission from the transmitter and the receiver, i.e. transmitter-receiver channel is weak enough). Only the M relay nodes that receive and decode message successfully (i.e. $SNR > \gamma_{thr}$) send training sequences at the rate R bits/symbol and power P_t to the receiver. These training sequences allow the receiver to estimate the channel gains (g_i) between each relay $i \in M$ and the receiver. Based on the channel gains ($g_{iD}, i \in M$), the receiver either declares an outage probability or it selects the subsets of M with the best channel gains to the receiver, and feeds back to them the required CSI. Given the knowledge of the CSI, each of the selected relay i will set the optimal transmission power (beam forming scheme).

  The simulation and numerical analysis of this scheme showed that it outperforms non-cooperative schemes as well as cooperative schemes that use either a single relay or all relays in terms of energy savings. As shown in the results, energy-efficient relay selection scheme consumes approximately 14% less total energy than the other two mentioned schemas.

- Priority List Based Relay Selection

  The authors in [45] consider three random-like selection schemes and analyzed their performance in terms of average user outage probability. In these schemes, a node selects relays for cooperative transmission based on a priority list. The following three ways of creating the priority list are proposed there.

  Random Selection

  In this scheme, for each transmission block, a user randomly orders the other $M-1$ users in a priority list, and attempts to decode and assists the first n nodes from the list.

  Receive SNR Selection

  In this scheme, each node measures its receptions and attempts to assist the n nodes which have the highest received SNR. That is, for each transmit block, a user prioritizes the other $M-1$ users in the descending order of the received SNR.

  Fixed Priority List FPL In this scheme each node has its own unique number associated with it and also has its own priority list used for relay selection that remains fixed for all transmission blocks. Each node attempts to decode and assist the first n nodes from its priority list. Unlike the first two schemes of creating the priority list which fail to achieve full diversity, full diversity in the order of $n+1$ could be achieved in this scheme as SNR goes to infinity. The key to full diversity in this scheme is to ensure that the list across the network has no systematic basis.

  To demonstrate the characteristics and gain achieved of the proposed algorithms. The authors simulate the three proposed algorithms and compare them with no cooperation transmission. The performance metric was characterized based on outage probability. Based on their simulation results and for outage probability 10^{-2}, the FPL protocol has a gain of approximately 8 dB over no cooperation while the other two protocols have a gain of only 2-3dB.

- Generalized Selection Combining Multiple relay Selection Scheme (GSC-MRS)

  In [53], multiple relay selection scheme is proposed by generalizing the idea of single relay selection to allow for multiple relays to cooperate, where the signals from the direct link and the n strongest paths among the M available relays are combined. Comparing this scheme with the best relay selection, the generalized-selection scheme is more robust toward channel estimation errors.

  The authors in [53] introduce the closed-form expressions of the error probability, outage probability and average channel capacity. Analysis results of this scheme show that the error probability slightly improves as the number of participated relays increase while the outage probability and channel capacity decrease as the number of participated relays increase.

- Output Threshold Multiple Relay Selection Scheme (OT-MRS)

  To avoid unnecessarily relays selected in the generalized multiple relay scheme. Amarasuriya and Tellambura in [54], propose multiple relay selection based on threshold. The idea of the proposed OT-MRS scheme is to select the first n arbitrary ordered relays out of M relays such that the maximal ratio combined signal-to-noise-ratio (γ_c) of the n relayed paths and the direct path exceeds a predefined target threshold γ_{thr}. The mode of operation of the proposed OT-MRS scheme is as follows:

  – Broadcast mode: during the first time slot, the transmitter broadcasts its information toward the receiver; where relays are also listening to the wireless medium and receiving the signal. In this phase, the combiner output at the receiver SNR_c is equal to the instantaneous SNR of the direct channel $\gamma_{S,D}$.

– Cooperation mode In this mode of operation, the first relay in the list forwards the amplified version of the transmitting message to the receiver. Thus, the combiner output in this case is equal to the combined signals from direct and relayed paths, and the output of the combiner becomes $\gamma_c = \gamma_{S,D} + \gamma_{1,D}$. Next, γ_c is compared with the predefined threshold γ_{thr}. If $\gamma_c \geq \gamma_{thr}$, no more relays are selected, and γ_c is set as the output SNR. Otherwise, the remaining relays $2, 3, ..., M-1$ are selected in subsequent time-slots until the output SNR exceeds the threshold. If the SNR of the $M-1$ relay nodes combined with the direct SNR is still less than the target threshold, finally all M nodes will be chosen as the relay nodes.

The numerical and simulation results shows that, the proposed scheme outperforms those of the optimal single relay selection and GSC-based MRS schemes for low to moderate SNRs.

2.4 Tools and Methodology

In this section, a brief background related to methodology used in this work such as interference model, graph theory, global optimization and interval arithmetic are presented.

2.4.1 Generic interference model

In a wireless ad hoc network, not all links can transmit simultaneously due to interference and resource contention. To characterize the radio transmission in the presence of interference, two different interference models have been used in the literature: physical and protocol model.

- Physical interference model

  In this model, a message can be transmitted successfully between two nodes if the received signal to interference plus noise ratio ($SINR$) exceeds a given threshold γ_{thr} that is,

$$SINR = \frac{P_{r,i}}{\sigma_n^2 + \sum_{j \neq i} P_{r,j}} \geq \gamma_{thr}, \tag{2.14}$$

  where γ_{thr} is the minimum $SINR$ required for a successful message reception. σ_n^2 is the ambient noise power, $P_{r,i}$ is the power received from the source, and $P_{r,j}, (j \neq i)$ is the power received from a set of transmitters that are transmitting simultaneously with the source which are considered as interference. Although the physical interference model imposes realistic condition for successful reception and it is widely considered as a reference model for physical layer, it is not appropriate for constructing the conflict graphs and the application of this model is limited in some scenarios specifically in multi-hop wireless networks due to its higher complexity. Thus, in this work, we adopt the protocol interference model.

- Protocol interference model

  In this model, any two nodes can communicate and their transmission is successful if and only if the receiving node is located within the transmission range of the intended transmitting node and is outside the interference range of any other node that is actively transmitting on the same band. In protocol interference model, the transmission from node i to node j is successful if both of the following conditions are satisfied for every other node k that is simultaneously transmitting or receiving that is,

$$d_{i,j} < r_C \ \text{ and } \ d_{k,j} > r_I, \tag{2.15}$$

  where r_C and r_I are a radio transmission and interference range sensitivity region respectively. We assume that each node knows its position (e.g. using GPS) and disseminates its position information to other stations in the local neighborhood. Each station then geometrically computes which stations are within an interference radius; we call such stations interfering neighbors.

2.4.2 Basic concepts of graph theory

Graph theory has been used as a modeling technique to analyse several properties of the wireless network including interference relationships between all of the links in a network. In this section we briefly review some of its concepts and definitions.

- Connectivity Graph

  Connectivity is one of the basic concepts of graph theory. A given network can be modeled as a connectivity graph $G = (V, E)$ where V is the set of vertices (nodes) and E is the set of edges (directed links). A link $l_{i,j} \in E$ exist if the range between nodes i and j is less than transmission range. The graph $G(V, E)$ is said to be connected if there is a path connecting any two vertices (nodes) in V. The cardinality of the graph is the number of vertices V , and the degree of vertices is the number of edges attached to that vertex.

- Conflict graph

  Conflict graph have been proposed by Jain et al. in [55] to describe the interference between neighboring nodes and links. The vertices of the conflict graph represent links in the connectivity graph $G(V, E)$ and there is an edge between any two vertices (links in the connectivity graph) if they interfere with each other. The authors in [55] use this abstraction to derive bounds for the optimal network throughput under ideal routing and scheduling decisions.

- Cliques

A clique in an undirected graph $G = (V, E)$ is a subset of the vertex set $H \in V$, such that for every two vertices in H, there exists an edge connecting the two (i.e., a clique is a complete sub-graph where all vertices are adjacent). In the interference graph, a clique represents the links which can not be active at the same time. Therefore, corresponding to each clique H in the interference graph, we get a constraint. We will use the concept of cliques on the conflict graph in Chapter 5 to capture the interference relation among all links when cooperative relaying is considered.

$$\sum_{(i,j)\in H} \mu_{ij} \leq 1 \tag{2.16}$$

where, $\mu_{i,j}$ is a fraction of time link (i, j) is active.

2.4.3 Optimization concepts

Optimization in general is the process of making something better. In other words, it is the way of finding the best set of admissible conditions to achieve the objective. Typically, many problem formulation including our problem in chapter 4 are non-convex non-linear programming problem (NLP) due to the presence of some non-convex term in their objective function and/or constraints. Hence, using the existing convex optimization techniques often leading the solver failing to locate the global optimum of the problem or even to determine a feasible solution. Thus, developing an algorithms that locate the global optimum becomes an important issue.

- Global optimization

  Global optimization is the task of finding the absolutely best set of admissible conditions for non-convex NLP to achieve an objective under given constraints. Recently, there has been a growing interest in this direction and some approaches are proposed.

Typically, the proposed approaches involve either linearizing the problem in a very confined region or restricting the optimization to a small region which can be classified as deterministic (i.e., Branch and Bound (BB) techniques [56]) or probabilistic approaches (i.e., Evolutionary Computation (EC) techniques such as genetic algorithm [57]).

The αBB algorithm is one of the deterministic methods and it is very well suited for our problem formulated in Chapter 4. Hence, we use this algorithm with appropriate changes made to suit for our problem and then obtain a solution that is asymptotically optimal. More detail about αBB algorithm will be discussed later in Chapter 4.

- Interval arithmetic

  The convergence characteristics of the αBB algorithm used to solve the problem formulated in Chapter 4 are significantly affected by the quality of the under-estimators used. In the general case, the determination of a values α which result in the construction valid convex under-estimator is a difficult task which requires the calculation the minimum eigenvalues of the functions involved, or of a valid lower bound on these eigenvalues. Thus, successful and simple computation methods must therefore curtail the complexities of the Hessian matrix analysis. This section presents the basic notions and main ideas of such method proposed [56] known as "interval arithmetic".

  Interval arithmetic, is a relatively new branch of mathematics. The concept of interval arithmetic is to compute with intervals of real numbers in place of real numbers. It is powerful enough to provide rigorous mathematical proofs and useful whenever we have to deal with uncertainties. The use of interval arithmetic serves two purposes: it reduces the computational complexity of the calculations and it can solve problems so that the results are guaranteed to be correct.

- INTerval LABoratory: INTLAB

INTLAB is a Matlab toolbox developed and implemented by Dr. Siegfried Rump [58]. It is freely available on-line and has resulted in the increased popularity of the use of interval analysis. INTLAB enables basic operations to be performed on real and complex interval scalars, vectors and matrices. These operations are entered similar to real and complex arithmetic in MATLAB. We use this toolbox to perform interval operations to calculate the value of α. For more information how to use this toolbox, readers can refer to [58] where a tutorial is provided for those who wish to learn how to use INTLAB.

- IBM ILOG CPLEX Optimization

  IBM ILOG CPLEX Optimization Studio or just (CPLEX) [20] is an optimization software package developed by IBM. The IBM ILOG CPLEX Optimizer can solves different types of optimization problems such as linear programming, mixed integer programming, quadratic programming, and quadratically constrained programming problems.

  ILOG CPLEX optimizer available free to academics through the IBM Academic Initiative. We used it to compute the maximum flow by solving our multi-commodity flow problem for multi-hop wireless ad-hoc network with and without cooperative transmission in Chapter 5.

2.5 Chapter Summary

In this Chapter, we mainly talked about four related topics. Cooperative transmission protocols, resource management, distributed relay selection and tools and methodology used in our work for modeling and analysis. In the first part, we have discussed the significant characteristics of the cooperative transmission environment, describing cooperative transmission systems, the relevant protocols and combining techniques proposed for this purpose. Then as a resource management plays an important and vital role of maximizing the diversity gain achieved in wireless cooperative communication systems. In the second and third sections, we discussed the resource management and provided a survey of the distributed relay selection schemes proposed in the literature for ad-hoc cooperative wireless networks respectively. We classified distributed relay selection schemes, and discussed a number of important schemes in each class. We discussed objectives, mechanisms, performance, advantages, and drawbacks of each scheme. We also compared these schemes on a common and representative set of metric. Finally, we outlined and briefly discussed research the methodology we have used to model and analysis our research works. In the following chapter, we have used this background to propose two routing approaches and use the listed tools to model our network and to analysis the performance of the proposed algorithms.

Chapter 3

Multi hop Routing with Cooperative Transmission

3.1 Introduction

As discussed earlier, a new form of distributed MIMO known as cooperative communication has been investigated in the literature, i.e., [21, 24, 26, 31, 36, 59]that leverages cooperation between wireless terminals. These proposed schemes show performance improvement in wireless relay networks and can provide the benefits of diversity without requiring multiple antennas per terminal. Cooperative communication also shows the ability to mitigate fading effects by exploiting spatial diversity. It can be also used to reduce the transmission power required to achieve certain quality of service (QoS). Moreover, cooperative transmission can have a higher communication transmission range with the same transmit power, which often reduces the number of hops along a communication path.

In Chapter 2, we have discussed some related topics such as resource management including power allocation and distributed relay-selection algorithms proposed for cooperative communication scheme to achieve high gain while guaranteeing full diversity order. It is assumed in all the algorithms discussed in the literature survey in chapter 2 that the source can reach the destination in a maximum of two hops. In other words, most of the analysis of cooperative diversity systems proposed in the literature focus on pairs of cooperating terminals only. However, in a multi-user multi hop scenario it is still not clear how relay/relays should be chosen and what would the best path towards the destination? When applying the basic cooperation model into multi-hop networks, routing becomes an important issue.

In recent years, several schemes are reported in the literature for designing efficient routing protocols for a cooperative multi-hop wireless network. A common approach at the network layer is to formalize the energy efficient routing problem. The objective function is either to minimize the energy consumption or to maximize the network lifetime. For example, several schemes are reported to minimize end-to-end energy consumption [4–7, 60], and maximize network lifetime [8]. Lately, different schemes emerge that considers other parameters such as end-to-end outage probability [9, 11] and achievable bit error rate [12, 13].

In this chapter, we consider a general case for a large network where the destination is not reachable directly by the source. We establish the benefits of cooperative transmission in multi hop scenario. Two different routing algorithms are proposed for a cooperative wireless ad-hoc networks. Further they are analyzed through simulation.

Our contributions in this chapter can be summarized as follows:

- We studied the relationship between cooperation and routing according to channel conditions in multi-hop wireless ad hoc networks, formulated the radio coverage for direct and co-operative links in the network and derived the range extension factor Ω, and Edge node based greedy cooperative routing (ENBGCR) algorithm is proposed based on the formulated range.

- We formulated link costs for direct and cooperative links in a network graph in terms of transmission power as a function of given rate. Based on the formulated link cost, we propose a cooperative routing algorithm, which can choose the path from source to destination node minimum-power while achieving the desired rate.

- Performance analysis results for both proposed algorithms and their evaluation in comparison with other non-cooperative routing schemes are discussed.

In this work, the initial analysis is done for a network that has only one flow from a single source to a single destination (ignoring the interference effect) that tries to find the optimum end-to-end path based on the cost metric formulated to show the benefit of using the cooperative transmission over direct transmission in multi-hop wireless ad hoc networks.

The rest of the chapter is organized into four main sections as follows. Section 3.2 describes the system model including network and channel models. Section 3.3 describes the outage analysis and the link cost formulation for both proposed algorithms. Section 3.4 describes the proposed Edge Node based Greedy Routing Algorithm (ENBGCR) and analyzes its performance. Section 3.5 describes the proposed joint relay selection and routing algorithm and analyzes its performance. Finally, the chapter is summarized in Section 3.6.

3.2 System Model

In this section, we describe the wireless channel model and the network model that we use to formulate cooperative routing problem.

3.2.1 Channel model

We consider a wireless ad-hoc network under a slow Rayleigh fading channel. The channel between any two nodes i and j in the network as shown in Fig.3.1 is modeled using a combination of small-scale fading, and path loss [26]. The small-scale fading is quasi-static

Rayleigh fading, where the channel remains the same for several block transmission , i.e., inter-node channels change very slowly (the channel coherence time is much longer than the block transmission duration). This model, called Rayleigh fading channel model, is reasonable for an environment where there are large number of reflectors [2]. The transmitted signal also suffers from propagation path loss that causes the signal to attenuate with distance. The signal received at the receiving node j from transmitting node i is modeled as,

$$y_{i,j} = \sqrt{P}h_{i,j}x_i + n_{i,j}; \quad i,j \in N, \; i \neq j, \tag{3.1}$$

where P is the transmit power, $h_{i,j}$ captures the channel fading gain, x_i is the transmitted symbol with average unit power, and $n_{i,j}$ is the additive white Gaussian noise (AWGN) with zero mean and variance σ_n^2.

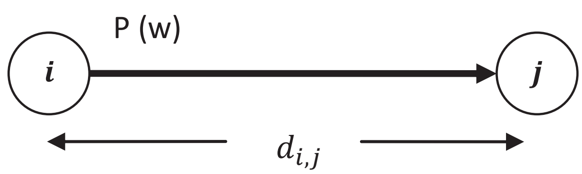


Figure 3.1: Channel model.

3.2.2 Network model

We consider a wireless ad-hoc network consisting of N user nodes including a source and a destination, where each node is equipped with a single omni-directional antenna and transmits with variable power[1] ranging from 0 to P_{max}. These N nodes are assumed to be uniformly distributed in a square area. Decode-and-forward cooperation protocol is considered, and all nodes implement the maximal ratio combing (MRC) technique to combine the received signals. We formulate two routing problems. Given any source-destination pair

[1]For the ENBGCR routing protocol , all nodes are adjusted to transmit with the same power level P

(S, D), the goal of the first scheme, is to find a $S-D$ path that minimizes the total number of hops and hence the transmit power, while satisfying a target outage. The goal of the second scheme, is to find a $S-D$ path that minimizes the total transmit power along the path, while satisfying the target rate.

3.3 Outage Analysis and Link Cost Formulation

We present in this section the outage analysis for direct and DF cooperative links, and derive outage probability for both cases.

3.3.1 Outage probability analysis

Outage probability for direct transmission (DT)

Direct transmission between source and destination is considered as a baseline with channel model defined in section 3.2.1. Using the transceiver channel model in (3.1) for direct transmission, the instantaneous signal-to-noise ratio (SNR) $\gamma_{i,j}$ at node j of the signal transmitted from terminal i can be expressed by,

$$\gamma_{i,j} = \Gamma_{i,j} |h_{i,j}|^2, \tag{3.2}$$

where $|h_{i,j}|$ is the Rayleigh distribution fading magnitude, and $\Gamma_{i,j}$ denotes the mean value of SNR over the fading and accounts for the combination of transmit power and large-scale path loss and shadowing effects.

$$\Gamma_{i,j} = \frac{P}{\sigma_n^2} d_{i,j}^{-\beta}, \tag{3.3}$$

The channel is in outage if the received $\gamma_{i,j}$ falls below selected threshold γ_{thr}, and the corresponding outage event is $\{\gamma_{i,j} < \gamma_{thr}\}$. Thus the outage probability $\mathcal{P}_{out}$ of the channel is given by [26, 45, 61]:

$$\mathcal{P}_{out} = \mathcal{P}_r\{\gamma_{i,j} < \gamma_{thr}\} = \int_0^{\gamma_{thr}} p_{\gamma_{i,j}}(\gamma_{i,j}) d\gamma_{i,j} \tag{3.4}$$

where, $p_{\gamma_{i,j}}(\gamma_{i,j})$ denotes the probability density function (pdf) of random variable $\gamma_{i,j}$. For the case of Rayleigh fading, $\gamma_{i,j}$ has an exponential pdf with parameter $1/\Gamma_{i,j}$ [45]. The outage probability for Rayleigh fading channel can be obtained by averaging over the exponential channel gain distribution, as follows:

$$\mathcal{P}_{out} = \int_0^{\gamma_{thr}} \frac{1}{\Gamma_{i,j}} \exp(-\frac{\gamma_{i,j}}{\Gamma_{i,j}}) d\gamma_{i,j} = 1 - \exp(-\frac{\gamma_{thr}}{\Gamma_{i,j}}). \tag{3.5}$$

where $\Gamma_{i,j}$ is a constant for fixed distance $d_{i,j}$.

