OPTIMUM OUTAGE ROUTING IN COOPERATIVE MULTI-HOP NETWORKS

by

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Dedication

To my parents, for making it possible to embark on this journey.
To my wife, for making it possible to conclude it.

Acknowledgments

A special thanks to Dr. Bijan Jabbari, my advisor for his countless hours of reflecting, reading, encouraging, and most of all patience throughout the entire process.

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Abstract

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Recently cooperative communications has gained considerable attention in research due to multi-path fading mitigation ability through spatial diversity while providing flexibility. In cooperative communication protocols, terminals and relays cooperate to form a virtual antenna array which enhances the capacity or network throughput.

This dissertation focuses on routing aspect of cooperative communications and proposes new routing protocols across relays operating in decode-and-forward mode. This approach results in improved power efficiency, reduced end-to-end outage required to achieve a desired network throughput, and maximize the lifetime of nodes in a network.

More specifically, we address one essential question, how cooperation can minimize outage in wireless multi-hop networks. Moreover, we illustrate the compromise between the achievable rate and the outage. We also present that the cooperation advantages can be leveraged to the network layer. In particular, emphasizing the relation between outage and power, we propose a novel cooperative routing algorithm, called Outage-aware K-shortest paths Cooperative Routing (OKCR), which minimizes the transmitted power while exploiting the merit of cooperative communication.

The OKCR algorithm finds the best route between the source and destination under an outage probability constraint. The proposed algorithm nominates k different optimum routes and then selects the best possible relay in each route on the basis of performance analysis. Simulation results show that this strategy enhances power-efficiency in comparison to non-cooperative and other existing cooperative algorithms investigated in the literature by more than 50%.

We then consider the joint routing and cooperation diversity problem in multi-hop networks, for which we seek to optimize the end-to-end outage. Simplifying the network structure via partitioning and identifying a set of nodes in each partition, we devise a routing strategy based on cooperative relays in decode-and-forward mode. In particular, this sub-optimal routing algorithm yields the best possible path between the source and destination pragmatically considering the outage probability as the optimization metric. To reduce the amount of required channel state information and the path computation complexity, we introduce a simplified realization, referred to as L-relay ad-hoc, in which a relay selection method based on channel gains is applied at each hop. We evaluate the performance of the proposed methods under practical conditions. Simulation results show that the proposed sub-optimal strategy can perform very closely to the optimal strategy with less channel information requirement, and the L-relay ad-hoc method can also demonstrate a good performance with significantly reduced complexity.

Chapter 1: Introduction

Wireless communication networks have been experiencing a rapid growth during the last decades. Much of this development owes to the huge improvements in solid-state electronics. Concurrent expansion of the computational power and increase in data rate on one hand, and decrease in the size of the chip on the other hand, give way to small wireless production.

Nowadays wireless networks are used for voice, video and data applications are becoming more and more widespread in every aspect of our life. Internet of Things (IoT) is another example of evolution in the area of wireless technologies in which objects, animals or people are equipped with unique identifiers and the capability to interconnect for transferring data without requiring human-to-human or human-to-computer interaction.

In spite of significant advancement in wireless communication technologies, supporting the increasingly high data rate traffic from diverse wireless applications and services, there still remain serious challenges. Most notably, they consist of multi-path fading, spectrum shortage, energy limitation and user mobility. In particular, the transmitted signal may change at the receiver side due to the effects of multi-path include constructive and destructive interference, and phase shifting. The destructive interference which is called fading and illustrated in Figure (1.1), has to be addressed because of its drastic effect on the system performance. Moreover, as the size of wireless networks increases, spectrum management becomes a critical issue due to the limitation in spectrum reuses. As a result, spatial reuse of the spectrum must be considered by the use of multi-hop transmission to extend coverage. These new features or trends of wireless communication networks bring us more challenges on performance modeling and analysis, and also more urgent demands for designing and developing new solutions to improve spectrum efficiency.

Cooperative communication has arisen as a promising technology to improve spectrum
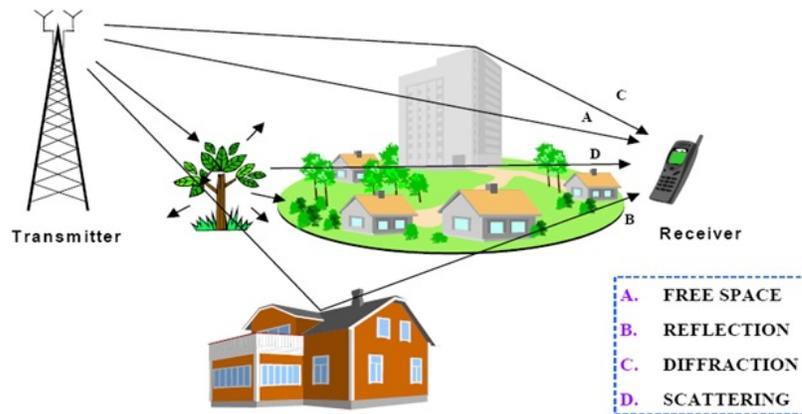
Figure 1.1: Examples of multi-path fading

efficiency. Different from traditional point-to-point communication, cooperative communication takes advantages of the broadcast nature of the radio spectrum, and allows nodes to cooperatively share their resources and facilitate information exchange for each other. By exploiting spatial diversity to combat the effects of multi-path fading, cooperative communication can enhance the reliability, increase the data rate, improve the energy efficiency, or extend the coverage of wireless networks.