<u>Outage probability for cooperative transmission (CT)</u>

For the cooperative transmission, the signal received at the receiving node j and relay r from transmitting node i can be modeled as,

$$\begin{aligned} y_{i,j} &= \sqrt{P} h_{i,j} x_i + n_{i,j}, \\ y_{i,r} &= \sqrt{P} h_{i,r} x_i + n_{i,r}, \end{aligned} \tag{3.6}$$

For decode-and-forward transmission, we require the relay to fully decode the source message, it forwards the packet to the destination as shown in Figure 3.2. The signal received at the

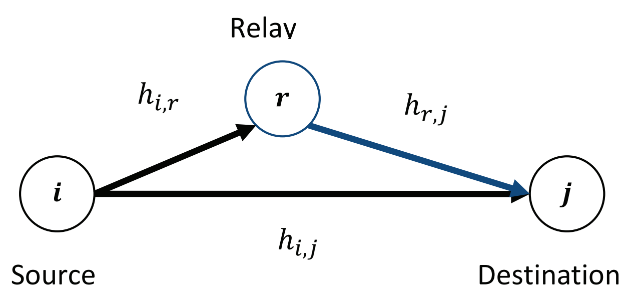


Figure 3.2: An example of cooperative link.

receiving node j from the relaying node can be modeled as,

$$y_{r,j} = \sqrt{P} h_{r,j} x_r + n_{r,j}. \tag{3.7}$$

The two messages from both i and r are combined at node j using the Maximum Ratio Combining (MRC) technique. The cooperative channel is in outage if the received SNR at the relay $\gamma_{i,r}$ or the combined SNR at the destination falls below selected threshold γ_{thr}, and the corresponding outage event is $\big(\min\{\gamma_{i,r}, (\gamma_{i,j} + \gamma_{r,j})\} < \gamma_{thr}\big)$, where the min operator means, it takes into account the fact that the relay only transmits if decoded correctly, and hence the performance is limited by the weakest link between the source−destination and source−relay [61]. For Rayleigh fading the outage probability for DF $\mathcal{P}_{out}^{DF}$ of the channel is given by:

$$\mathcal{P}_{out}^{DF} = \mathcal{P}_r\Big\{\gamma_{i,r} < \gamma_{thr}\Big\} + \mathcal{P}_r\Big\{\gamma_{i,r} > \gamma_{thr}\Big\}\mathcal{P}_r\Big\{(\gamma_{i,j} + \gamma_{r,j}) < \gamma_{thr}\Big\} \tag{3.8}$$

where the term $\mathcal{P}_r\{\gamma_{i,r} < \gamma_{thr}\}$ corresponding to the event that the source-relay channel is in outage, $\mathcal{P}_r\{\gamma_{i,r} > \gamma_{thr}\} = \big(1 - \mathcal{P}_r\{\gamma_{i,r} < \gamma_{thr}\}\big)$ corresponding to the event that the source-relay channel is not in outage, $\mathcal{P}_r\{(\gamma_{i,j} + \gamma_{r,j}) < \gamma_{thr}\}$ the event that the cooperative source-relay-destination channel is in outage, and $\gamma_{thr} = 2^{2R} - 1$ which defined as the SNR threshold that can support the desired rate. The outage probability can be re-written as,

$$\mathcal{P}_{out}^{DF} = \mathcal{P}_r\Big\{|h_{i,r}|^2 < \frac{\gamma_{thr}}{\Gamma}\Big\} + \mathcal{P}_r\Big\{|h_{i,r}|^2 > \frac{\gamma_{thr}}{\Gamma}\Big\}\mathcal{P}_r\Big\{(|h_{i,j}|^2 + |h_{r,j}|^2) < \frac{\gamma_{thr}}{\Gamma}\Big\} \tag{3.9}$$

Assuming the channel is Rayleigh fading, the above random variables are all exponential random variables with parameter one. Averaging over the channel conditions, the outage probability for decode-and-forward at high SNR is given by [26, 45, 61]:

$$\mathcal{P}_{out}^{DF} \simeq \frac{1}{\sigma_{i,r}^2}\frac{\gamma_{thr}}{\Gamma} \tag{3.10}$$

Some simulation results and analysis of the outage defined above are provided to illustrate the effect of cooperation on the required SNR for successful reception. Figure 3.3 shows the required SNR for both cooperative and direct links. As can be seen, the required SNR for cooperative link is much lower than the direct link, which can be translated to a lower transmit power or longer transmission range for the same QoS requirements using cooperative link. For example, from this figure to achieve a target outage probability of 10^{-3} at $R = 0.1$ bit/s/Hz, the required SNR for direct and cooperative transmission are 39dB and 24dB respectively. This outage analysis is useful to formulate the cooperative transmission range extension and the required transmit power in the next two sections.

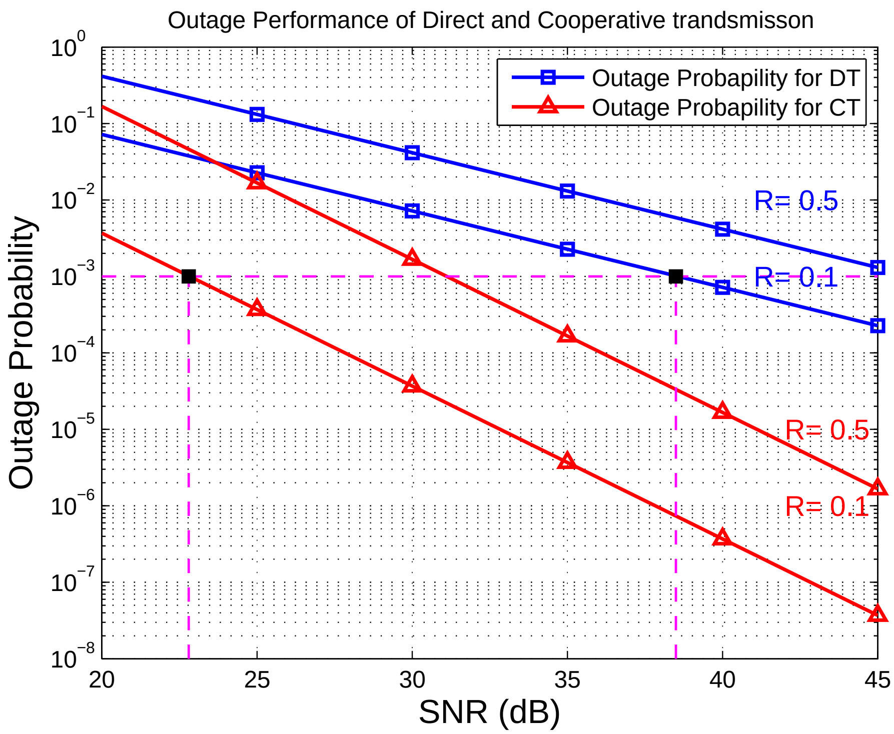


Figure 3.3: Outage probability for direct and cooperative transmission.

3.3.2 Cooperative transmission coverage extension

As discussed previously in outage analysis, using cooperative transmission leads to improve the link quality and reduce the required SNR for successful reception. In this section, we show the benefit of low SNR requirement in cooperative transmission compared with direct transmission, as transmission range extension while satisfying the same outage probability using the same transmit power. The transmission range for cooperative link is extended by the factor of Ω compared with the direct link as shown in Figure 3.4.

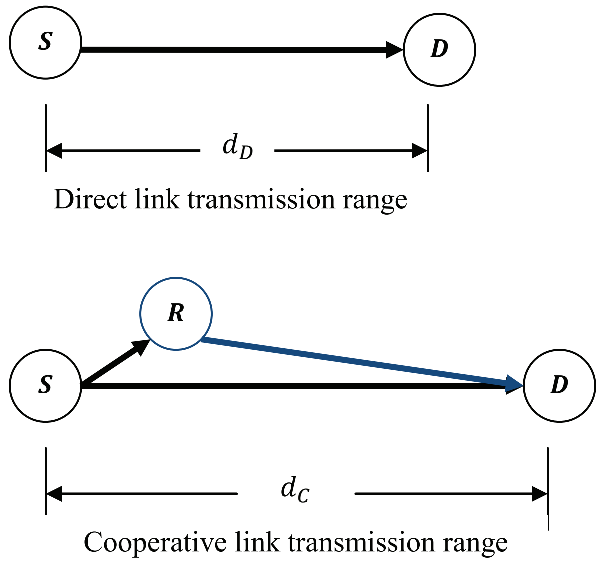


Figure 3.4: Cooperative transmission range extension factor $\Omega = \frac{d_C}{d_D}$, where ($\Omega \geq 1$), and d_C and d_D are the cooperative and direct transmission range respectively.

Lemma 1 *(Cooperative Coverage Lemma): For a given outage probability, the cooperative transmission range of node i is extended by a factor ($\Omega \geq 1$) compared with direct transmission.*

Proof: For a single cooperative relay (i.e., $L = 2$, two independent links direct and cooperative) we give the proof. To simplify our formulation, we assume that the relay node always successfully decode the received message (i.e., the event that the source-relay channel is not in outage, $\mathcal{P}_r\{\gamma_{i,r} > \gamma_{thr}\}$=1) and the distances between source-destination and relay-destination are approximately the same $d_{i,j} \simeq d_{r,j}$. Thus, to achieve the required QoS (i.e., to maintain target outage probability $\mathcal{P}_{out}$), the probability that the received SNR for both direct and cooperative link should be the same as.

$$\mathcal{P}\Bigg\{|h_{i,j}|^2 \leq \gamma_D\Bigg\} = \mathcal{P}\Bigg\{\{|h_{i,j}|^2 + |h_{r,j}|^2\} \leq \gamma_C\Bigg\} = \mathcal{P}_{out} \tag{3.11}$$

where $\gamma_D = \frac{\gamma_{thr}.\sigma_n^2}{P}.d_D^\beta$, $\gamma_C = \frac{\gamma_{thr}.\sigma_n^2}{P}.d_C^\beta$, and γ_{thr} is the SNR thresholds for both direct and cooperative link to maintain the QoS requirement. The sum of $\{|h_{i,j}|^2 + |h_{r,j}|^2\}$, has a Chi-squared distribution with mean[2] L [61], where L is the number of cooperative channels. Finally, we can get the range extension factor Ω as:

$$\Omega = \frac{d_C}{d_D} = \left(\frac{\gamma_C}{\gamma_D}\right)^{\frac{1}{\beta}}, \tag{3.12}$$

Fig.3.5, Ω is calculated for different values of $\frac{\gamma_C}{\gamma_D}$ and β, and it is observed that Ω increases as $\frac{\gamma_C}{\gamma_D}$ increase, and $\beta = 2$ gives larger extension factor values. Clearly, by adding more relays as cooperative relays, the range extension factor Ω increases. However, this can cause significant increase in system complexity. Further, given the same transmit power for all nodes, the SNR gain of cooperation increases the benefit in terms of range extension factor as the data rate increases. In other words, data rate ($R_2 > R_1$) needs higher SNR in order to have the same outage probability as data rate R_1. Since the the transmit power in our system model is fixed, the transmission range varies with data rates. Figure 3.6 gives a better understanding of how data rate affects the expansion factor Ω. In this figure, we show for different path loss exponent β that, as the rate of the link increases, the expansion factor Ω increases.

3.3.3 Transmit power required for direct and cooperative links

Consider that each node can transmit with variable power ranging from 0 to P_{max}, the question is what is the minimum transmit power required to achieve the target rate for both direct and cooperative transmission? In this section we explore answer to this question by formulating the link cost (i.e., power required) for direct and cooperative links as follows:

<u>Direct transmission link:</u>

The link cost for direct transmission (Fig. 3.7) is defined to be the minimum power P_S^D

[2]The mean of the Chi square distribution is the same as degree of freedom

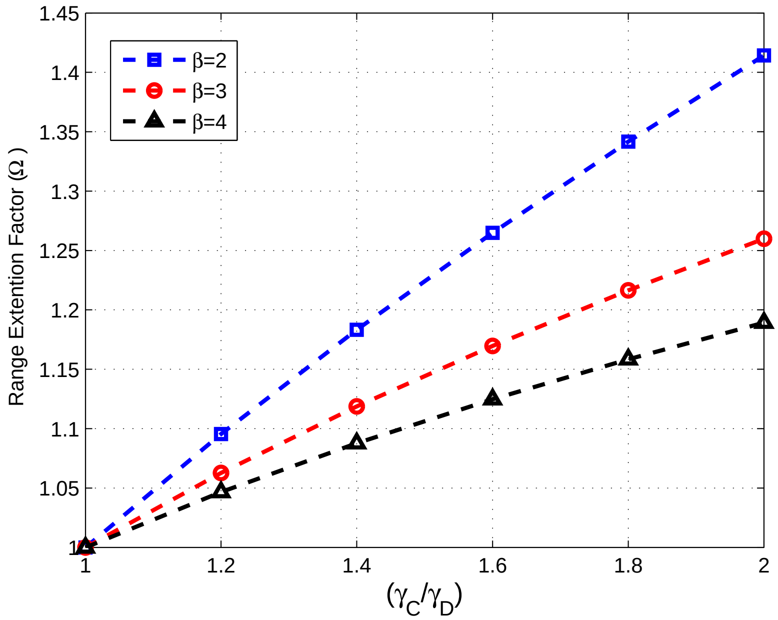


Figure 3.5: Range extension factor using cooperative transmission for different values of β.

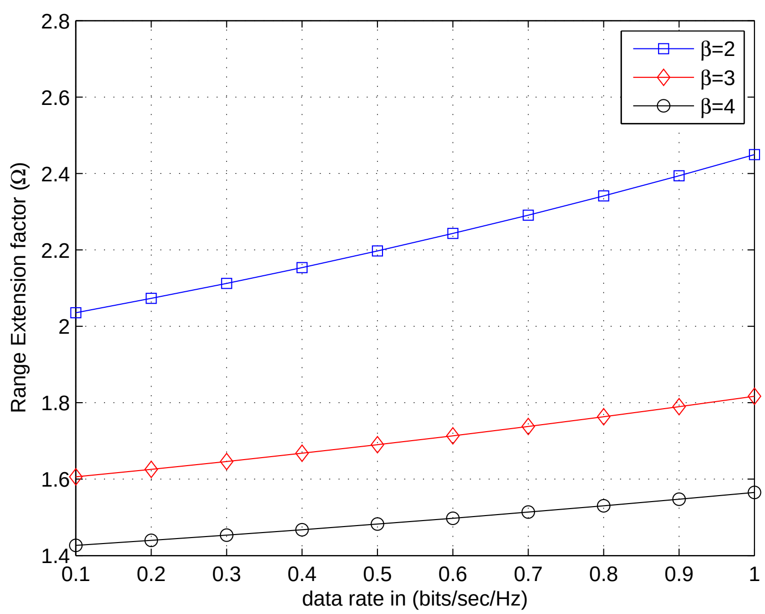


Figure 3.6: Data rate vs range extension using cooperative transmission.

required for transmitting data on a direct link from a transmitter (source) S to a destination D at a target rate R_T which can give by.

Figure 3.7: Direct transmission link.

$$P_S^D = \frac{(2^{R_T} - 1)\sigma_n^2}{d_{S,D}^{-\beta}\mathbb{E}\{|h_{S,D}|^2\}}, \tag{3.13}$$

where d is the distance between two nodes, and R_T is the target data rate in bit/s/Hz, which is defined by the quality of service (QoS) requirement as given below.

$$R_T = \log_2(1 + \gamma_{S,D}) \ \text{ bits/s/Hz.} \tag{3.14}$$

Cooperative transmission link:

The link cost for cooperative transmission (Fig. 3.8) is defined to be the minimum total power required for transmitting data on a cooperative link from a transmitter (source) S with the help of a relay R to the destination D at a target rate R_T.

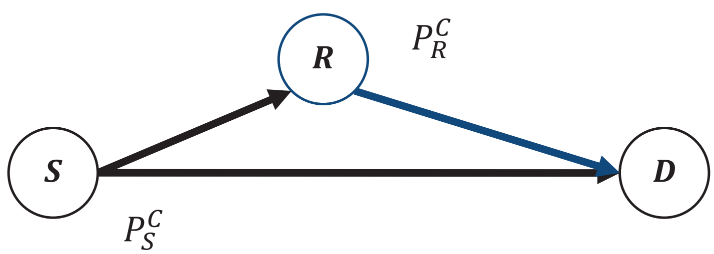


Figure 3.8: Cooperative transmission link

The optimization problem to minimize the total transmit power consumption of a cooperative link with a target end-to-end rate R_T can be formulated as.

$$\begin{aligned}
&\text{minimize } \ \{P_S^C + P_R^C\} \\
&\text{subject to } \ R_T = \frac{1}{2}\min\Big\{ I(\gamma_{S,R}),\ I(\gamma_{S,R,D})_{MRC} \Big\} \\
&\qquad\qquad 0 \leq P_S^C \leq P_{max} \\
&\qquad\qquad 0 \leq P_R^C \leq P_{max}
\end{aligned} \tag{3.15}$$

where $I(\gamma_{S,R})$ and $I(\gamma_{S,R,D})_{MRC}$ are the the mutual information between transmitter-relay and transmitter-relay-receiver respectively which are given by:

$$\begin{aligned}
I(\gamma_{S,R}) &= \log_2\{1 + \gamma_{S,R}\} \text{ bits/s/Hz} \\
I(\gamma_{S,R,D})_{MRC} &= \log_2\{1 + \gamma_{S,D} + \gamma_{R,D}\} \text{ bits/s/Hz}
\end{aligned} \tag{3.16}$$

and the SNR received at the destination D and relay R from the transmitting node (source) S in the first phase is given by:

$$\begin{aligned}
\gamma_{S,D} &= \frac{P_S^C}{\sigma_n^2} d_{S,D}^{-\beta} \mathbb{E}\{|h_{S,D}|^2\} = a_0 P_S^C \\
\gamma_{S,R} &= \frac{P_S^C}{\sigma_n^2} d_{S,R}^{-\beta} \mathbb{E}\{|h_{S,R}|^2\} = a_1 P_S^C
\end{aligned} \tag{3.17}$$

While the SNR received at the destination D from the relay node R in the second phase is given by,

$$\gamma_{R,D} = \frac{P_R^C}{\sigma_n^2} d_{R,D}^{-\beta} \mathbb{E}\{|h_{R,D}|^2\} = a_2 P_R^C \tag{3.18}$$

where $a_0 = \frac{d_{S,D}^{-\beta}\mathbb{E}\{|h_{S,D}|^2\}}{\sigma_n^2}$, $a_1 = \frac{d_{S,R}^{-\beta}\mathbb{E}\{|h_{S,R}|^2\}}{\sigma_n^2}$, and $a_2 = \frac{d_{R,D}^{-\beta}\mathbb{E}\{|h_{R,D}|^2\}}{\sigma_n^2}$, $|h_{S,D}|^2$,$|h_{S,R}|^2$, and $|h_{R,D}|^2$ are mutually independent exponential random variables with unit mean, and $\mathbb{E}\{.\}$ represents the expected value of the random variables. Clearly, the optimum solution exists when $\gamma_{S,R} = \gamma_{S,D} + \gamma_{R,D}$:

$$\begin{aligned}
a_1 P_S^C &= a_0 P_S^C + a_2 P_R^C \\
(a_1 - a_0)\, P_S^C &= a_2 P_R^C
\end{aligned} \tag{3.19}$$

The minimum transmission power allocated to transmitter and relay nodes is based on the values of a_0, a_1, and a_2.

Case I: If $a_0 < a_1$, and $a_0 < a_2$, then cooperative transmission gives optimal result and the allocated power can be expressed as follows:

$$\begin{aligned} P_S^C =& \frac{\left(2^{2R_T} - 1\right)}{a_1} \\ P_R^C =& \frac{(a_1 - a_0)}{a_2} P_S^C \end{aligned} \tag{3.20}$$

Case II: If case I is not satisfied, direct transmission gives optimal result and transmitter transmits its information directly to the receiver without the help of relay. The allocated power is given by:

$$\begin{aligned} P_S^C =& P_S^D = \frac{\left(2^{R_T} - 1\right)}{a_0} \\ P_R^C =& 0 \end{aligned} \tag{3.21}$$

These link cost formulation obtained in 3.13, 3.20, 3.21 will be used as a routing metric for the second proposed routing protocol in 3.5.

In this section, we have discussed the outage analysis and link cost formulation. First, we formulate the transmission range extension factor Ω using cooperative transmission for the same outage level, and then we derived the link cost in terms of transmit power required to achieve the target rate R_T for both the direct and the cooperative transmission modes. In the next section, we describe our proposed cooperative routing algorithms.

3.4 Minimum Hops Cooperative Routing: Edge Node based Greedy Routing Algorithm (ENBGCR)

In this section, we aim at designing a routing protocol to minimize the number of hops involved and, hence, end-to-end latency and power by exploiting the cooperative transmission at physical layer while maintaining the QoS requirements. The extended coverage range for cooperative transmission formulated in 3.3.2 will be used as a performance measure for this algorithm.

3.4.1 Routing protocol

Our objective in designing ENBGCR is to minimize the end-to-end delay, which increases with number of hops. Therefore, our goal is to minimize the number of hops along a path by searching for the next hop located at the edge of the cooperative transmission range that is extended by the factor of Ω compared to direct link. Based on the characteristics of cooperative transmission analysis in Section 3.2 and 3.3.2, we propose a routing algorithm to establish a cooperative route that minimizes the number of hops involved while ensuring the QoS requirement (i.e, outage and data rate).

Geographic routing (GR) is a class of ad hoc routing algorithms that are simple, efficient, and scalable where geographic locations of wireless nodes are used for making routing decisions. It has been shown that GR outperform topology-based approaches such as AODV and DSR with respect to packet delivery ratio and latency [62], also greedy forwarding to neighbors closer to the destination guarantees loop-free operation [63].

In general, the next hop selection in greedy forwarding is based on different criteria, but among them the most widely used criterion is MFR (Most Forward within Radius) [64] which uses Euclidean distance from a node to the destination as metric for selection next hop, i.e. a node forwards a packet to the next hop with least distance to the destination. For example node C in Figure 3.9 is selected as next hop because is lying closer to destination D than node S. In this figure, direct and cooperative radio ranges are denoted by the dotted circle around S with radiuses d_D and d_C respectively, and the arc with radius equal to the distance between nodes A and C to the destination D is shown as the dashed (green and red) arc around D. In case of direct transmission, the source S forwards the packet to A, as the distance between A and D is the shortest than the distance of any other neighbor to the destination D. In case of cooperative transmission, node C will be selected as a next hop. This greedy forwarding process repeats until the packet reaches D.

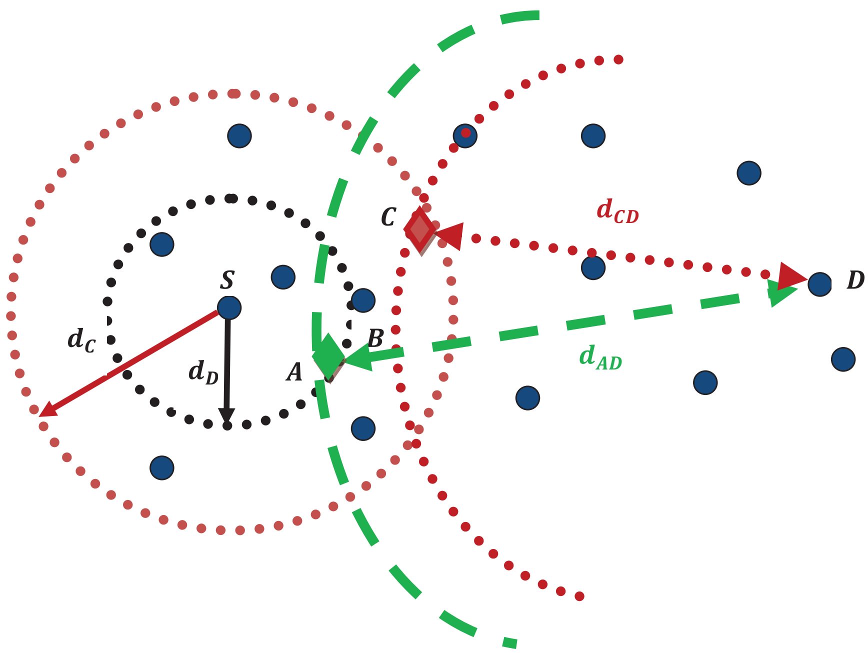


Figure 3.9: Greedy forwarding example: node C is closest to D among the S neighbors .

We assume that all wireless nodes know their own positions, either from a GPS device if they are outdoors or through other means, and the position information is disseminated by an appropriate location service (i.e., via periodic message broadcast). All nodes located within the cooperative transmission range d_C to node i are considered as neighbors (i.e node i should collect their information). The Most Forward within R (MFR) scheme tries to minimize the number of hops a packet has to traverse in order to reach the destination D by selecting a next hop at the edge of transmission range closer to D, thus the latency will be minimized. We define the neighbor of node as follows.

Definition 1: *Node j is considered as a neighbor to node i if the distance between i and*

j is less than the cooperative transmission range. (i.e., $d_{i,j} \leq d_C$; $d_C = \Omega.d_D$)

We modify the GR algorithm to incorporate the new neighbor relationship due to range extension of cooperative transmission. The next hop will be selected according to the MFR scheme in which the source or a next hop node sends packet to one of its neighbors with the least distance towards the destination node (closest neighbor to the destination which is usually the one located at the edge of the cooperative transmission range d_C). We denote this heuristic algorithm as edge node based greedy cooperative routing algorithm (ENBGCR) which constructs the route from the source by adding the "next hop" node one by one until the destination is reached.

3.4.1.1 ENBGCR algorithm

Given the source S and destination D, the heuristic ENBGCR algorithm is described as follows.

1. Given source and destination nodes S, D, and the route $\mathcal{M} = \{\emptyset\}$.
2. Start with the source node $i = S$ and append it to the route: $\mathcal{M} = \{S\}$.
3. Define the cooperative transmission range of the selected node i according to the cooperative transmission range defined in Lemma 1.
4. Form the set $\mathcal{N}(i)$, which is the set of neighbors to the selected node i according to Definition 1.
5. For every neighbors node $j \in \mathcal{N}(i)$, find the distance between those nodes and the destination D.
6. Let j^* be the node with the shortest distance to the destination D. Append node j^* to the route as the next hop node: $\mathcal{M} \leftarrow \mathcal{M} \cup \{j^*\}$, and set $i = j^*$

7. Repeat steps 2-5 until the destination is added to the route.

3.4.2 Results and discussion

In this section, we discuss the results of the proposed ENBGCR scheme. A linear network scenario is assumed for simplicity to provide some insights on the benefits of network performance when cooperative diversity is used. This is obviously a simple case, but it constitutes an important special case of more general networks. Linear networks were considered in many other previous works (e.g., [4, 7, 10]). We assume a dense wireless network where enough number of nodes can be found between source and destination such that at least one cooperative link always exists as in Figure 3.10.

In this figure, there are n nodes placed along a line between the source and destination with inter-node distances $\{d_0, d_1, d_2, \cdots, d_n\}$, where $d_i = d_{i,i+1}$ is the distance from nodes i to $i+1$ and d_0 is the distance from the source S to node 1. The distance from the source to the destination node, $d = \sum_{i=1}^{n} d_i$. We further assume that only one link can be active at any given time. Though the physical layer characteristics (bandwidth and power) are the same for all hops, the average packet delay increases with the number of hops.

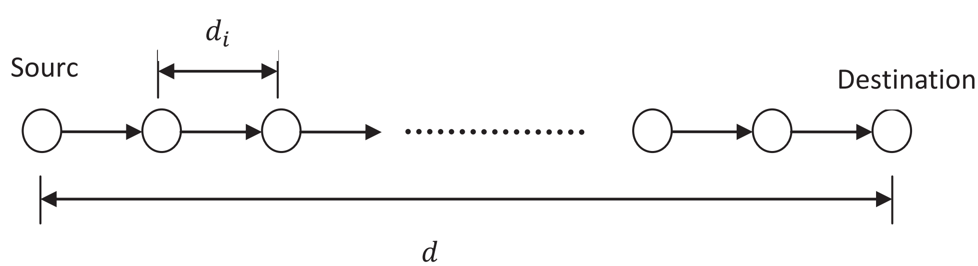


Figure 3.10: Regular linear topology network.

- <u>End-to-End Delay</u>

Let us define the end-to-end delay per packet for cooperative and non-cooperative routing as the time taken (in slots) by a data packet to travel from its point of origin to its destination through a typical path. For a linear topology, with a given distance from the source to the destination d, the minimum number of hops (slots) required to maintain target outage for both direct and cooperative paths is given by $K_{direct} = \lceil \frac{d}{d_D} \rceil$ and $K_{coop} = \lceil \frac{d}{d_C} \rceil$, where $\lceil . \rceil$ is the ceiling function. We focus on the number of hops, since the paths with lower number of hops is expected to incur low end-to-end delay and lower energy consumption.

For data rate $R = 0.1$ bits/sec/Hz and outage probability $p_{out} = 0.1$, Figure 3.11 shows that the performance of the proposed algorithm is better than the shortest non-cooperative path (SNCP) and the cooperation along the shortest non cooperative path (CASNCP) [4]. As the end-to-end distance increases, our algorithm finds paths with fewer hops due to longer cooperative link transmission range as evident from the figure.

- Energy Efficiency of ENBGCR

We compare the average end-to-end energy consumption between SNCP, CASNCP, and ENBGCR algorithms in a linear network topology. In this simulation, a simple energy model [65] is used to calculate the total power consumed along the path of a packet, given a node can transmit with only a single transmit power level P that satisfies the minimum BER required for direct transmission.

In the direct transmission of one bit to a distance d_D, the network consumes energy $E_D = E_{Tx} + E_{Rx}$, where E_{Tx}, and E_{Rx} are the energy expended in transmission and reception by the nodes RF transceivers. The $E_{Tx} = E_{elec} + E_t$ and $E_{Rx} = E_{elec}$, where E_{elec} is the energy required to operate the transmitter or receiver circuitry and E_t is the required transmit energy to achieve the required BER. Assume the size of a data

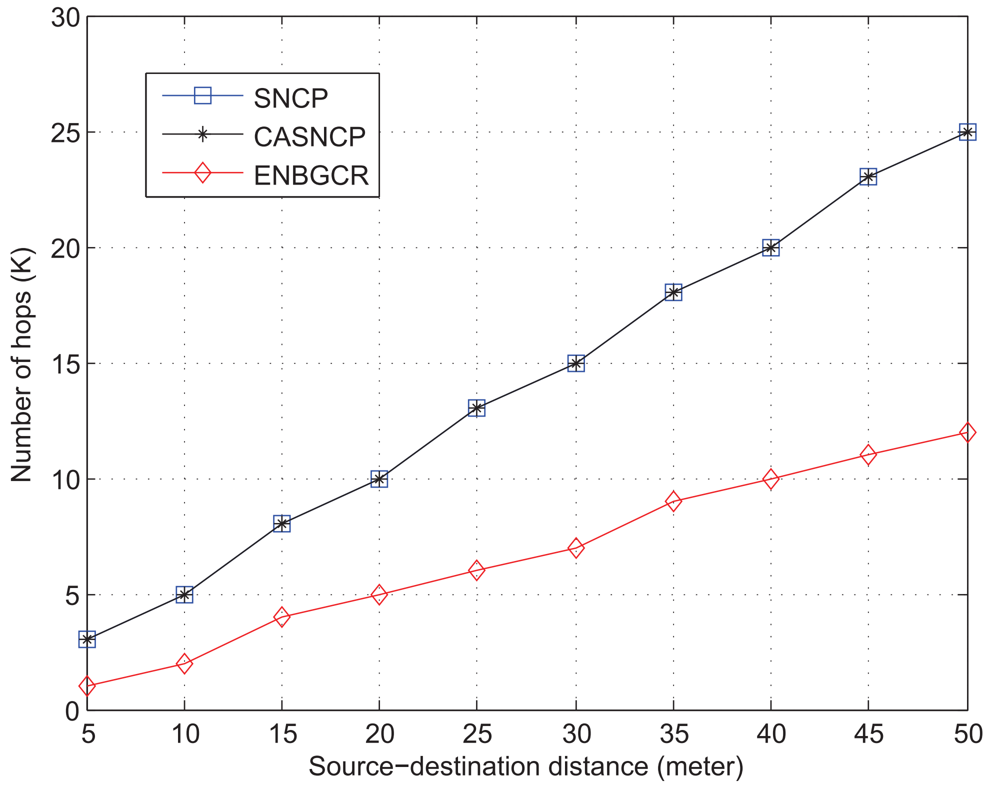


Figure 3.11: Number of hops with multi-hop routing for cooperative transmission and direct transmission for $p_{out} = 0.1$ and $\beta = 2$, and $R = 0.1$ bits/s/Hz

transmission packet be M bits. Therefore, the energy consumed to transmit one data packet (M bits) on a direct transmission link is given by,

$$E_D = M(2E_{elec} + E_t). \tag{3.22}$$

In cooperative transmission, the total energy consumed to transmit one data packet is $E_C = E_1 + E_2$, where E_1, and E_2 are the energy expended in the first and second phase of cooperation which can be calculated as follows.

In the first phase, source transmits the packet and both relay and destination receive the packet. Thus the energy expended in the first phase is $E_1 = M(E_{Tx} + 2E_{Rx})$. In the second phase, relay retransmits the packet to the receiver that consumes energy $E_2 = M(E_{TX}+E_{Rx})$.

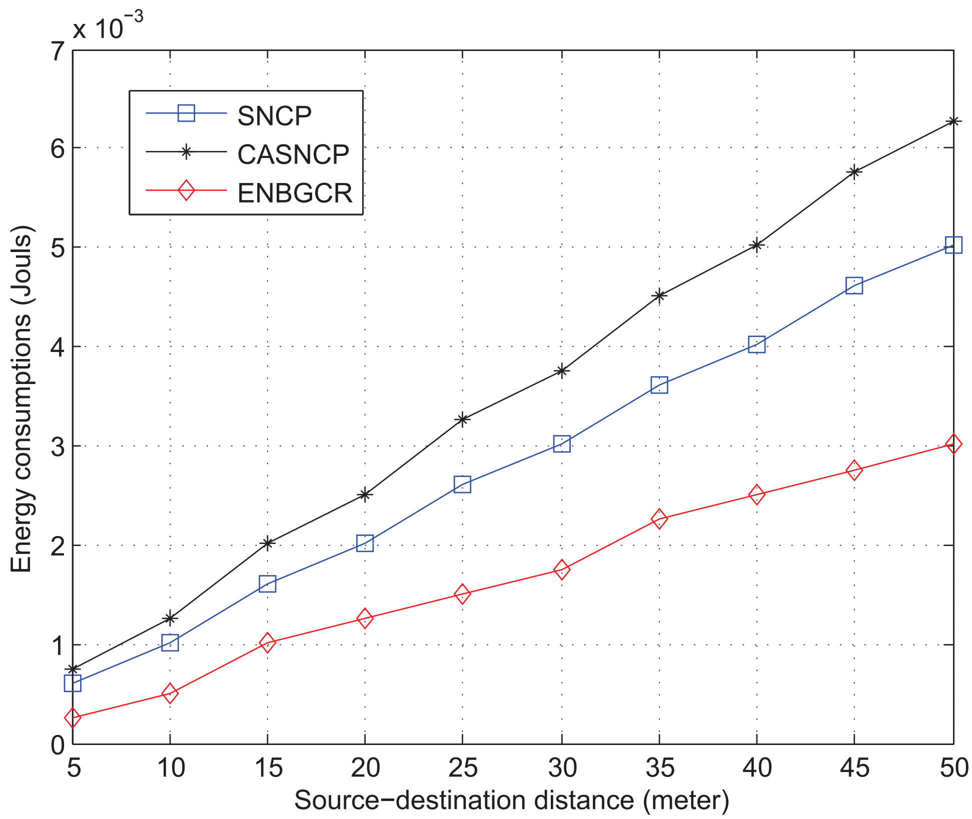


Figure 3.12: Total system energy dissipated using SNCP, CASNCP and ENBGCR routing for the linear network shown in Figure 3.10. $E_{elec} = 50$ nJ/bit, $E_t = 100$ pJ/bit/m^2, and the messages are 2000 bits long.

Therefore, the energy consumption for transmitting one data packet on a cooperative link is given by:

$$E_C = E_1 + E_2 = \frac{M}{2}(5E_{elec} + 2E_t) \tag{3.23}$$

The end-to-end energy consumption is the energy consumed at each hop multiplied by the number of hops. For the energy model used where all nodes transmit with the same power, ENBGCR minimizes the number of transmit and receive operations for each message, which is achieved by minimizing the number of hops. Therefore, ENBGCR requires less energy than SNCP, and CASNCP. The curves in Figure 3.12 show the energy consumption for each protocol. It can be seen that as the distance between source and destination increases

ENBGCR is more energy-efficient than the other two schemes.

3.5 Energy Efficient Routing Protocol: Joint Relay Selection and Routing

We now view the problem of multi hop cooperative transmission from the power-efficient perspective, in which we are investigating the efficiency of cooperative transmission in multi-hop ad hoc network. The objective is to minimize the total end-to-end transmit power while achieving the target data rate. In a multi-hop network, the data from the source node may need to traverse multiple hops before reaching its destination node. Further, cooperative communication can be exploited along the path to minimize the total transmit power.

3.5.1 Routing algorithm

Based on the characteristics of cooperative transmission analyzed in Section 3.3.3, we propose a distributed routing algorithm to establish a cooperative route with minimum total end-to-end transmission power that ensures each link rate no less than a certain target rate R_T.

Similar to [60], our proposed routing scheme uses Dijkstra's algorithm as the basic building block. But the scheme presented in [60] does not consider the effect of fading parameter and consider a simple signal propagation model where the signal power attenuates with distance ($d^{-\beta}$). It is also assumed in the scheme that the last L nodes along the path are allowed for cooperative transmission to the next hop. The worst case complexity of our proposed routing algorithm is $\mathcal{O}(N^2)$, which is the same as that of Dijkstra's algorithm. Since it requires two loops to calculate the cost at each node, and each has maximum length of $N-1$, where N is the number of nodes in the network. Our proposed algorithm can be summarized as follows.

- Given a wireless network modeled as a basic rate connectivity graph $G = (V, E)$, where V is the set of nodes and E is the set of edges/links in the network. The link $(i, j) \in E$ implies that node $i \in S_i$ can directly communicate with node j at the basic rate with certain transmit power level.

- Each node performs the optimization specified in (3.15) to find the optimal transmit power to each of their neighbors at given target rate R_T. Assume that each node broadcasts *HELLO* packet periodically to its neighbors to update the topology information.

- Construct a new connectivity graph $G_1 = (V_1, E_1)$, by replacing those direct links for which cooperative links are found that achieve the given target rate at lower transmit power. The link cost of this new graph (could be direct or cooperative links) is the minimum power required to achieve the target rate.

- The final step is simply to run a shortest path algorithm (e.g. Dijkstra , or Bellman Ford) [66] on the new connectivity graph $G_1 = (V_1, E_1)$, and find a path with the minimum power path which is the minimum total power needed to transmit data along a path from $S \rightarrow D$

3.5.2 Simulation results

In this section, we compare the performance of the proposed algorithm with that of Dijkstra's shortest path routing in the network with no cooperative communication. Our main performance metric is to measure the total power saving achieved compared with non-cooperative shortest path routing. We define the power savings for cooperative routing strategy relative to the optimal non-cooperative strategy by:

$$Saving = \frac{P_T^{non-coop} - P_T^{coop}}{P_T^{non-coop}} \%, \tag{3.24}$$

where $P_T^{non-coop}$ is the total end-to-end power of non cooperative routing, and P_T^{coop} is the total end-to-end power of cooperative routing (our proposed scheme).

We have simulated the algorithm using MATLAB to evaluate their performance. In the following subsections, we present our simulation results and compare the performance with non cooperative algorithm in terms of power saving.

Simulation Setup:

We simulated a network with a varying number of nodes N uniformly distributed in a 100mx100m square area. We choose two nodes as source and destination located at the lower left (0,0) and the upper right (100 ,100) corners of the network, respectively. To show the effect of some parameters on the algorithm, we use different values of path-loss exponent β= 2.5, 3,4 and target rate R_T. For simplicity, the power of additive white Gaussian noise at each receiver is assumed to be equal and unity, i.e. $\sigma_n^2 = 1$. In each plot shown, the results are averaged over 1000 fading realizations and 10 randomly generated topology to get a good statistical relevance.

Impact of the network density on power saving:

Fig. 3.13 and Fig. 3.14 show the impact of network density on the performance of the algorithm in terms of average power saving compared with non-cooperative minimum power routing algorithm. The number of nodes varies from 25 to 50, with different values of β and R_T. The simulation results shows that when the number of nodes increases, the average power savings of the proposed scheme compared with non-cooperative scheme increases. As we can see in Fig 3.13 and Fig 3.14, for the network size of 50 nodes, 57% and 74% of total transmission power can be saved by using cooperative communication when $R_T = 2$ b/s/Hz, and $R_T = 4$ b/s/Hz respectively. This is due to the fact that a larger number of nodes N reduce the distance between neighbors and offers more cooperative transmission opportunities, which leads to more power savings.

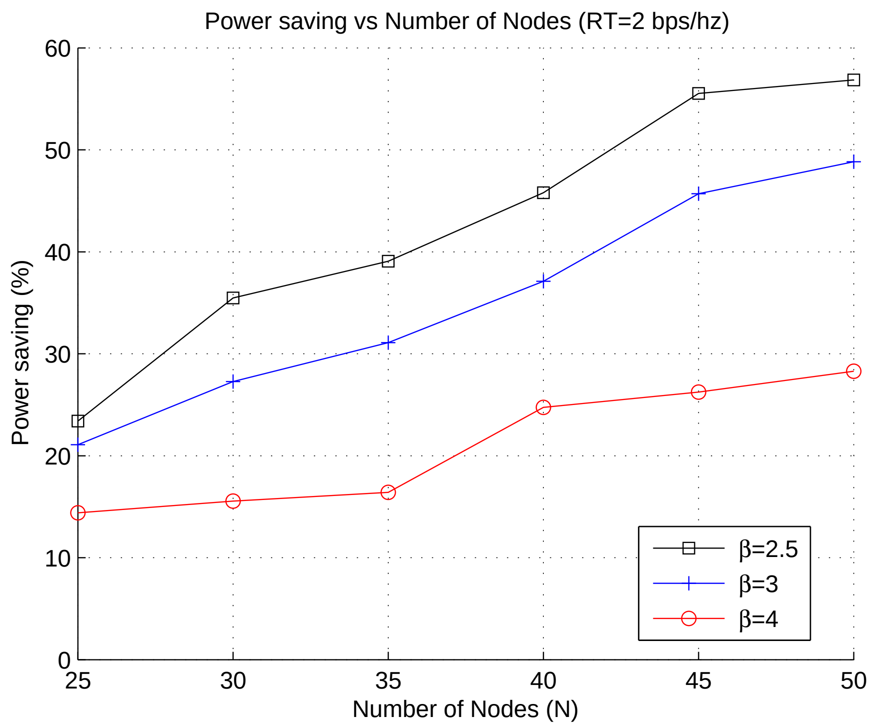


Figure 3.13: Power saving vs. number of nodes for R_T=2 b/s/Hz and different values of β.