In cooperative communication protocols, a number of relay nodes are assigned to assist a source in forwarding its data to its destination, hence forming a virtual antenna array. In the rest of this section, first we present our motivation and objectives. Second we introduce the outline of this dissertation along with the main contributions. Figure (1.2) shows two nodes communicating with the same destination. Each node is quipped with single antenna and is not capable of spatial diversity. However, it is possible for one node to receive the other node's data. In this case, because of two independent fading paths, spatial diversity is achieved [1].

1.1 Motivations and Objectives

Energy efficiency is one of the main objectives in wireless networks, especially in ad-hoc or sensor networks, where network nodes are normally battery-driven. For instance, consider wireless sensor networks which are widely used in a variety of applications ranging from
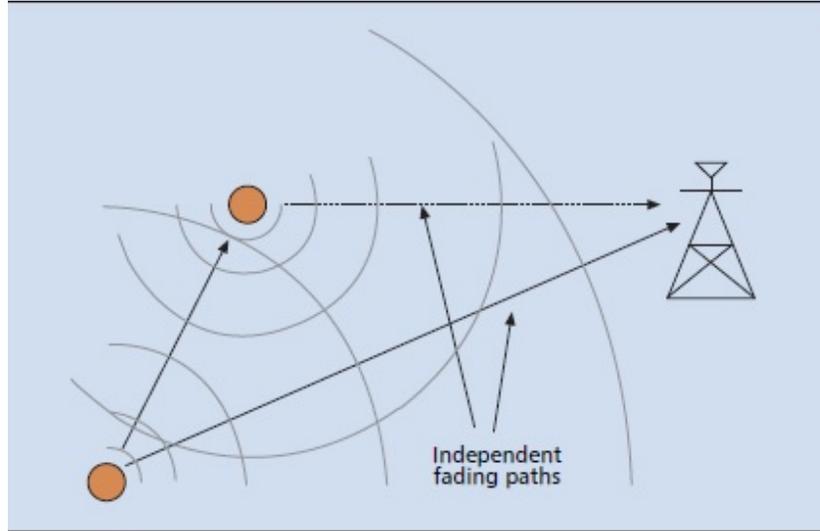
Figure 1.2: Cooperative communications

home to industry. In many cases, the energy supplies are non-renewable and size-limited sensors dictate energy conservation in order to prolong the network life-time. Recently, energy saving in the form of cooperative communication has attracted considerable attention, owing to the fact that cooperation can diminish multi-path fading through obtaining spatial diversity and presents flexibility in comparison with the more conventional forms of space diversity with physical arrays [2].

Although most of prior works in this area address the combined optimization of the routing and power allocation, only a few employ end-to-end outage probability as a performance evaluation metric in cooperative communication. Moreover, majority of the proposed algorithms are established on a single shortest path between source and destination. In this manner, benefit of cooperation-based routing is confined to only one path which might be far from being optimal. Indeed, since the most advantageous cooperative route might be totally different from the shortest-path route, these routing algorithms do not completely make use of the cooperative communications qualities at the physical layer. Additionally, most of cooperative routing algorithms must have global information about all the nodes in the network in order to compute the best route based on a certain source-destination pair. This necessitates a central node, which may not be available in some infrastructure-less

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networks. Hence, each node can choose the next node towards the destination independently and routes are established in a distributive fashion. This motivates us to propose an approach to take various shortest paths into consideration in order to fully utilize the advantage of cooperative transmission.

We have two main motivations in this work. First of all, the importance of energy efficiency in wireless networks encourages us to address the urgent need for optimizing the energy utilization. The lifetime of a wireless network is entirely relies on the energy consumption of each node. On the other hand, the energy sources at each node such as batteries are restricted. As a result, to prolong the life of such networks, energy-efficient and power-aware protocols and methods as well as link layer, MAC, routing and transport protocols must be employed to minimize the power consumption. As will be seen later in this chapter, the cooperative shortest path algorithm can save up to 50% power compared with non-cooperative shortest path algorithm. The simulation results show that a higher node density in the network will lead to even more power savings, given that a dense network provides more chances for cooperative transmission.

The second motivation is network scalability. One of the most common issues in wireless networks (particularly large networks) is scalability. Transmission at maximum power from one node often causes rigorous interference with other nodes. In contrast, as discussed in [3], in a wireless network we say two nodes are linked together, when the transmitting node transmits with satisfactorily far above the given threshold at the receiver. Moreover, wireless channel naturally has substantial issues caused by attenuation, multi-path fading, reflection, scattering etc., in addition to interference and noise. It motivates us to optimize the network via cooperation among nodes such that for instance each link outage is compared with the target constraint. In this way all links are almost utilized equally based on the predefined parameter (we will have more discussion on this in the next chapter). Consequently, the offered approach diminishes interference between transmitting nodes with noticeably decreased power.

1.2 Dissertation Contributions

We consider a set of users, who are trying to communicate with each other in an arbitrary wireless network, and propose the distributed power optimized cooperative routing algorithm, which needs less transmission power as compared to the usual routing schemes. This algorithm is vital to the minimum-power routing problem, given the link target outage forced at a certain level. This new strategy combines the physical and network layer mechanism to select the best relay in each hop. To be more specific, we first derive a cooperation link cost formula that captures the benefit of cooperative transmission. Then, try to find the route that requires the minimum transmitted power, while guaranteeing certain Quality of Service (QoS). The QoS here is described by the end-to-end outage.

We investigate transmit diversity in the wide-ranging framework of cooperative routing where multiple nodes are allowed for cooperative transmissions. In cooperative routing approach multiple nodes all along the path transmit collaboratively toward the next hop as long as the joint signal at the receiver satisfies the threshold value of SNR (signal-to-noise ratio).

In most of cooperative routing approaches, a successful transmission occurs when the SNR of the received signal at the receiver is above an agreed threshold value, say SNR_{min}. The threshold value of SNR_{min} is selected to yield a preferred BER (bit error rate) for the specified outage probability and data rate. Conventional routing methods exclusively choose the route on the basis of some criteria such as the number of hops on the path, the cost of the path and/or some QoS constraints.

It is also crucial in cooperative routing to have a metric for choosing relays, which can be hop count, received SNR, or remaining energy. However, there is a trade-off in these factors; for instance, nodes with good channel condition (especially large received SNR) will probably forward more packets and consume more energy, which will affect the lifetime of the battery-powered nodes. Consequently, the cooperative routing approach combines route selection and transmit diversity analysis to reach a cross-layer design, which is more practical in wireless networks.

In this dissertation, we develop the relations between the transmitted power and link outage behavior in cooperative wireless communication to find energy cost-effective routes. The main contribution of this work is the proposed Outage-aware K-shortest Cooperative Routing (OKCR) algorithm, which is capable of finding the most optimal energy efficient route, given the preferred quality- of-service (QoS) requirements defined by outage probability at the destination. It is shown that OKCR yields energy saving of 51.92% over non-cooperative, and of 43.18% with respect to CASNCP algorithm [4], which uses the shortest-path route in cooperative communication and employs the combination of cooperative and point-to-point modes in a single-relay model.

We also employ end-to-end outage probability as the performance metric to study the relation between cooperation and routing. To be specific, an efficient sub-optimal routing algorithm is devised to choose the best path among all possible paths between the source and the destination. In this method, the network is divided into a number of clusters, and at each cluster all possible paths are established from the source toward temporary destinations within the local relay cluster. The best path is the one with minimum outage probability, which is selected at each hop distributively. Although, this method improves the outage performance significantly, the channel state information requirement increases with the number of nodes. To reduce the amount of overhead needed, a simpler realization of the same algorithm is implemented with less complexity level. By the use of a relay selection method based on channel gains, at each hop L relays are selected to forward the information toward the destination. To reflect the effects of fading and path loss, a practical channel model is also considered, and the performance comparison with other known algorithms in the area, is carried out.

Our contributions can be summarized as follows:

- Formulate the direct and cooperative link cost in terms of outage behavior, between a source and a destination as an optimization problem.

- Formulate the optimized power routing problem and derive the closed-form expressions for the minimum transmission power to guarantee a certain end-to-end outage

probability.

- Find routes that are energy efficient while assuring minimum end-to-end throughput in a wireless cooperative network.

- Propose a distributed optimal and heuristic routing algorithm to establish a cooperative route assuring each link outage below a certain target level.

- Evaluate the performance of the proposed algorithms using simulations.

- Simplify the network structure via clustering.

- Find the most possible optimal path with regard to outage probability independent from the shortest path.

- Reduce the complexity and amount of CSI needed in finding the optimal path in a multi-hop network.

1.3   Dissertation Organization

In this dissertation, we develop and analyze a cross-layer framework for utilizing the cooperative communication paradigm in wireless networks. The ultimate goal of our research is to develop new relay deployment and selection protocols across the network that can minimize the end-to-end outage, reduce the required transmission power to achieve a desired network throughput, and maximize the lifetime of a given network.