<u>Impact of target rate on power saving:</u>

Fig. 3.15 shows the average power saving with increasing target rate for β=2.5 and β=4, and N=50 nodes. We fix β and N and run the simulation for different values of R_T. Simulation results show that the average power saving of the proposed protocol compared with non-cooperative minimum power routing ranges from 45% to 82%. We can also see for higher target rate, the proposed protocol can save more power. It can be concluded from the above results that power saving in the proposed algorithm scales well both with the network size and the rate requirement.

<u>Impact of the network density on the percent of cooperative link in the network</u> :

In Fig. 3.16, we plot the percentage of hops that uses cooperative links versus the number of

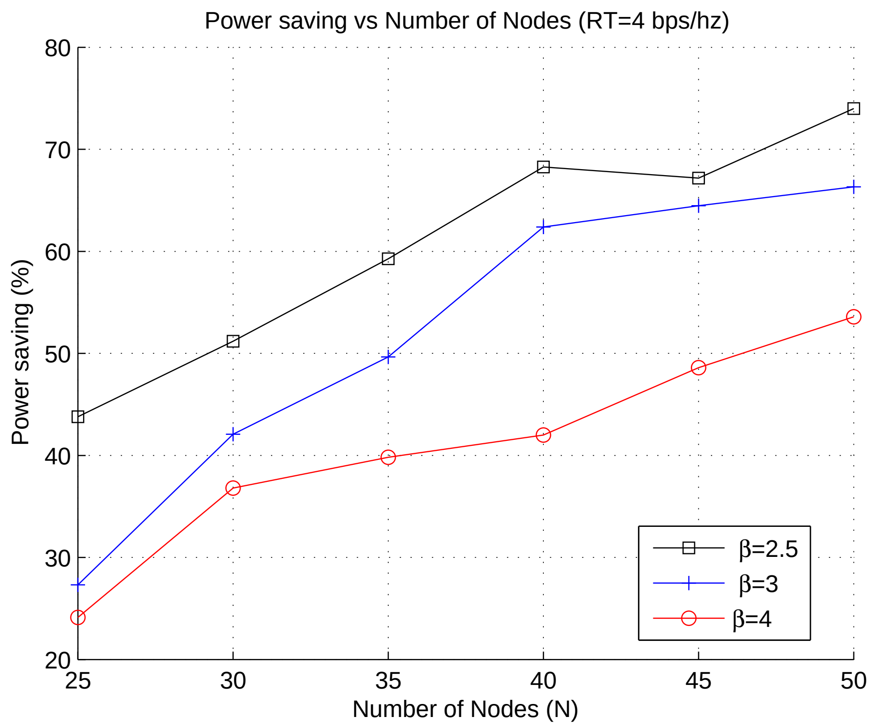


Figure 3.14: Power saving vs. number of nodes for R_T=4 b/s/Hz and different values of β.

nodes in the network N. The average percent of cooperative links in the network is defined as:

$$\eta = \frac{l}{L}\,\% \tag{3.25}$$

where l is the number of cooperative links, and L is the total number of links in the network. As shown in Fig. 3.16, using cooperation becomes more advantageous as the number of nodes in the network N increases; for instance, the percent of cooperative links in the network reaches 95% when R_T=4 b/s/Hz and β=2.5. This shows that the network density as well as the target rate are very important factors in increasing the percent of cooperative links in the network.

Impact of cooperation on individual nodes:

The proposed co-operative routing algorithm tends to minimize total power consumption in routing the packets in the network and its performance scales well with the network size.

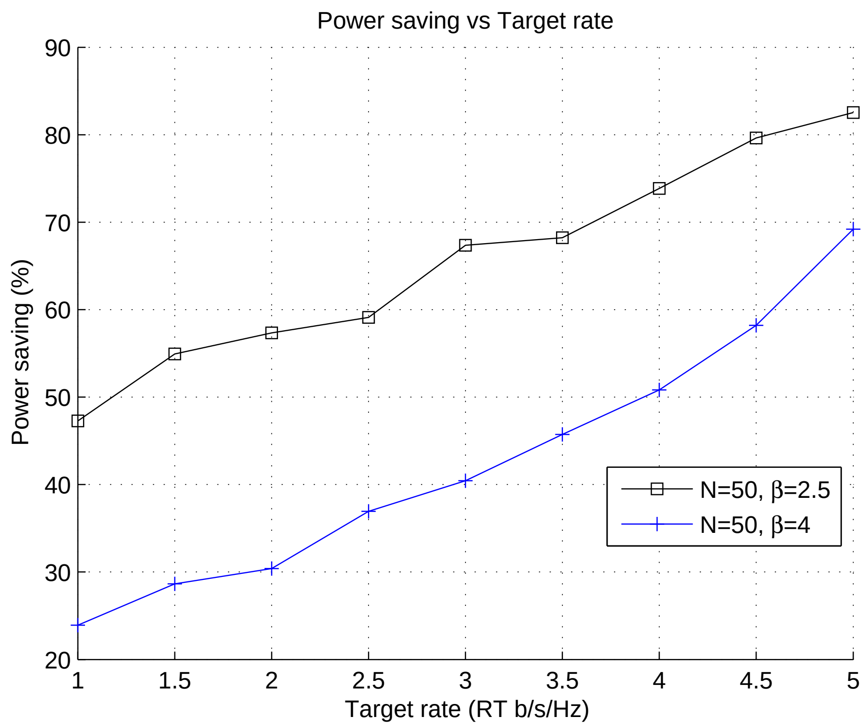


Figure 3.15: Power saving vs. target rate R_T b/s/Hz for β=2.5 and β=4, and N=50 nodes

However, this global optimization has a risk of ignoring conservation of power of individual nodes. In this section we present some simulation results to investigate the overhead, if any, and its impact on the power conservation of single nodes.

To show the effect of using cooperation on the power consumption pattern of individual nodes, we measure and study three performance metrics: power consumption for non-cooperative routing, power consumption of each node when the node serves as a relay, and power consumption of each node when the node serves as a source/transmitter. We simulated the network consisting of 25 nodes randomly distributed in a 100mx 100m square area and computed optimal paths for all possible source/destination pairs. We consider a target rate of $R_T = 4$ b/s/hz and the path loss exponent β= 2.5. The non-cooperative and cooperative routes are found by the Dijkstra's algorithm using the link-based metric derived in section 3.3.3.

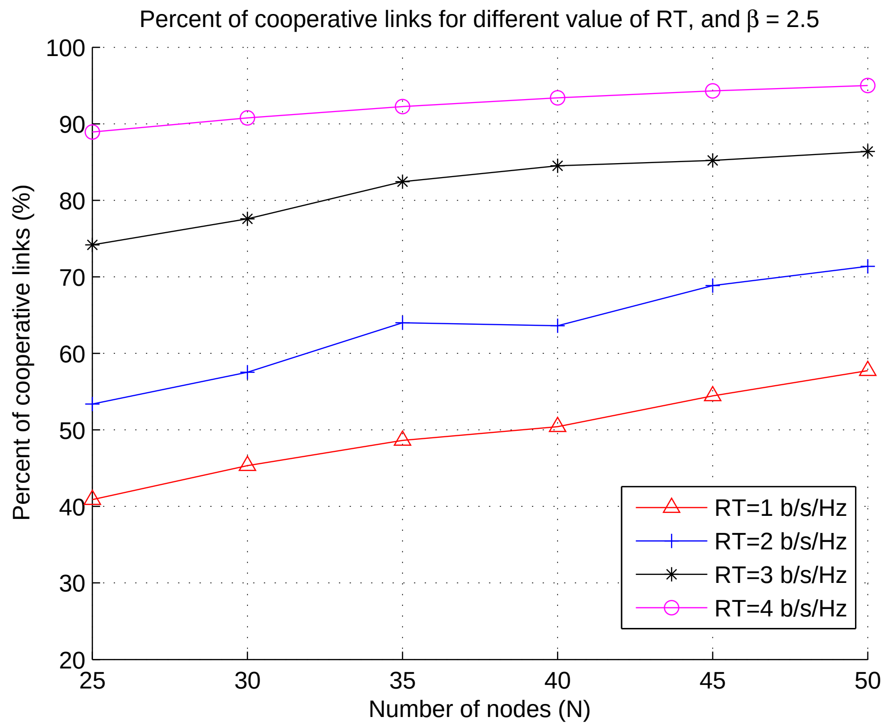


Figure 3.16: Percent of cooperation links vs. network density

The simulation results are presented in Fig. 3.17, which shows that the total power consumption of each node under different source destination pair. From this result we notice that the cooperative routing algorithm essentially outperforms the non-cooperative algorithm, but based on the result shown in Figure 3.17 for the same size and setting of the network, we have more than 12 nodes (48% of all the nodes) have power consumption larger in the case of cooperative routing which clearly shows the overhead in co-operative communication due to using nodes as cooperative relays.

3.6 Chapter Summary

In this chapter, we proposed cooperative routing schemes that exploits the benefits of cooperative transmission in extending the transmission range and in reducing the transmit power

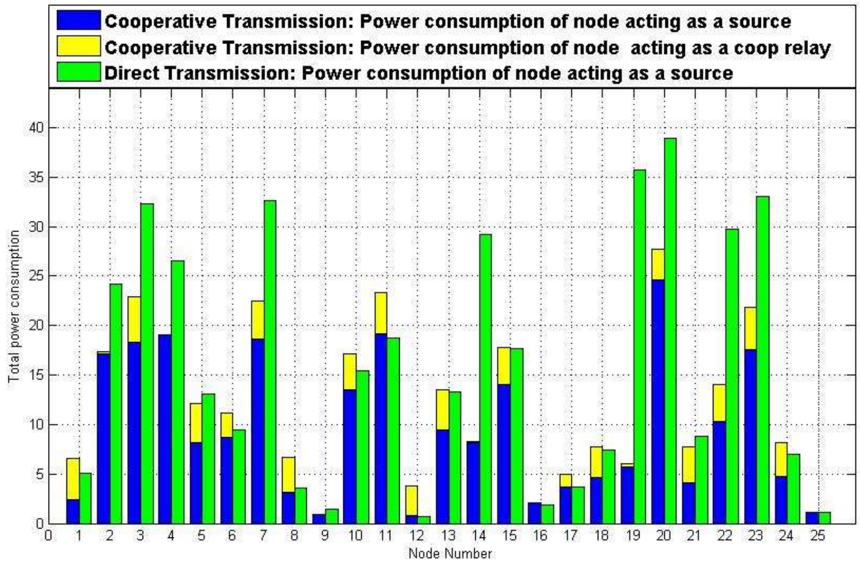


Figure 3.17: Power consumption of each node in the network for β=2.5, N=25 nodes, and target rate R_T=4 b/s/Hz

for a given rate.

First, we proposed a cooperative routing scheme for a multi-hop ad hoc network, with the objective of minimizing the end-to-end number of hops while maintaining the QoS requirement for constant transmit power. We formulated the radio coverage for direct and co-operative links in the network and derived range extension factor Ω. We proposed an edge node based greedy cooperative routing (ENBGCR) algorithm minimizes the number of hops in the path, which results in minimizing the end-to-end delay and total energy consumption along the path. Simulation results demonstrate that our proposed routing scheme can reduce the number of hops which yields substantially less end-to-end delay compared with traditional routing using direct transmission at the physical layer as well as the cooperation along the shortest non-cooperative path. Moreover, the proposed ENBGCR algorithm shows significant power savings as compared to the conventional approaches.

Second, we investigated the problem of routing in a multi-hop ad hoc cooperative network, with the objective of minimizing the end-to-end total power consumption while exploiting the benefit of co-operative transmission in reducing transmit power for a given rate. We formulated link costs for direct and co-operative links in a network graph in terms of transmit power as a function of given rate. Using the link metric our scheme selects minimum energy path for a source-destination pair. The total power consumption along a path can be minimized by choosing co-operative links that consumes less transmission power as compared to their corresponding direct links. Through some reasonable and practical approximations, a distributed routing scheme is proposed based on Dijkstra algorithm. The simulation results demonstrate that our cooperative routing scheme consumes substantially less energy and can achieve considerable power gain compared with non-cooperative routing. The power optimization achieved through the proposed algorithm scales well with the network size and the target rate.

In the next chapter, we consider another parameter (i.e., packet size) in our optimization problem joint with the transmitted power to further increase the energy efficiency of the network.

Chapter 4

Packet Size and Power Joint Optimization of Cooperative Transmission in Wireless Ad Hoc Networks

4.1 Introduction

One of the most important objective and active research area in recent years is the design of energy efficient strategies using cooperative relaying at the physical layer to prolong lifetime of the network. In digital communication, it is well known that energy efficiency can also be improved by choosing optimal packet length at the data link layer. In other words, shorter packets suffer increased overhead, hence reduces the useful fraction of total energy expenditure while longer packets may experience reduced reliability (i.e., experience higher loss rate), thus re-transmissions are required which increases the energy consumption per packet. The packet size optimization jointly with power allocation can further increase the energy efficiency of the cooperative networks. Therefore, in this chapter, we consider the energy-efficient packet size and power allocation optimization problem for cooperative networks. Our work is to jointly determine the optimal packet size as well the optimal power allocation for both the transmitter and the relay with the purpose of optimizing communication energy-efficiency. There are few papers focused on the energy efficiency problem for non-cooperative communication scheme, and the first work in this area investigated it in [67].

The main contribution of this work is that we formulate the energy efficiency and packet optimization problem of the cooperative communication in wireless ad hoc networks and then provide an effective solution method to solve it. To solve the problem, we present an algorithm called α-branch-and- bound (αBB) which yields a global optimum. Our approach is based on the convex relaxation of the original non-convex formulation. This requires the convex lower bounding of all non-convex expressions appearing in the formulation. Based on the terms appearing in the objective function and constraints (i.e., non- convex of special structure, non-convex of generic structure, etc), a convex lower bounding function can be defined for each term.

The rest of this chapter is organized as follows. Section 5.1 describes the system model. Section 4.3 presents the problem formulation and describe the global optimization algorithm. Section 4.4 presents the algorithm implementation and numerical results. Finally, we summarize in Section 5.5.

4.2 System Model

We consider single-relay cooperation strategy with two phases in a wireless ad hoc network. In phase 1, the transmitter sends information to its receiver, and the information is also received by the relay at the same time due to the nature of wireless propagation. In phase 2, the relay node helps the transmitter by forwarding the information to the receiver that it receives in phase 1. The relay node decodes the received information and forwards it, or simply amplifies and forwards it according to the cooperation strategy employed by the relay node (decode-and-forward (DF) or amplify-and-forward (AF) relaying). A suitable model for our analysis is shown in Fig. 4.1.

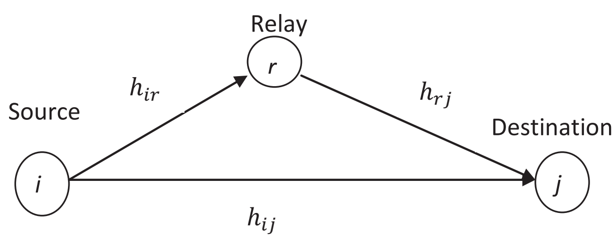


Figure 4.1: System model.

The channel between any two nodes i and j in the network is modeled using a combination of small-scale fading and path loss [26]. The small-scale fading is quasi-static Rayleigh fading in nature, where the channel remains the same for several transmission blocks, i.e., inter-node channels change very slowly. The transmitted signal also suffers from propagation path loss that causes the signal to attenuate with distance. The signal received at the receiving node j from transmitting node i is modeled as,

$$y_{i,j} = \sqrt{P_i} h_{i,j} x_i + n_{i,j}; \quad i \neq j, \tag{4.1}$$

where P_i is the transmitting power at the node i (transmitter), x_i is the transmitted information symbol, $h_{i,j}$ captures the channel fading gain and it is modeled as zero-mean, complex

Gaussian random variables with variances $\delta^2_{i,j}$, and $n_{i,j}$ is the additive white Gaussian noise AWGN which is also modeled as a zero-mean complex Gaussian random variable with variance σ^2_n. According to channel model in (4.1), the received signals $y_{S,D}$ and $y_{S,R}$ for our model in phase 1 at the receiver and the relay respectively can be written as,

$$y_{S,D} = \sqrt{P_S} h_{S,D} x_S + n_{S,D}; \tag{4.2}$$

$$y_{S,R} = \sqrt{P_S} h_{S,R} x_S + n_{S,R}. \tag{4.3}$$

In phase 2, the relay forwards a processed version of the sources signal to the destination, and this can be modeled as,

$$y_{R,D} = h_{R,D} f(y_{S,R}) + n_{R,D}; \tag{4.4}$$

where the function $f(y_{S,R})$ depends on the relaying strategy employed by the relay node. For an AF cooperation protocol, the relay amplifies the received signal by a factor that is inversely proportional to the received power and forwards it to the receiver with transmitted power P_R. The received signal at the receiver in phase 2 in this case is given by,

$$y_{R,D} = \frac{\sqrt{P_S P_R}}{\sqrt{P_S |h_{S,R}|^2 + \sigma^2_n}} h_{R,D} h_{S,R} x_S + \tilde{n}_{R,D}; \tag{4.5}$$

where $\tilde{n}_{R,D} = \frac{\sqrt{P_R}}{\sqrt{P_S |h_{S,R}|^2 + \sigma^2_n}}$. Assuming that $n_{S,R}$ and $n_{R,D}$ are independent, the equivalent noise $\tilde{n}_{R,D}$ is a zero-mean complex Gaussian random variable with variance $\left(\frac{P_R |h_{R,D}|^2}{P_S |h_{S,R}|^2 + \sigma^2_n} + 1\right)\sigma^2_n$.

The receiver receives the two copies of the transmitted signal through the source link and relay link. The signal-to-noise ratio at the output of the MRC is equal to the sum of the received signal-to-noise ratios from both branches which is given by:

$$\gamma^{AF} = \frac{\gamma_{S,R} \gamma_{R,D}}{\gamma_{S,R} + \gamma_{R,D} + 1} \gamma_{S,D}. \tag{4.6}$$

For a DF cooperation protocol, if the relay is able to decode the transmitted symbol correctly, then the relay forwards the decoded symbol with power P_R to the receiver; otherwise, the relay does not send or remains idle. The received signal at the receiver in phase 2 in this case can be modeled as,

$$y_{R,D} = \sqrt{\tilde{P}_R} h_{R,D} x_S + n_{R,D}; \tag{4.7}$$

where $\tilde{P}_R = P_R$ if the relay decodes the transmitted symbol correctly; otherwise, $\tilde{P}_R = 0$. Assume that the receiver combines the two independent copies of the transmitted packet using maximum ratio combining (MRC) technique, the output of MRC is given by:

$$\gamma^{DF} = \gamma_{S,D} + \gamma_{R,D}. \tag{4.8}$$

4.2.1 Cooperative link symbol error rate SER

In this section, we estimate the raw channel SER (Symbol Error Rate) for typical wireless cooperative communication links (DF and AF). We assume B-PSK modulated Rayleigh fading channel model where the SER is equal to the BER [3], the symbol error probability for DF and AF is given as follow [61, 68].

<u>SER of decode and forward DF:</u>

In case of DF and MRC combining, assume that all the channel coefficients are known to the receiver, thus the SNR of the MRC output is maximized which can be defined as:

$$\gamma^{DF} = \gamma_{S,D} + \gamma_{R,D}. \tag{4.9}$$

With the instantaneous SNR γ defined in (4.9), the conditional SER with the channel coefficients $h_{S,D}$, $h_{S,R}$ and $h_{R,D}$ can be written as [69],

$$SER = p_b^{DF} = \Psi(\gamma) \triangleq \frac{1}{\pi} \int_0^{(M-1)\pi/M} \exp(-\frac{b_{PSK} \gamma^{DF}}{sin^2\theta}) d\theta \tag{4.10}$$

where, $b_{PSK} = \sin^2(\pi/M)$. Taking into account the two scenarios (i.e., the relay decodes the transmitted symbol correctly ($\tilde{P}_R = P_R$) or not ($\tilde{P}_R = 0$), we further calculate the conditional SER in (4.10) as follows:

$$SER = p_b^{DF} = \Psi(\gamma_{S,R}).\Psi(\gamma)|_{\tilde{P}_R=0} + \left[1 - \Psi(\gamma_{S,R})\right]\Psi(\gamma)|_{\tilde{P}_R=P_R}. \tag{4.11}$$

Averaging over the Rayleigh fading channels, the SER of the cooperation system with M-PSK modulation can be given by [61],

$$\begin{aligned} p_b^{DF} =& F_1\left(1 + \frac{b_{PSK}P_S\delta_{S,D}^2}{\sigma_{S,D}^2\sin^2(\theta)}\right)F_1\left(1 + \frac{b_{PSK}P_S\delta_{S,R}^2}{\sigma_{S,D}^2\sin^2(\theta)}\right) + \\ & F_1\left((1 + \frac{b_{PSK}P_S\delta_{S,D}^2}{\sigma_{S,D}^2\sin^2(\theta)})(1 + \frac{b_{PSK}P_S\delta_{S,D}^2}{\sigma_{R,D}^2\sin^2(\theta)})\right)\left[1 - F_1\left(1 + \frac{b_{PSK}P_S\delta_{S,D}^2}{\sigma_{S,D}^2\sin^2(\theta)}\right)\right] \end{aligned} \tag{4.12}$$

where

$$F_1(x(\theta)) = \frac{1}{\pi}\int_0^{(M-1)\pi/M} \frac{1}{x(\theta)}d\theta \tag{4.13}$$

SER of amplify and forward AF:

With M-PSK modulations, a closed-form SER formulations are given for AF cooperation systems [61]. Similarly, with the instantaneous SNR γ defined in (4.6), the conditional SER of AF cooperation systems with the channel coefficients $h_{S,D}$, $h_{S,R}$ and $h_{R,D}$ can be written as follows:

$$p_b^{AF} \approx \frac{1}{\pi}\int_0^{(M-1)\pi/M} \exp\left(-\frac{b_{PSK}\gamma^{AF}}{\sin^2\theta}\right)d\theta \tag{4.14}$$

where, $b_{PSK} = sin^2(\pi/M)$. By averaging over the Rayleigh fading channels $h_{S,D}$, $h_{S,R}$ and $h_{R,D}$, we obtain the SER of AF cooperation systems as:

$$p_b^{AF} \approx \frac{1}{\pi}\int_0^{(M-1)\pi/M} \mathcal{M}_{\gamma_1}\left(\frac{b_{PSK}}{\sin^2\theta}\right)\mathcal{M}_{\gamma_2}\left(\frac{b_{PSK}}{\sin^2\theta}\right)d\theta \tag{4.15}$$

where, $\gamma_1 = \gamma_{S,D}$, $\gamma_2 = \frac{\gamma S,R\gamma R,D}{\gamma S,R+\gamma R,D+1}$, and $\mathcal{M}_{\gamma_1}$ and $\mathcal{M}_{\gamma_2}$ denotes the moment-generating function (MGF) of a random variables γ_1 and γ_2 respectively. The moment-generating function (MGF) of a random variable Z can be expressed for any real number s as:

$$\mathcal{M}_Z(s) = \int_{-\infty}^{\infty} \exp(-sz)p_Z(z)dz, \tag{4.16}$$

4.3 Problem Formulation and Solution

The goal of our work is to obtain the optimal packet size and power allocation for the transmitter and the relay that maximizes the energy-efficiency of the network by minimizing our objective function defined in (4.17), which represents the energy consumption for useful bit between a particular transmitter receiver pair. Minimizing $\mathcal{F}(l, P_S, P_R)$ results in optimal packet size values that achieve high energy efficiency.

$$\mathcal{F}(l, P_S, P_R) = \frac{P_S + P_R}{l(1 - PER)} = \frac{P_S + P_R}{l(1 - p_b^*)^{\frac{L}{b}}}, \tag{4.17}$$

where P_S and P_R are the transmitter and the relay transmit power respectively, which represents the total energy consumption to transport a packet from a source to a destination, PER represent the packet, p_b^* represent the symbol error rate of the DF and AF cooperative link defined in (4.12),(4.15) respectively, the asterisk symbol (*) represents the cooperative technique used (DF or AF), l and L are the payload and the total packet size respectively where ($L = l + \tau$) and τ is the header size, and b is the number of bits per symbol. Using the above objective function, the basic optimization problem formulation is given by:

$$\begin{aligned} \underset{l, P_S, P_R}{\text{minimize}} \quad & \mathcal{F}(l, P) = \frac{P_S + P_R}{l(1 - p_b^*)^{\frac{l+\tau}{b}}} \\ \text{subject to} \quad & 0 \leq P_S \leq P_{max} \\ & 0 \leq P_R \leq P_{max} \\ & 1 \leq l \leq l_{max} \end{aligned} \tag{4.18}$$

4.3.1 Globally optimal solution

Typically, the problem formulation shown in (4.18) is a non-convex nonlinear programming problem (NLP) due to the presence of non-convex term in our objective function $\mathcal{F}$. Hence, using the existing convex optimization techniques may fail to locate the global optimum of the problem. Many methods are proposed in the literature to determine the optimal solution of such type of problems and most of them rely on generating a valid convex under-estimation for the non-convex function. The α-BB algorithm proposed in [56,70] is one of those methods and it is very well suited for our problem. Hence, we use this algorithm with appropriate changes made to suit our problem, and then obtain a solution that is asymptotically optimal.

4.3.1.1 The branch and bound global optimization algorithm α-BB

α-BB is a global optimization algorithm designed to handle general constrained non-convex optimization problems with twice-differentiable functions. It combines a convex lower bounding procedure based on interval arithmetic where the general non-convex terms are under-estimated through quadratic functions derived from second-order information within a branch and bound framework.

The key idea is the construction of upper and lower bounds on the global minimum through the convex relaxation of the original problem. It is based on the improvement of converging lower and upper bounds, where lower bounds are obtained through the solution of the underestimated convex problem and upper bounds based on the solution of the original problem with any local methods. The flowchart structure of the algorithm is illustrated in Fig.(4.2)

4.3.2 Objective function under-estimation:

To simplify the formulated problem, we assume the source and relay nodes transmit with the same power (i.e., $P_S = P_R = \frac{P}{2}$). A twice-differentiable function $\mathcal{F}$ defined over a region l, P can be under-estimated by the function $\mathscr{L}(l, P)$:

$$\mathscr{L}(l,P) = \mathcal{F}(l,P) + \alpha\Bigg[(l^{LB} - l)(l^{UB} - l) + (P^{LB} - P)(P^{UB} - P)\Bigg]; \tag{4.19}$$

where α is a positive scalar. Furthermore, it was shown that this under-estimator is convex

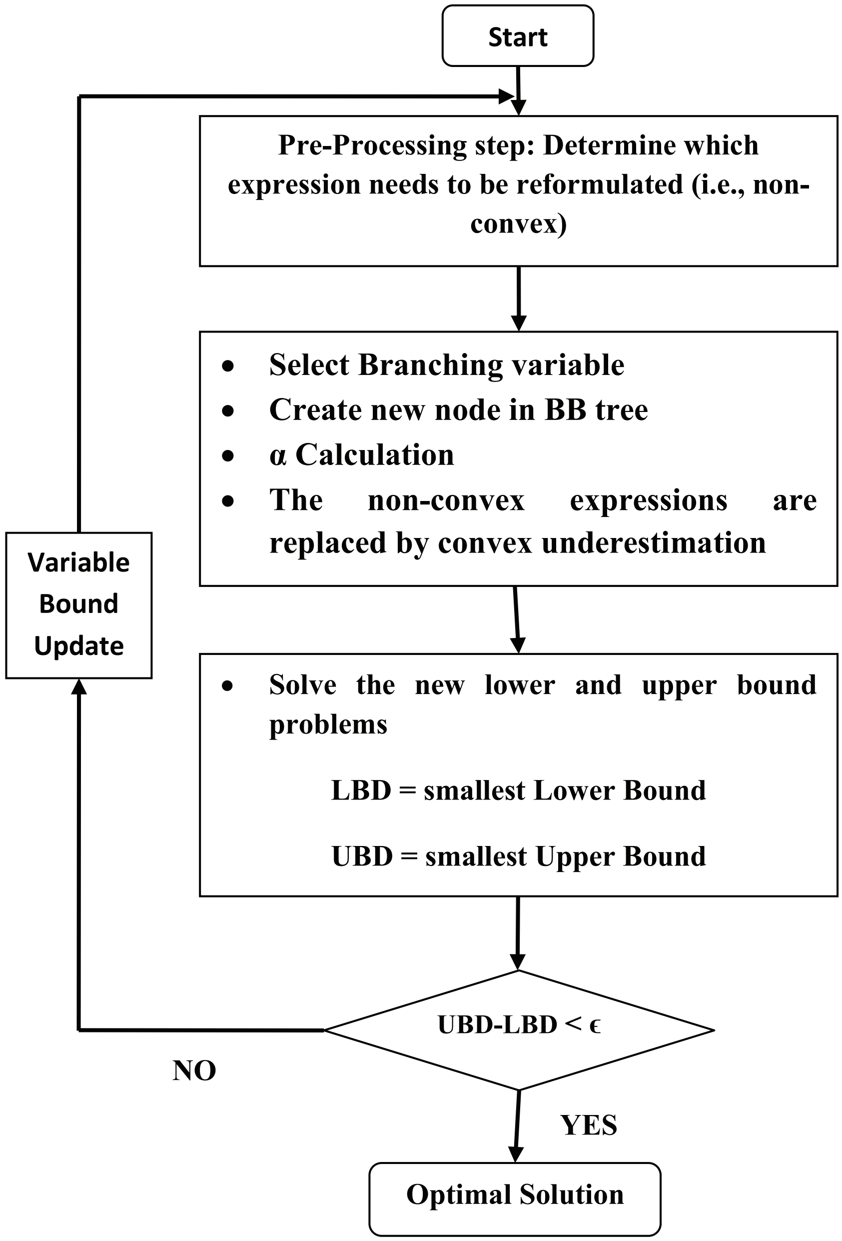


Figure 4.2: Flowchart for the algorithm α-BB.

if and only if the following condition is imposed:

$$\alpha = \left\{0, -\frac{1}{2} \min_{\substack{i \\ l^{LB} \leq l \leq l^{UB} \\ P^{LB} \leq P \leq P^{UB}}} \lambda_i(l, P)\right\}; \tag{4.20}$$

where the $\lambda_i(l, P)$'s are the eigenvalues of the function $\mathcal{F}(l, P)$.

Theorem 1. *Under-estimator $\mathscr{L}(l,P)$ for the function $\mathcal{F}(l,P)$, as defined in (4.19), is convex if and only if $H_{\mathcal{F}}(l,P) + 2\Delta = H_{\mathcal{F}}(l,P) + 2diag(\alpha_i)$ is positive semi-defined for all $l \in [l^{LB}, l^{UB}]$ and $P \in [P^{LB}, P^{UB}]$, where Δ is a diagonal matrix whose diagonal elements are α's.*

The fundamental ideas of the α-BB approach are illustrated in Fig. (4.3) where first two stages of illustrative BB procedure and the underestimating of the objective function $\mathcal{F}$ are shown. In node 0, a convex relaxation $\mathscr{L}$ (dashed line) of a non-convex problem $\mathcal{F}$ (solid line) is found on a given interval of variable. In the first and second node (node 1 & 2), the interval is branched and the convex relaxations of original problem is estimated on each branch. At each stage the global optimal solution is known to be between lower (LB) and upper (UB) bound. If LB is sufficiently close to UB, the algorithm terminates. If not, the feasible region is subdivided into parts as shown in Fig. (4.3) node 1&2.

4.3.2.1 Hessian matrix of the original objective function:

Before we describe the methods of calculation α, let us derive the Hessian matrix $H_{\mathcal{F}}(l,P)$ of the original function $\mathcal{F}(l,P)$. by inserting the SER of DF or AF defined in (4.12) and (4.15). The Hessian matrix of $\mathcal{F}(l,P)$ can be derived by taking the first and second derivative of the objective function defined in (4.17) as:

$$H_{\mathcal{F}(l,P)} = \begin{pmatrix} \frac{d^2}{dl^2}\mathcal{F}(l,P) & \frac{d^2}{dl.dP}\mathcal{F}(l,P) \\ \frac{d^2}{dl.dP}\mathcal{F}(l,P) & \frac{d^2}{dP^2}\mathcal{F}(l,P) \end{pmatrix} \tag{4.21}$$

4.3.3 α calculation:

The α is an important parameter that controls the convexity of the under-estimator $\mathscr{L}(l,P)$. The calculation of α parameter is directly related to the minimum eigenvalue of the Hessian matrix of the objective function (4.21). Minimum eigenvalue of the Hessian matrix can be

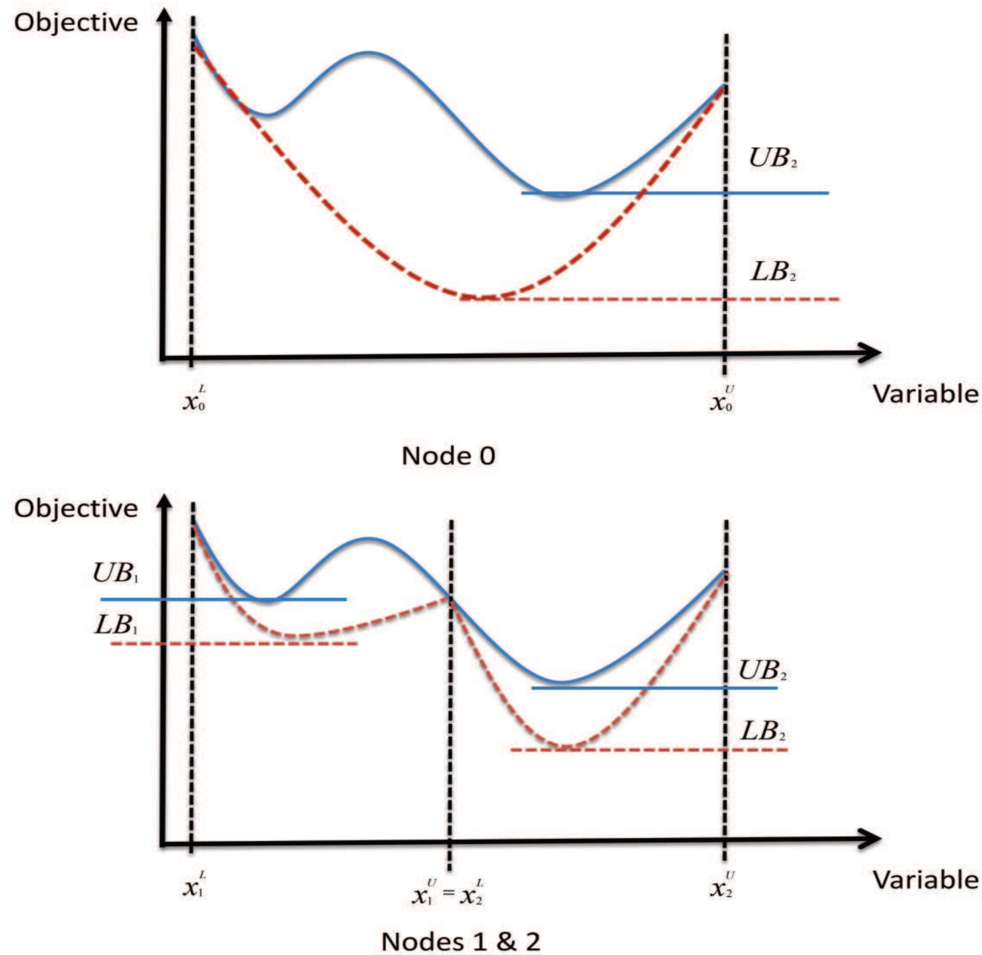


Figure 4.3: Graphical interpretation of the first two stages of α-BB algorithm.

obtained by solving the minimization problem in (4.20); however, this problem in general is a difficult non-convex optimization problem which can not be solved to global optimality using available optimization techniques (i.e., exact λ_{min} can not be obtained). To avoid the issue, alternative simpler approach was proposed to calculate λ_{min} and then α, through the use of interval analysis matrices technique [56]. In this approach, an interval Hessian matrix $[H_{\mathcal{F}}] \supseteq H_{\mathcal{F}}(l, P)$ is introduced. In general, a Hessian matrix $H_f(x)$ of twice deferential function $f(x)$ defined over x can be transformed into an interval matrix $H_{f,X}$. Based on the Hessian matrix $H_{\mathcal{F}}(l, P)$ in (4.21), an interval Hessian family $[H_{\mathcal{F}}]$ which contains $H_{\mathcal{F}}(l, P)$

over the domain of interest can be determined as.

$$H_f(x) = \begin{pmatrix} a_{11} & ... & a_{1n} \\ . & . & . \\ . & . & . \\ . & . & . \\ a_{n1} & ... & a_{nn} \end{pmatrix} \subseteq H_{f,X}$$

$$H_{f,X} = \begin{pmatrix} [\underline{a}_{11}, \overline{a}_{11}] & ... & [\underline{a}_{1n}, \overline{a}_{1n}] \\ . & . & . \\ . & . & . \\ . & . & . \\ [\underline{a}_{n1}, \overline{a}_{n1}] & ... & [\underline{a}_{nn}, \overline{a}_{nn}] \end{pmatrix} \tag{4.22}$$

To find the values of α's that satisfy the condition of convexity of the under-estimator, variety of methods have been proposed to compute a bound on the minimum eigenvalue of symmetric interval matrix, one method based on Gerschgorin's theorem [71] is considered in our work. Thus, for interval matrix, to find its eigenvalue, we can use Theorem 3 [56] which is straightforward extension of Theorem 2 for real matrix.

Theorem 2. *For a real matrix $A = (a_{ij})$, the eigenvalues are bounded below λ_{min} such that:*

$$\lambda_{min} \geq \min_i \Big[a_{ii} - \sum_{j \neq i} |a_{ij}| \Big].$$

Theorem 3. *For an interval matrix $[A] = ([\underline{a}_{ij}, \overline{a}_{ij}])$, a lower bound on the minimum eigenvalue is given by:*

$$\lambda_{min} \geq \min_i \Big[\underline{a}_{ii} - \sum_{j \neq i} max(|\underline{a}_{ij}|, |\overline{a}_{ij}|) \Big].$$

4.4 Algorithm Implementation and Results

The αBB algorithm was implemented in MATLAB 7.11 on a workstation with 3.2 GHz Intel Duo Processor with 4GB RAM. The interval calculations needed were performed using INTLAB Toolbox by Rump [58]. This toolbox finds the eigenvalues of interval family matrices using Gerschgorin's theorem for interval matrices.

In our problem, our objective is to optimize the packet size and power allocation such that the energy efficiency gain is maximized. Without the loss of the generality, we assume that the S, R, and D nodes lie along a straight line, the S-D is 30 m away, and the S-R distance is equal to $d_{S,R} = \rho d_{S,D}$ where $0 < \rho < 1$. The path loss exponent β is taken to be 3, and the packet header is fixed to 2^5 bits.

4.4.1 Effects of relay locations on optimal packet size and power allocation

We study the effects of relay locations on the packet size that maximize the energy efficiency. Figure 4.4 shows the optimum packet size that maximizes the energy efficiency of cooperative link for different relay locations. The S-D distance is 30m. The energy efficiency can be maximized with different packet sizes at different relay locations.

The optimization results reveal that, the maximum optimal packet size is allocated when the relay node is located in the middle between transmitter and receiver, which means that the S-R distance equals to the R-D distance and the energy efficiency gain is best among all of relay locations. As expected, this is because the received SNR for cooperative link is maximized when the relay located in the middle between S-D and hence the best performance of probability of error is achieved as shown in the dashed line. Our results also show that the power allocated to the transmitter and relay are the same for all relay locations.

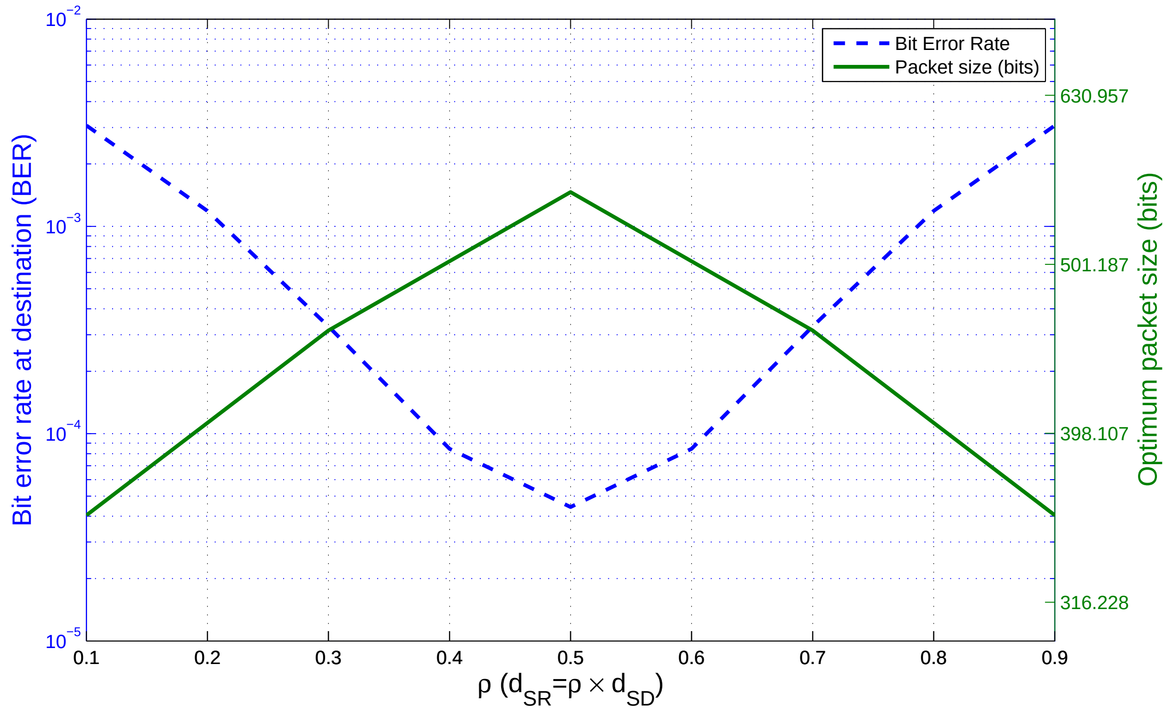


Figure 4.4: Packet size and BER vs relay location.

Similarly, for the same power allocated in the case of cooperative link, we run the solver to find the optimal packet sizes for direct link scenarios which is (250 bits), here we further discuss the performance gain achieved from the packet size optimization compared to direct transmission. We study the data transmission efficiency ξ which is defined as the ratio of the difference between the optimum cooperative and direct data payload to the optimum cooperative payload.

As depicted in Fig. 4.5, the data transmission efficiency increases with the relay location and reaches the maximum efficiency ($\approx 55\%$) at $\rho = 0.5$.

4.4.2 Algorithm convergence

Fig. 4.6 shows the typical convergence behavior of the α-BB algorithm for a single channel realization. It can be observed that α-BB algorithm which exploits the reformulation intro-

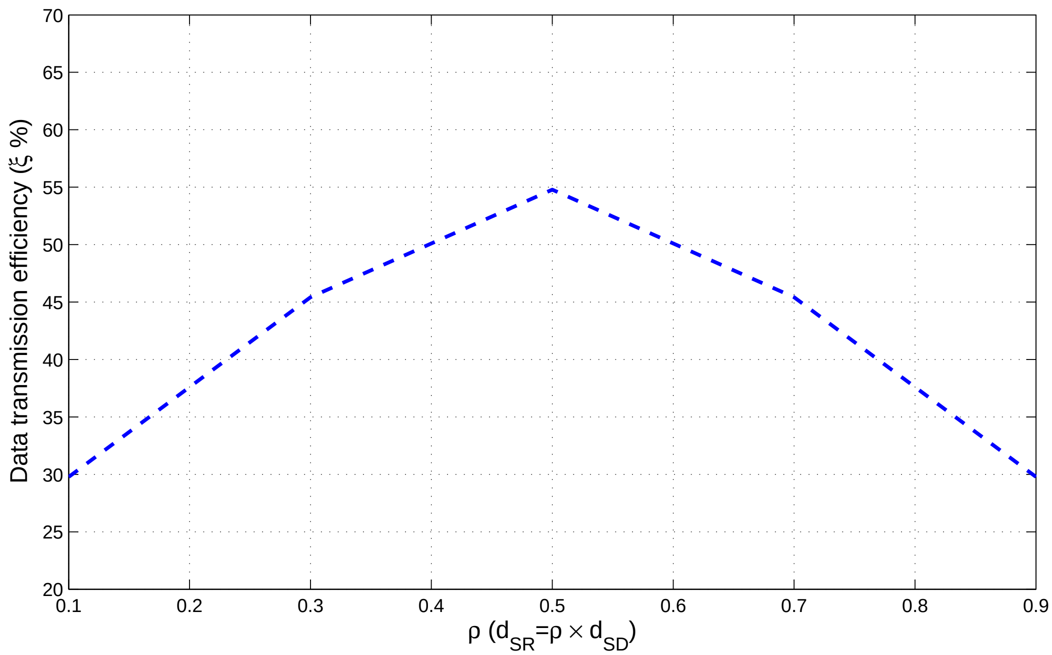


Figure 4.5: Data transmission efficiency vs relay locations.

duced in Section 4.3 converges to optimum solution in acceptable time. The α-BB algorithm with convex under-estimators takes about 60 iterations to identify the global minimum.

4.5 Chapter Summary

In this paper, an efficient joint packet size and power allocation problem for a cooperative wireless ad hoc network has been proposed. The objective is to improve the energy efficiency of the network by optimizing the packet size and transmit power. Joint packet size and power allocation is a non-linear non-convex optimization problem which is combinatorially hard and traditional algorithms may end with local solutions. For that, an efficient and global solution with low complexity using convex relaxation approach has been proposed. The global optimization method α-BB, is introduced for solving our formulated optimization problem. A convex relaxation of the original problem is constructed by replacing all non-convex terms

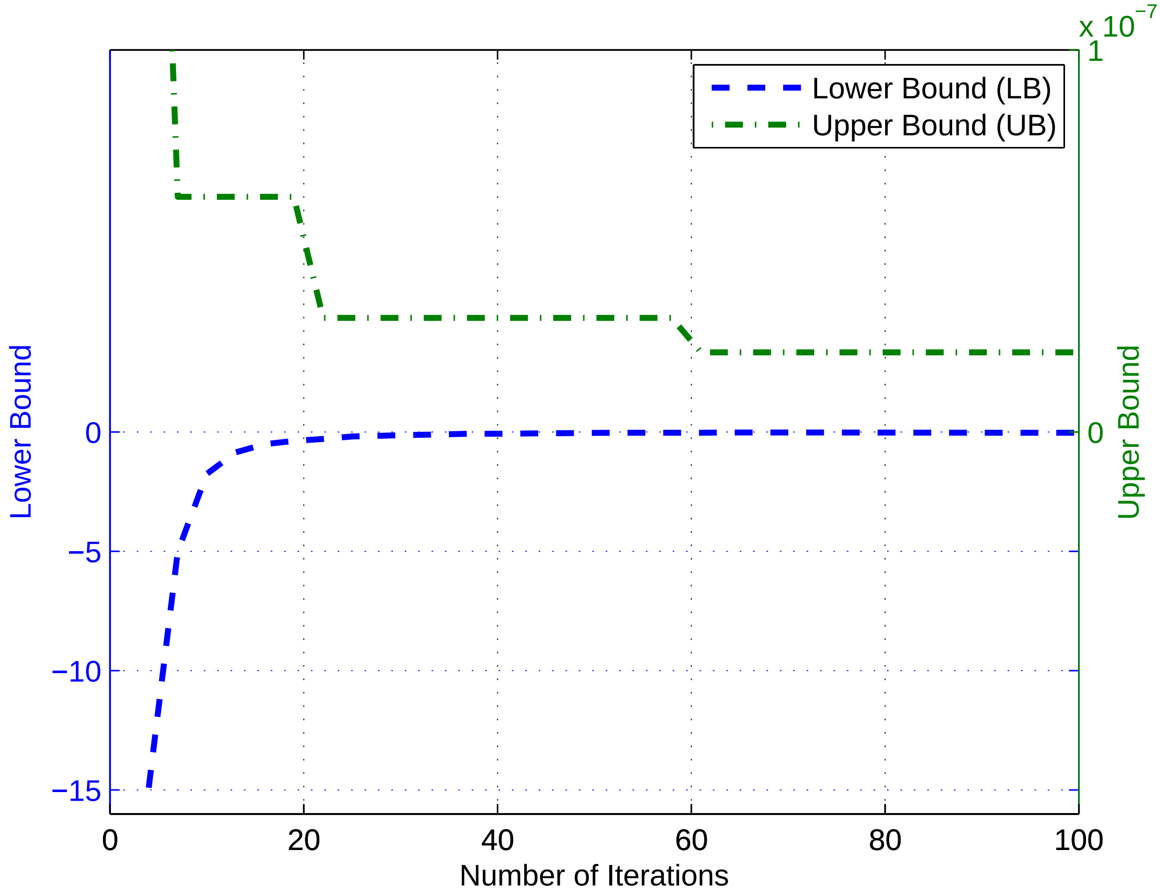


Figure 4.6: Convergence of α-BB algorithm vs number of iterations.

with customized tight convex lower bounding functions. The numerical results show that, this algorithm offers mathematical guarantees for convergence to a point arbitrarily close to the global minimum in reasonable computational time. Moreover, the results show that the optimum packet size that maximizes the energy efficiency gain is the largest among all of the different relay locations when the S-R distance equals the R-D distance (i.e., the relay located in the middle).

In this chapter, we consider another parameter (i.e., packet size) in our optimization problem joint with the transmitted power to further increase the energy efficiency of the network. However, up to this point we only consider single flow in the network that does not take into account inter-flow interference, which may affects the total throughput of the network. In the next chapter, we consider this issue and analyze the total network throughput of cooperative networks in a multi flow scenario.

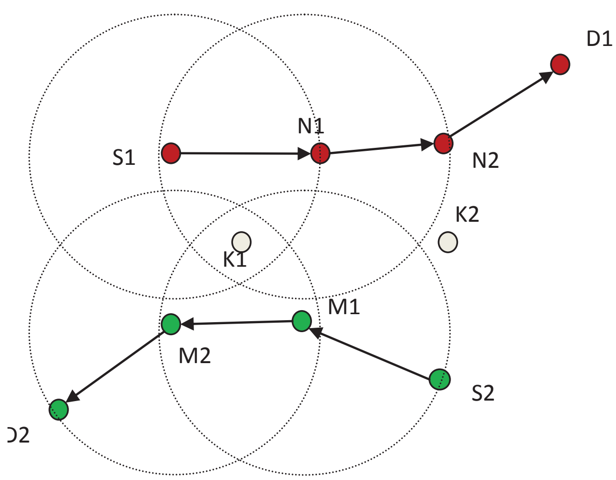
Chapter 5

Network Capacity Gain by using Cooperative Transmission

In Chapter 3, we proposed two routing protocols to exploit the spatial diversity gain offered by the cooperative transmission. The objectives were to minimize the end-to-end transmission power for a given data rate and to minimize the total number of hops for reducing delay respectively. In Chapter 4, we further improved the link cost by optimizing the transmitted power jointly with the packet size and finding a globally optimal solution for the problem.

Although the performance analysis of the proposed algorithms proves to achieve spatial diversity gains of wireless ad-hoc networks as expected, it is assumed that there is only one flow in the network and the source can reach the destination using multi hops ignoring inter-flow interference introduced by other active links carrying other flows. It is important to investigate the capacity gain that is expected from using cooperative transmission in a generalized network with multiple flows and inter-flow interference. What is missing in those studies is the investigation of the impact of interference on the capacity gain. Interference has a tendency of diminishing this gain.

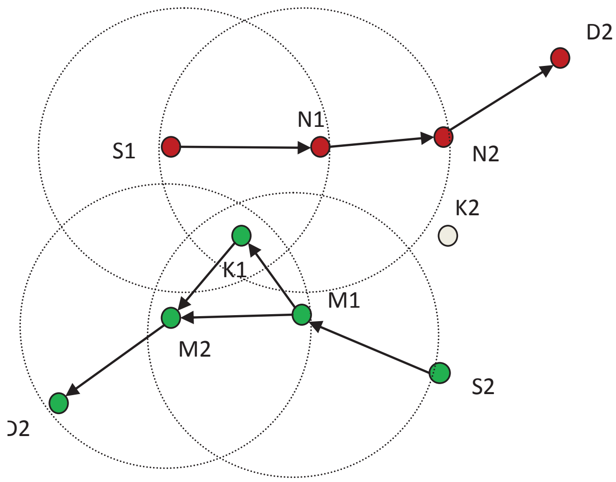
It is known that cooperative transmission enhances the individual link capacity at the cost of increasing the interference region of that link, as formulated in chapter 3. In fact, interference is a dominant factor in limiting the capacity of wireless networks [55], increasing interference range reduces the number of multiple concurrent transmissions in the vicinity of a given transmission. Cooperative communication tends to increase the interference range as compared to direct transmission; which may causes decrease in the network capacity. Figure 5.1 illustrates this point with a simple scenario. Assume there are two flows in the network. The paths of flows f_1 and f_2 are: $\{S1 \rightarrow N1 \rightarrow N2 \rightarrow D1\}$ and $\{S2 \rightarrow M1 \rightarrow M2 \rightarrow D2\}$ respectively. We assume direct transmission on all the links for that interference range are shown as circles around each node. It is obvious that there is no conflict between a pair of links a and b such that f_1 is scheduled on a and f_2 on b. Thus, the network achieves maximum possible network capacity.



(a): Traditional Network with two flows

Figure 5.1: An example to illustrate the conflict between flows in case of direct transmission

Now consider direct transmission on link (M_1, M_2) is converted into cooperative communication by involving node $K1$, as a relay as shown in Fig. 5.2. Since nodes S_1, N_1, M_1 and M_2 are in the interference range of transmitter K_1, the links (S_1, N_1) and (M_1, M_2) become mutually conflicted links. Thus, the two links $S1 \rightarrow N1$ and $M1 \rightarrow M2$ can not be active at the same time and the per-flow-throughput for each link is decreased by 50%, as compared with the direct transmission scenario discussed above. Thus, the network may not achieve the maximum network capacity. This example illustrates that cooperative strategy is bene-



(b): Cooperative Network with two flows

Figure 5.2: An example to illustrate the conflict between flows in case of cooperative transmission.

ficial in the case of single flow scenario; when used in the network with multiple flows, it may cause conflict due to the interference caused by the relay and, thus reduce the overall system throughput. Moreover, increasing the number of cooperative links in the network increases the likelihood of more links being blocked that may cause degradation of total throughput. In this chapter, we investigate the capacity gain that can be achieved using cooperative transmission in wireless ad-hoc networks with multiple flows, and how we can exploit the benefit of using cooperation in the situation of increased inter-flow blocking. Given a specific network topology, and specific traffic flows, we compute the optimal throughput bound of the ad-hoc network with direct transmission only. We further evaluate the capacity gain when the same network uses cooperative transmission in some links.

Most of the research done in the context of cooperative transmission attempted to enhance the network capacity, but few researchers addressed the fundamental question of the optimal capacity gain of cooperative ad-hoc networks in the presence of inter-flow interference. We model the problem as a Multi-Commodity Flow (MCF) problem. An additional constraint is added to traditional MCF formulation to capture the impact of the interference when it is applied to cooperative wireless ad-hoc networks. The conflict graph [55] is used to model the interference and find the additional constraints. The conflict graph can be used to determine the groups of links that are mutually interfering and thus cannot be active simultaneously. A key distinction of our work from previous works on MCF formulations is that we consider cooperative transmission that changes the link definition and introduce new interference constraints in the network.

The rest of the chapter is organized as follows. In the next section, we describe the system model. Then, in Section 5.2 we derive a generic interference model and define the interference region for direct and cooperative links. In Section 5.3, we define the conflict graph and cliques to derive a novel interference constraints. Finally, we formulate the MCF problem by adding interference constraints derived from the conflict graph. We present our evaluation of the throughput bound of multi-hop wireless networks with and without cooperative transmission. We summarize the chapter in Section 5.5.

5.1 System Model

We consider a multi-hop wireless ad hoc network consisting of N nodes, where each node is equipped with single omni-directional antenna. These N nodes are assumed to be uniformly distributed in a square area. The decode-and-forward (DF) cooperation scheme is employed.

We model the multi-hop wireless network as a directed graph $G = (V, E)$ where $V \in \{1...N\}$ is the set of vertices (nodes) and $E \in \{1...L\}$ is the set of edges (links). Without loss of generality, we assume that all nodes employ similar modulation and coding scheme and implement the maximal ratio combing (MRC) technique to combine the received signals.

The channel between any two nodes i and j in the network is modeled using a combination of small-scale fading and path loss [26]. The small-scale fading is quasi-static Rayleigh fading in nature, where the channel remains the same for several transmission blocks, i.e., inter-node channels change slowly (i.e., the channel coherence time is much longer than the block transmission duration). The transmitted signal also suffers from propagation path loss that causes the signal to attenuate with distance. The signal received at the receiving node j from transmitting node i is modeled as,

$$y_{i,j} = \sqrt{P} h_{i,j} x_i + n; \quad i, j \in \{1...N\}, \;\; i \neq j, \tag{5.1}$$

where P is the transmitting power, $h_{i,j}$ captures the channel fading gain between i and j, x_i is the transmitted signal with average unit power, and n is the AWGN with zero mean and variance σ_n^2.

5.2 Generic Interference Model

In a wireless network, each transmission imposes an interference region which is based on the link (direct or cooperative). To characterize the radio transmission in the presence of this interference, two different interference models have been used in the literature homely, physical and protocol model as discussed in Section 2.4.1. In this section, we present an interference protocol model that we derive generic constraints for a successful wireless transmission. The interference region affects all the nodes in its vicinity where two active links in the same vicinity could cause collision. To avoid the collision, at most one node should be transmitting in the neighborhood of the receiver, transmitter and relay (for cooperative transmission). Using disc graph model [72] the interference region of node is the circular region around the node at its center which is typically greater than the communication range. The interference region of a link is the combined area of the interference regions of the two nodes of link. For a successful communication, the receiver (and the transmitter in some MAC protocols such as IEEE802.11) should be free of interference. The interference region formulation for both direct and cooperative links are shown below.

direct link interference region

The interference sensitive region of the direct link is simply the combination of the interference regions of the two end-nodes as shown in Fig. 5.3. It is approximated by a disk with a radius of $r_{direct} = d_{direct}/2$ its center at the median between S-D, where d_{direct} is given by.

$$d_{direct} = r_I + r_C = (\varphi + 1) r_C \tag{5.2}$$

where $\varphi = \frac{r_I}{r_C}$ is refereed to as the interference sensitive range and; r_I and r_C are the interference and communication range respectively.

Cooperative link interference region

The interference region of the cooperative link is the combined area of the interference regions of the two end-nodes plus cooperative relay, as shown in Fig. 5.4.

Cooperative interference range is approximated by a disk with a radius of $r_{coop} = d_{coop}/2$ and its center at the median between S-R-D, where d_{coop} are given by.

$$d_{coop} = \begin{cases} r_I + r_C = (\varphi + 1) r_C & : r_1^2 + r_2^2 \leq r_C^2 \\ r_I + \frac{1}{2} r_C \left(\sqrt{1 + \frac{(r_1^2 + r_2^2 - r_C^2)^2}{4 r_1^2 r_C^2 (r_c^2 + r_1^2 - r_2^2)^2}} + 1 \right) & : \text{Otherwise} \end{cases} \tag{5.3}$$

where r_1 and r_2 are the distance between source-relay and relay-destination respectively.

It is clear from (5.3) that a cooperative link has a much larger interference region than direct link. Larger interference range means it blocks more concurrent transmission in the vicinity, which leads to degradation of the total network throughput.

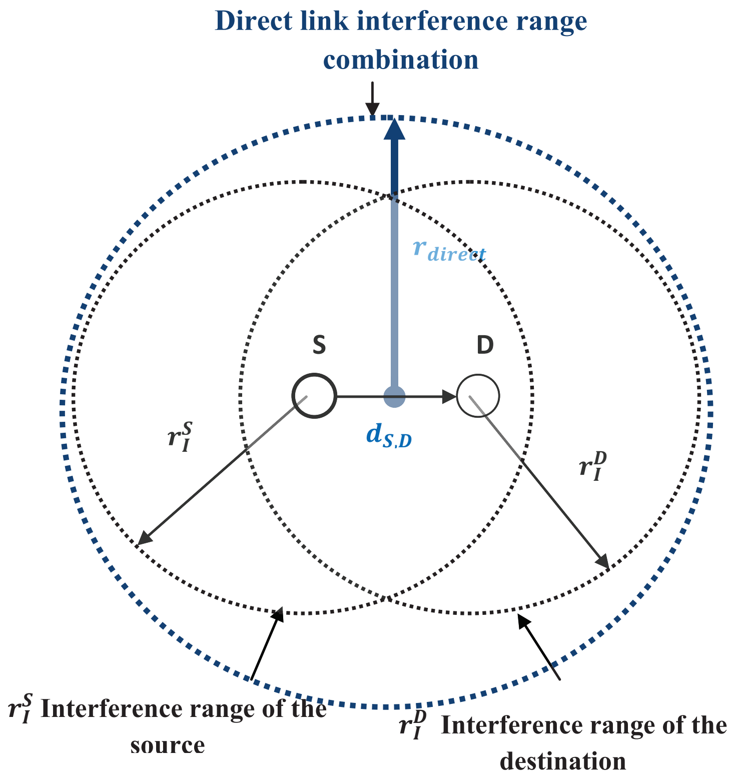


Figure 5.3: An example to illustrate the interference range for direct transmission link

5.3 Optimization Problem Formulation

5.3.1 The conflict graph and cliques

Graph theory has been used as a modeling technique to analyze several properties of the wireless network including interference relationships among links in a network.

Connectivity Graph:

A given network can be modeled as a connectivity graph $G = (V, E)$ where V is the set of vertices (nodes) and E is the set of edges (directed links). A link $l_{i,j} \in E$ exists if the range between nodes i and j is less than transmission range, i.e., there is a directed link from vertex i to vertex j if $d_{i,j} < r_C$. The graph $G(V, E)$ is said to be connected if there is a path connecting any two vertices (nodes) in V . The cardinality of the graph is the number

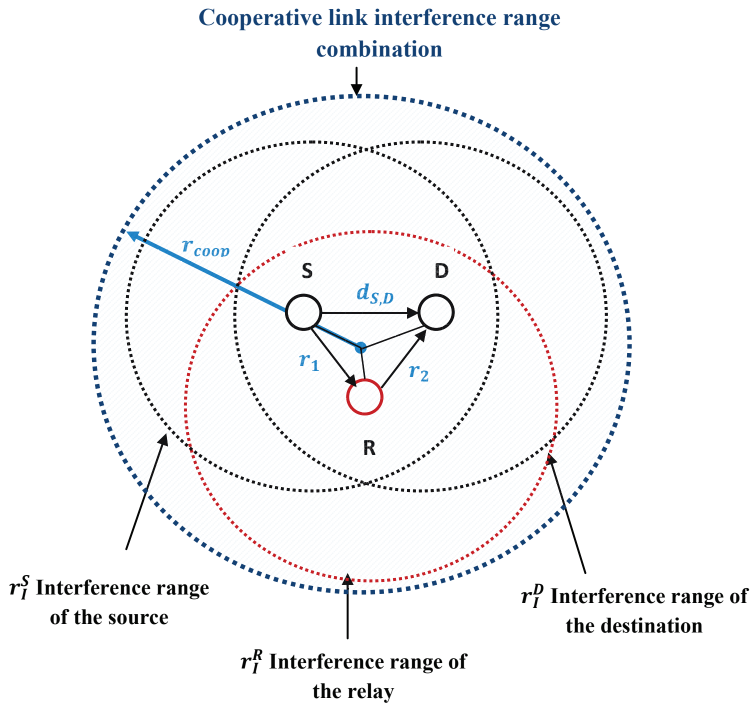


Figure 5.4: An example to illustrate the interference range for cooperative transmission link

of vertices V , and the degree of vertices is the number of edges attached to that vertex.

When cooperative transmission is employed in the network, some direct links will emerge into a virtual link (cooperative link), therefore, a virtual link based connectivity graph $G = (V, \acute{E})$ is constructed based on the original connectivity graph $G = (V, E)$, where, $\acute{E} = E \cup E_c$, and E_c is the set of new edges (virtual links) introduced by using cooperation.

Conflict Graph:

Conflict graph (CG) is used to model contention among links and to obtain link capacity constraints imposed by interference among links. It is derived from the connectivity graph. There is a one to one correspondence between an edge in connectivity graph and a vertex in the conflict graph $CG(V^C, E^C)$ and there is an edge between any two vertices of the conflict graph (links in the connectivity graph) if the corresponding links interfere with each other. Generally, any two links in the connectivity graph that have a node in common are connected in the conflict graph, but the nature of a link in cooperative transmission has changed, which may include one or more relays helping the source to forward its data and should have an edge in a generic conflict graph. We call direct conflict graph as the conflict graph corresponding to a connectivity graph with only direct links, whereas conflict graph corresponding to a connectivity graph with cooperative links is called cooperative conflict graph.

We augment the direct conflict graph to include the conflicts due to relaying nodes of cooperative links. Figures 5.5 & 5.6 illustrate an example of the conflict graph formation in a simple network with four links. As we can see in Fig. 5.5 where no cooperation is used, link 1 (l_1) could simultaneously transmit with link 4 (l_4). However, they may not be active simultaneously when cooperative transmission is imposed with link 1 (l_1) as shown in Fig. 5.6. In our modified conflict graph, we generalized the direct CG to reflect the new contention relation between direct and cooperative links (new virtual links), therefore, new edges should be added to the graph accordingly.

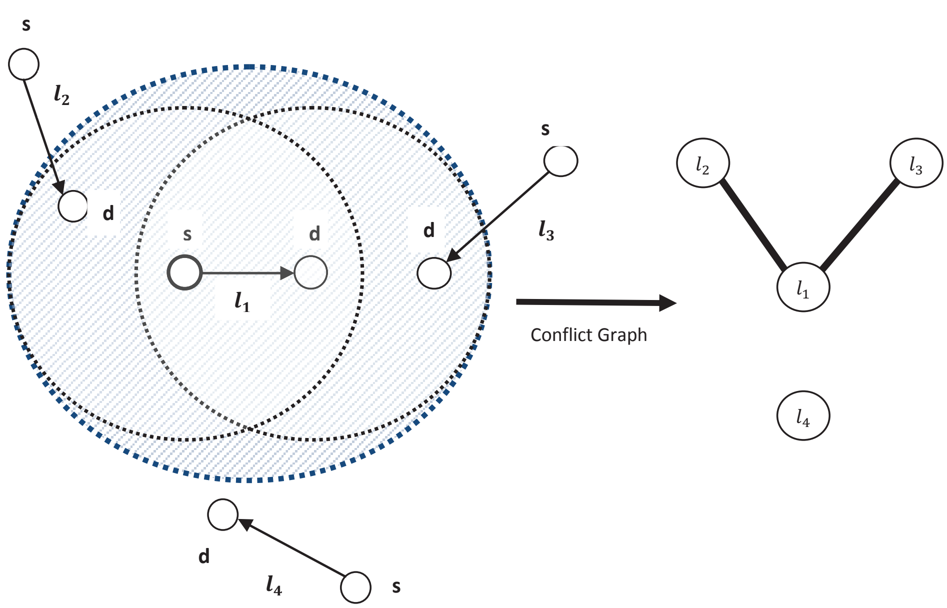


Figure 5.5: Conflict graph for a network with four active direct transmission links

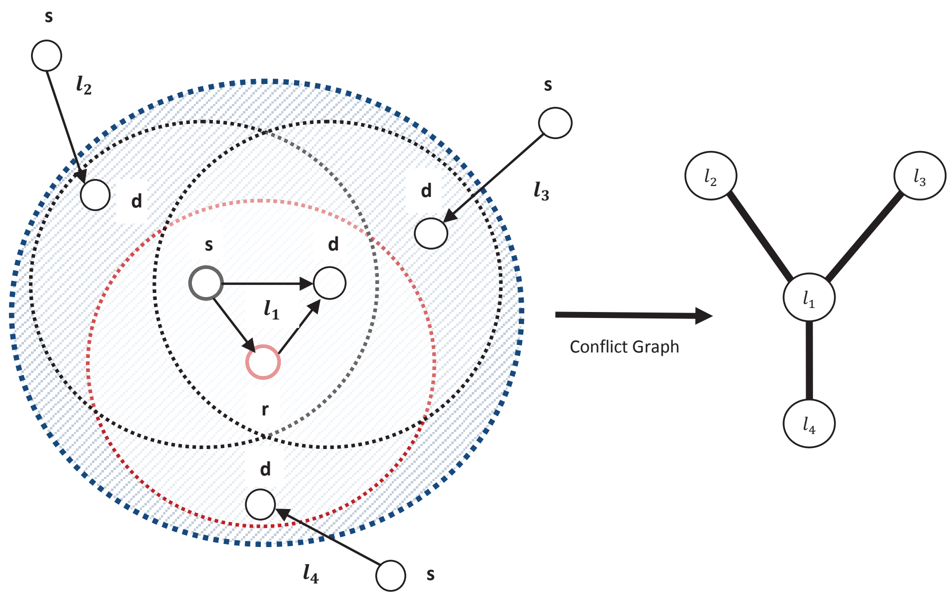


Figure 5.6: Conflict graph for a network with three active direct one cooperative transmission links.

Cliques:

A clique in an undirected graph $G = (V, E)$ is a subset of the vertex set $H \in V$, such that for every two vertices in H, there exists an edge connecting the two (i.e., a clique is a complete subgraph where all vertices are adjacent). We use the concept of cliques on the conflict graph to capture the interference relation among links, and to obtain the conflict regions; then derive new constraints by identifying various maximal cliques in the conflict graph. In the conflict graph, a clique represents the links that cannot be active at the same time. Therefore, corresponding to each clique H in the conflict graph, we get a constraint.

$$\sum_{(i,j)\in H} \mu_{i,j} \leq C \tag{5.4}$$

where, $\mu_{i,j}$ is fraction of time link (i, j) is active, and C is the link capacity

The fraction of link capacity, which corresponds to the clique constraints derived in 5.4 are necessary but not always sufficient for link scheduling [55] and hence, the solution of the optimization problem is the upper bound for the network capacity.

5.3.2 Linear programming formulation

Given a conflict graph CG, we apply linear programming formulation to compute the optimal network capacity in the cooperative networks. In particular, we formulate the problem as a multi-commodity flow (MCF) optimization problem, augmented by the additional interference constraints derived from the cooperative CG due to introducing cooperative relaying in some links in the network. The solution of the MCF formulation not only presents the maximum achievable capacity for wireless cooperative networks, but also jointly indicates the optimal scheduling of link transmissions, and the optimal routing.

Given each commodity is associated with a source destination pair (S, D), a common formulation is to maximize the total throughput (or capacity) over all source destination pairs. However, such an objective function may lead to starvation of some commodity flows[1]. Given $G(V, E)$ and a set of M commodities each with source destination pair S^m, D^m, the MCF formulation can be expressed as a mixed-integer linear programming problem as follows:

$$\max \sum_{m \in M} f^m \tag{5.5}$$

subject to:

$$\sum_{(i,j)\in \acute{E}} x_{i,j}^m - \sum_{(j,i)\in \acute{E}} x_{j,i}^m = \begin{cases} f^m & , \quad i = S^m \\ -f^m & , \quad i = D^m \\ 0 & , \quad \text{Otherwise} \end{cases} \tag{5.6}$$

$$\sum_{(i,j)\in q} \sum_{m \in M} x_{i,j}^m \leq C \quad \forall q, \tag{5.7}$$

[1] In this work we are interested on the total capacity, considering the fairness issue presented in some literature that seeks to maximize the total throughput of the network and at least some amount of throughput can be ensured for each commodity.

$$\sum_{m \in M} x_{i,j}^m . \phi_{i,j}^m > 0 \quad \forall i, j \in E_c, \tag{5.8}$$

$$\phi_{i,j}^m \in \{0, 1\} \quad \forall i, j \in E_c, \tag{5.9}$$

$$x_{i,j}^m \geq 0, \quad \forall (i, j), m \tag{5.10}$$

where $x_{i,j}^m$ is the amount of flow from the m^{th} commodity over link $(i, j \in \acute{E})$ normalized with respect to the capacity of the channel. The term f^m denotes the normalized flow coming out from source S^m, and q is the maximal clique belongs to the set of maximal cliques Q.

In the above formulation, the objective in (5.5) is to maximize the total throughput of all commodities. The first constraint in (5.6) represents the flow conservation constraints at each node for each commodity. The second constraint in (5.7) represents the clique's capacity constraint, the sum of all flows on all the link belonging to each maximal clique is bounded by the channel capacity C. Constraints (5.8) and (5.9) are used to ensure that at least one cooperative link is scheduled in the network, where $\phi_{i,j}^m$ is a set of binary value integer variables taking values 0 or 1. The last constraint in (5.10) ensures that the flow over each link is a positive quantity.

5.4 Performance Evaluation and Numerical Results

In this section, we present some numerical results of our problem formulation. Our goal is to evaluate the impact of cooperative transmission on the whole network interference compared with direct transmission, and how this affects the maximum throughput of the network. We compare the conflicts between links under direct and cooperative transmission. We used ILOG CPLEX optimizer [20] to compute the maximum flow by solving the multi- commodity flow problem for multi-hop wireless networks with and without cooperative transmission.

The problem of finding the size of a clique for a given graph is an NP-complete problem [73]. Although there is no polynomial algorithm for clique calculation for general graphs, the algorithm we have used that perform pretty well with limited number of nodes known as the Bron-Kerbosch Algorithm [74, 75].

To show the effectiveness of using cooperative relaying in a network with multiple commodities (flow demands) between different source and sink nodes, we consider two different scenarios. First, we consider a light traffic load in the network where a static multi-hop wireless network with varying number of nodes n ranging from 10 to 25 nodes, which are randomly deployed in 5kmx5km area to represent different node densities. In each topology, a set of five flows is randomly chosen and three nodes are selected to form a cooperative link in the network. Second, we consider heavy traffic load in the network where each node in the network always has data to be sent. We assume a network with $n = 24$ nodes and each node sends a data to a random destination. In this analysis, we consider five different interference threshold such that the lowest threshold value indicate that the interference range is equal to the transmission range which is considered as a base line of our analysis.

5.4.1 Light traffic analysis with different node density

In this scenario, we evaluate the capacity of the cooperative network with varying network density. We assume there are five flows in the network ready to be scheduled in a network.

Impact of cooperation on the number of conflicts with varying network density:

Figure 5.7 shows the average differences of the total number of edges in the conflict graph (conflicts between links) between direct and cooperative conflict graph for different network sizes. As expected, the network has slightly larger number of conflict links when cooperative transmission is used due to the interference caused by the relays. Further, conflicts increases exponentially with the network size.

Impact of cooperation on the capacity gain with varying network density:

Figure 5.8 shows the upper bounds on the maximum flow in the network with respect to the

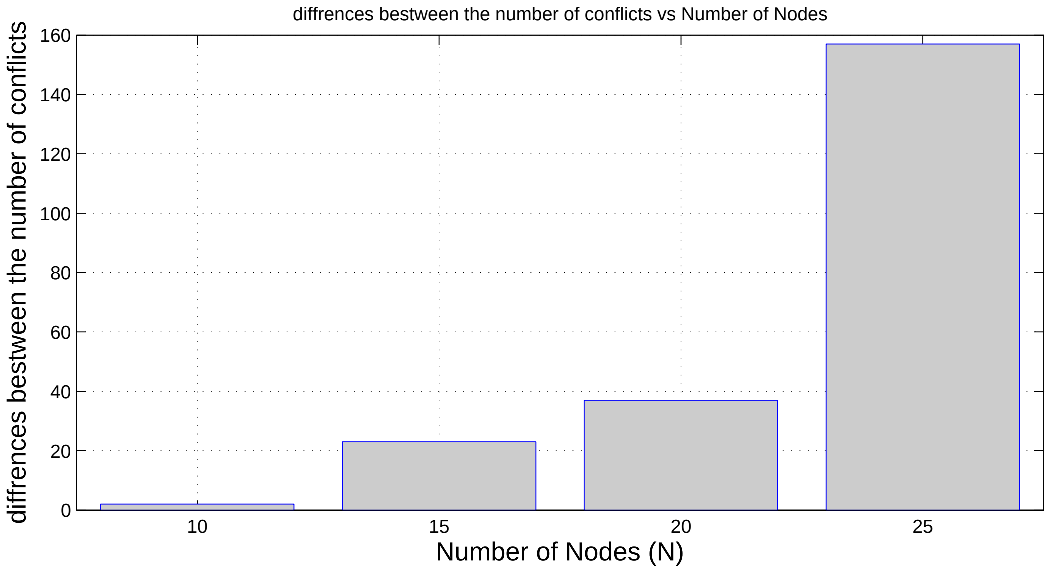


Figure 5.7: Differences of the number of conflict graph edges between cooperative and non-cooperative network with different node densities.

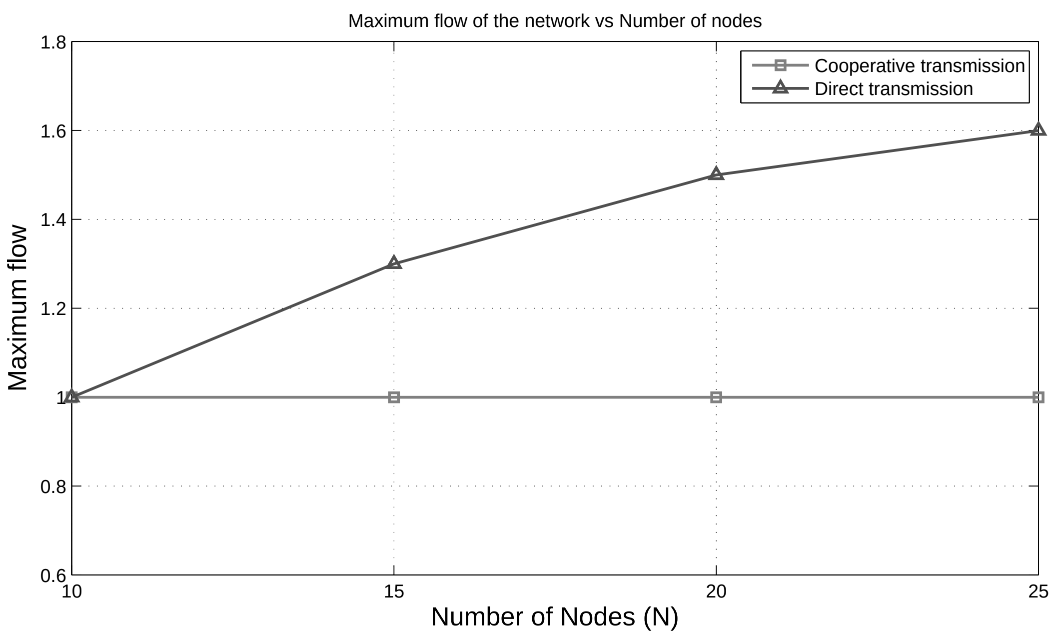


Figure 5.8: Maximum flow of the network with and without cooperative transmission.

number of nodes with one cooperative zone[2] in the network. Here, the number of flows is

[2]We mean by cooperative zone here is that, select of a group of three nodes such that creating a cooperative

set to be 5. By increasing the number of nodes the total capacity of the network decreases when cooperative transmission is used, as compared to the capacity of the network with only direct links. This is because, with cooperative transmission over a links its interference range is increased and thus more links are blocked due to transmission on that link. This result is important since the benefits of cooperative transmission are known in non-interference scenario, while interference mitigates the benefit. To avoid degradation of the total network capacity which is much more likely to occur, better cost for channel allocation should be designed.

5.4.2 Heavy traffic analysis

In this section, we evaluate the impact of cooperative transmission by considering heavy traffic condition. We consider a static wireless network with 24 nodes randomly positioned in an area of 5kmx5km, each node is a source of flow that sends a data to a random destination in the network. We consider five different interference range indexes ϕ which define the relation between the transmission and interference range of node and defined as $r_I = (\phi)^{\frac{1}{\beta}} r_c$ and the baseline is when the interference range is equal to the transmission range.

Impact of cooperation on the number of conflicts with varying interference index:

Figure 5.9 depicts the total number of edges in the conflict graph (conflicts between links) in direct and cooperative conflict graphs for different interference indexes. It is clear that the number of conflicts increases as interference index increases, and the network with cooperative transmission has slightly larger number of conflicts due to the interference caused by the relays.

Impact of cooperation on the capacity gain with varying interference index:

Figure 5.10 shows the upper bounds on the maximum flow in the network with respect to the

link between any pair by using the third node as a relay.

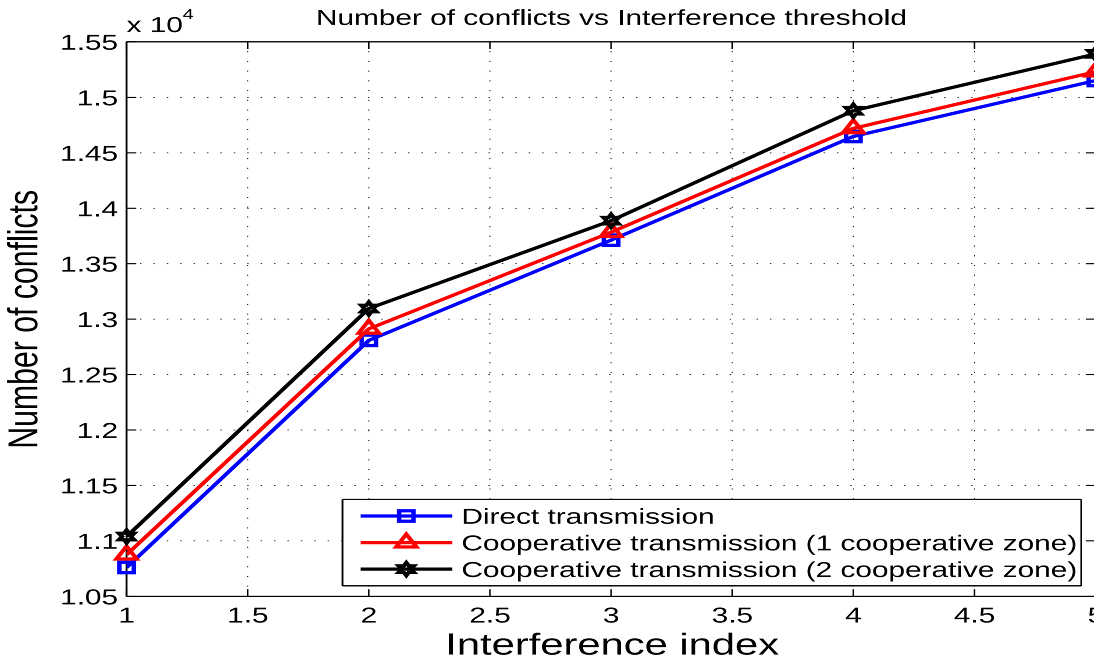


Figure 5.9: Number of conflicts with and without cooperative transmission for different interference range indexes ϕ.

interference index in the network. The number of flows is set to be equal to the number of nodes (heavy traffic). As the interference index increases, the total capacity of the network, when cooperative transmission is used between some nodes slightly decreased as compared to the direct transmission. This shows that the capacity decrease is due to, interference range of cooperative links, which has increased and thus more links are blocked.

Impact of cooperation on the number of flows scheduled with varying interference index:

In Figure 5.11, we plot the number of flows scheduled in each case. This figure represents the number of scheduled flows so the network achieve maximum throughput. As we can see, the number of flows scheduled is slightly higher in direct transmission scenario than the case of cooperative transmission specially when the interference index is high.

Impact of cooperation on the number of hops with varying interference index:

Furthermore, to get more insights we plot in figures 5.12, 5.13 and 5.14 the number of hops

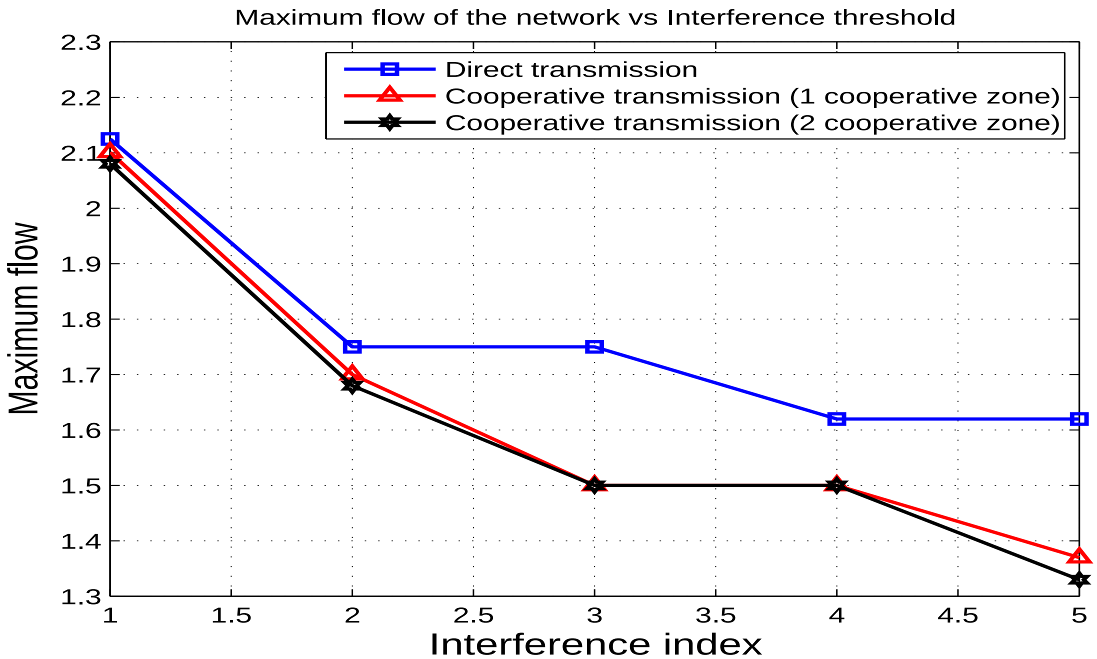


Figure 5.10: Maximum flow of the network with and without cooperative transmission for different interference range indexes ϕ.

transverses by flows in the network with all direct links, and with a combination of direct and cooperative links that can maximize the network throughput. The data is also summarized in tables 5.1, 5.2 and 5.3. As we can see, cooperative links turned to increase the hop counts of paths, which shows that more conflicts incase of cooperative transmission leads to losing the shortest path and larger paths is chosen, as compared with direct transmission

5.5 Chapter Summary

In this chapter, we investigated the performance of multi-hop wireless ad hoc networks with cooperative transmission. We addressed the feasibility of a given set of flows on an arbitrary ad-hoc cooperative network, by formulating the problem as a multi-commodity flow problem and derived the upper bound on the capacity of such networks. We used the conflict graph

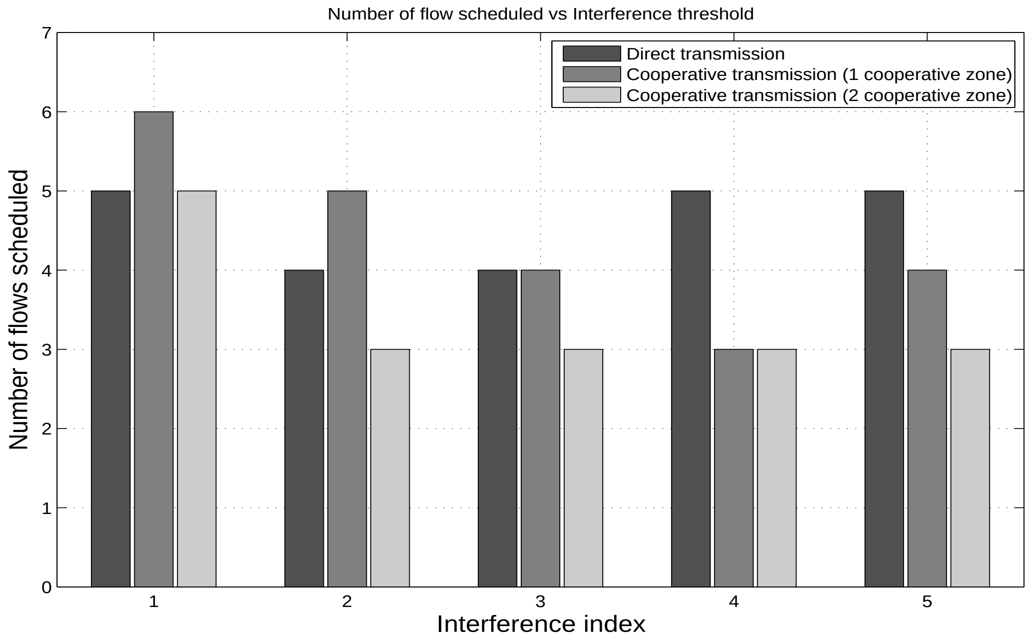


Figure 5.11: Number of flows scheduled of the network with and without cooperative transmission for different interference range indexes ϕ.

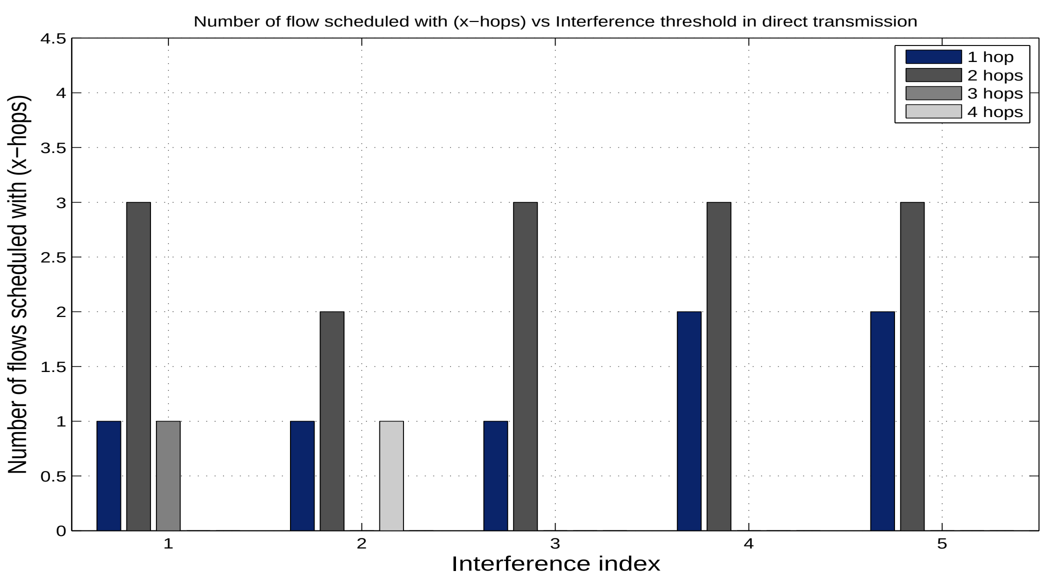


Figure 5.12: Number of hops scheduled of the network with direct transmission.

Table 5.1: Number of hops scheduled for direct transmission

Interference index	1 hop	2 hops	3 hops	4 hops	5 hops
1	1	3	1	0	0
2	1	2	0	1	0
3	1	3	0	0	0
4	2	3	0	0	0
5	2	3	0	0	0

Table 5.2: Number of hops scheduled for cooperative transmission (1 cooperative zone)

Interference index	1 hop	2 hops	3 hops	4 hops	5 hops
1	1	1	1	2	0
2	0	1	0	2	0
3	1	2	0	0	0
4	1	2	0	0	0
5	1	1	0	1	0

and its cliques to drive the interference constraints. We then used these cliques to write constraints that provide sufficient conditions for feasibility within a constant bound of the optimal.

Our results show that the capacity of cooperative multi-hop wireless networks can be significantly decreased even with only one cooperative link in the network. These results consider realistic scenarios by including the interference range of cooperative links, which is greater than the direct links, which results in blocking some new links. This implies that the effect of the interference induced from the cooperative relay is significant and should not be ignored.

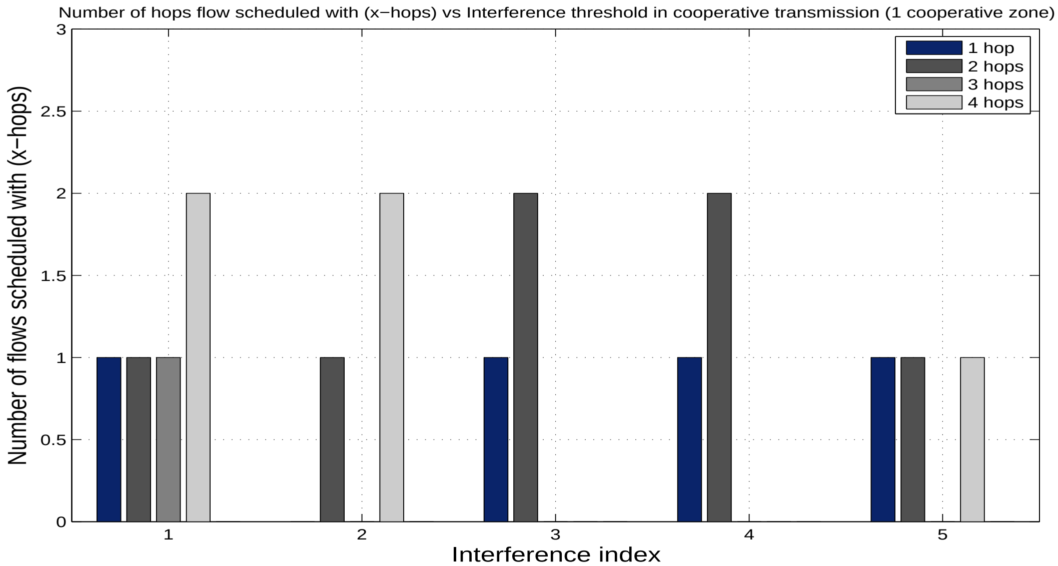


Figure 5.13: Number of hops scheduled of the network with cooperative transmission (1 cooperative zone)

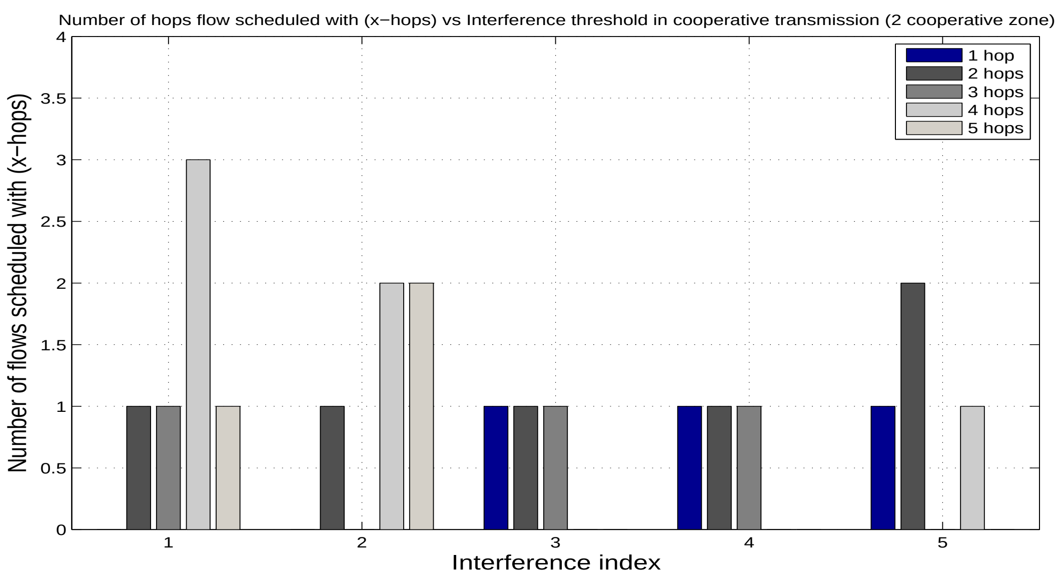


Figure 5.14: Number of hops scheduled of the network with cooperative transmission (2 cooperative zone)

Table 5.3: Number of hops scheduled for cooperative transmission (2 cooperative zone)

Interference index	1 hop	2 hops	3 hops	4 hops	5 hops
1	0	1	1	3	1
2	0	1	0	2	2
3	1	1	1	0	0
4	1	1	1	0	0
5	1	2	0	1	0

To mitigate the impact of interference among concurrent transmissions in multi-hop settings and thus enhance the performance of cooperative networks, multiple channels should be considered that could reduce the wireless interference giving rise to diversity gain and is expected to improve overall network capacity.

Chapter 6

Conclusions and Future Work

Applications of ad hoc multi-hop networking is growing into a large and diverse fields to provide new services which require high data rates with increased reliably provided through wireless networks. Unlike wired link, wireless channel suffers from unwanted effects (e.g. shadowing, path loss, multi-path fading etc), which make it harder to establish reliable communication. The new service requirements and the unwanted effects of the wireless channels force the researchers to explore innovative techniques to enhance the performance of multi-hop wireless networks and hence satisfy QoS requirements. These requirements can be achieved by using the concept of cooperative communication where a source node can use a neighboring node, called relay, which has high quality communication channels to both source station and the destination. These techniques have been investigated in the last few years as a potential technology to effectively improve the network performance. But, to exploit this potential benefit in ad hoc multi-hop wireless networks, several new challenges need to be addressed.

This thesis investigates the application of cooperative transmission techniques in wireless multi-hop ad hoc networks. We investigate the possible benefits achievable of multi-hop wireless ad hoc networks using cooperative transmission and under which conditions and constraints.

6.1 Conclusions

In large ad hoc wireless networks, a single message is relayed through a number of wireless links before reaching its intended destination, which in turn requires a routing table or, alternatively, some sort of updated geographical knowledge at each node. In these kinds of networks, cross layer protocols have shown excellent performance; cooperation can be also implemented at different layers, and with different purposes. The main constraint is the fact that a finite amount of resources must be shared not only by normal direct transmissions, but also by cooperative ones, which in general also requires additional signalling and coordination.

This dissertation is mainly focused on studying the benefits of cooperative transmission considering both relay selection (physical) and routing (network) activities in different layers of multi-hop wireless networks. Specifically, the routing problem in multi-hop ad hoc cooperative networks is considered. The main contributions of this dissertation are summarized as follows:

First, we investigated the problem of routing and the effects of cooperative transmission in a multi-hop ad hoc network, with the objective of minimizing the end-to-end transmission delay while maintaining the QoS requirement. We formulated the radio coverage for direct and co-operative links in the network and derived the range extension factor. Our target is to minimize the number of hops in the path, and thus minimizing the end-to-end delay. Analytical results demonstrate that our proposed routing scheme can greatly reduce the number of hops which yields to substantially lower end-to-end delay compared with traditional routing using direct transmission at the physical layer as well as the cooperation along the shortest non-cooperative path. Moreover, the proposed ENBGCR algorithm shows significant power savings compared to the conventional approaches.

Secondly, with the objective of minimizing the end-to-end total power consumption while reaping the benefit of co-operative transmission in lowering transmission power for a given rate, we formulated link costs for direct and co-operative links in a network graph in terms of transmission power as a function of given rate. Our target is to minimize total power consumption in the network by selecting minimum energy path for each communication between-destination pair. The power consumption along a path can be minimized by choosing co-operative links along the path which consume less transmission power as compared to their corresponding direct links. Through some reasonable and practical approximations, a distributed routing scheme is proposed that employs Dijkstra's shortest path computation algorithm. The simulation results demonstrate that our cooperative routing scheme consumes substantially less energy and can achieve considerable power gain compared with non-cooperative routing. The power optimization achieved through the proposed algorithm scales well with the network size and the target rate.

In the next chapter, the optimal packet size which can improve the full benefit of cooperative transmission in multi-hop ad hoc networks is analyzed. Our objective was to find an effective way to adapt cooperative transmission with an ad hoc network and ensure optimal performance. In this chapter, a joint packet size and power allocation problem formulation for a cooperative wireless ad hoc network has been proposed. The objective was to improve the energy efficiency of the network by optimizing the packet size and transmit power. Joint packet size and power allocation is a non-linear non-convex optimization problem which is combinatorially hard and traditional algorithms may end with local solutions. For that, an efficient and global solution with low complexity using convex relaxation approach has been proposed. The global optimization method α-BB, was introduced for solving our formulated optimization problem. A convex relaxation of the original problem was constructed by replacing all non-convex terms with customized tight convex lower bounding functions. The numerical results show that, this algorithm offers mathematical guarantees for convergence to a point arbitrarily close to the global minimum in reasonable computational time. Moreover, the results show that the optimum packet size that maximizes the energy efficiency gain is the largest among all of the different relay locations when the source-relay distance equals the relay-destination distance (i.e., the relay located in the middle).

Finally, we analyzed the impact of the extended interference caused by relays in cooperative links and asses the maximum network capacity of the network with multiple flows simultaneously. In this chapter, we addressed the feasibility of a given set of flows on an arbitrary ad-hoc cooperative network, by formulating the problem as a multi-commodity flow problem and derived the upper bound on the capacity of such networks. We used the conflict graph and its cliques to derive the interference constraints. We then used these cliques to write constraints that provide sufficient conditions for feasibility within a constant bound of the optimal. Our solution results show that the capacity of cooperative multi-hop wireless networks can be significantly decreased even with only one cooperative link. Our results are based on realistic scenarios since the sensitive interference range of cooperative links is greater than direct links which means that some new links will be blocked. The results show that conflicts increase by increasing the interference, which also result in extending the hop counts.

6.2 Future Work

This thesis presents an evidence that cooperative transmission can improve power efficiency and data rate, but it requires careful consideration of interference. Implementing cooperative transmission in a network such as ad hoc networks is still challenging and there are some issues that could limit the benefits of cooperative transmission. Thus, further research work is needed to realize the benefits of cooperative communication in wireless ad hoc networks.

We addressed several aspects related to that such as the design of a new routing protocols for ad hoc networks with cooperative transmission. However, there are some relevant issues that warrant further consideration in the future work. For instance, we have considered in this work, a static network where node mobility is not involved. However, it would be interesting to evaluate the performance of the proposed protocols in the presence of mobility. Also, in this thesis we considered a simple three-node cooperative links in the network (i.e., each source selects only one node as cooperative relay). Thus, another way to enhance this research would be to use more than one relay. Scaling the analysis to a such system might have a lot of potential but does not appear to be easy. Multiple relay nodes mean each relay node can independently decode and forward information to the destination and many parameters should be addressed such as: the effect of imperfect transmission as the number of relay nodes that decode incorrectly may not be known a-priori, the effect of geometry and the interference caused by the relays. Moreover, we only assessed outage and power-optimized routing in this work, yet, some other criteria may be considered for optimization, e.g., BER as future research.

In chapter 4, we considered a joint optimization problem to enhance the energy efficiency of the network. An efficient joint packet size and transmit power allocation problem was proposed and an efficient and global solution with low complexity using convex relaxation approach has been proposed for solving our problem. This work can be extended by relaxing our assumption for transmitter and relay transmit power to be unequal and some other criteria may be considered for formulating our optimization problem. Moreover, the α is an important parameter that controls the convexity of the under-estimator which leads the algorithm to rigorously identify the global solution. This parameter can be calculated in several ways listed in the literature. We only used the Gerschgorin's theorem in this work and some other methods may be considered in the future

In chapter 5 we studied the total network throughput and conflict performance analysis using conflict graph. Our result shows that, the total network capacity may be affected as the cooperation transmission is not used probably. To mitigate the impact of interference among concurrent transmissions in multi-hop settings and thus enhance the performance of cooperative networks, one solution is to consider multiple channels which could reduce the wireless interference giving rise to diversity gain and thus greatly improve overall network capacity.

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