The dissertation is organized as follows. In Chapter 2, we introduce the common terms and assumptions in the cooperative communication, review related work in the literature, and the performance metrics considered in this dissertation. We also provide an overview of what have been addressed in the area of cooperative communication. In Chapter 3, we formulate the cooperative link cost between a set of transmitters and receivers and propose two heuristic algorithms of polynomial complexity. In Chapter 4, we propose an outage-aware power saving cooperative routing algorithm that reduces end-to-end transmission power.

Minimum Outage Routing in Cooperative Multi-hop Networks is discussed in Chapter 5. Simulation results are presented also in this chapter. Chapter 6 discusses the results of the dissertation and presents possible directions for future work.

Chapter 2: Cooperative Relaying: Background and Literature Survey

In this chapter, we investigate the available literature in the area of cooperative communication relevant to this dissertation. After defining some general terms and definitions we begin to investigate what have been done in cooperative communication with regard to power-saving approaches. In the following section we focus on contributions which concentrate on various types of cooperative communication and relay forwarding strategies. Next section presents the main challenges in the area of cooperative diversity and serves as an introduction to the problems encountered in multi-hop cooperative relay networks. For more clarity, we begin with common terms, definitions and performance metrics.

2.1 Common Terms, Definitions and Metrics

2.1.1 Definition of a Route

Although the concept of a link has been well defined for wired networks, the notion of a route in wireless networks appears to be less clear. According to [5] a route is the path taken by a datagram between source and destination. The datagram moves from one hop to another hop. The data can be received only from a node behind or forwarded only to the node in front. However, in the cooperative communication paradigm, this typical definition of a route is disregarded. In cooperative communication data can be originated from multiple transmitters or there are also concurrent transmissions, which violate the original definition of a route. In cooperative communication, nodes are supplied with a single antenna. These nodes are able to obtain diversity gain just like multiple antenna communication by cooperatively transmitting data [6]. For this reason, we can say that multi-hop communication is a particular case of cooperative communication.

We redefine a route in this new wireless communication as a path taken by a message from the source to the destination. Basically, this path is a set of nodes participating in transmission and encoding [7]. Hence our definition is based on the nodes that forward the message not just capturing it. As an example, in a network depicted in Figure (2.1), when S send a message to D, all the nodes in between $\{1, 2, \ldots, L\}$ are able to capture and decode the message. But only node 1 forwards the message to the destination. As a result, according to our definition, the route is $\{S, 1, D\}$. We can apply this definition to broad range of multi-hop networks from wireless to wired.
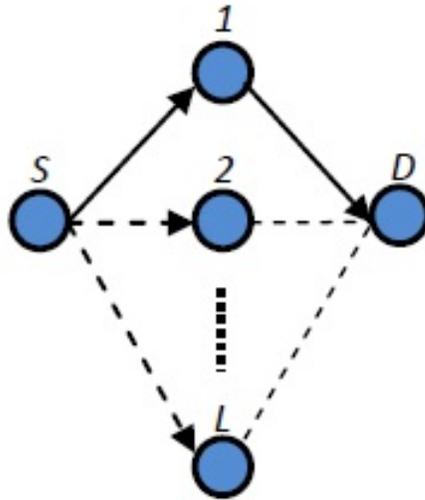
Figure 2.1: A network model with L relays

2.1.2 Performance Metrics

Before going further into the current literature on cooperative communication, we discuss some of the most important metrics used to evaluate the performance of different methods.

Outage Probability

Generally, the mobile Rayleigh or Rician radio channel is characterized by rapidly unstable channel characteristics. As commonly a certain minimum (threshold) signal level is needed

for acceptable communication performance, the received signal will experience periods of acceptable signal strength (non-fade intervals) or insufficient signal strength or fades. During fades the user experiences a signal outage.

For fading channels, a common metric is the outage probability P_{out}. Outage occurs if the signal drops below the noise power level. The signal outage probability is quite easy to calculate if we know the probability distribution of the fading (e.g. Rayleigh or Rician / Nakagami) and determined as the probability that the mutual information, I between a source and a destination drops below a certain desired rate, R:

$$P_{out} = Pr[I \leq R] \tag{2.1}$$

Therefore, outage probability is a common metric to investigate the performance of cooperative networks due to the fact that its calculation is easier than other error-related metrics.

Diversity Order

Diversity order is also considered as a popular metric for performance evaluation of cooperative systems. It is the slope of average frame error probability in log-scale in the high SNR regime, i.e., [8]

$$d = -\lim_{SNR \to \infty} \frac{\log_2 P_{out}(SNR)}{\log_2(SNR)} \tag{2.2}$$

It means that, a method with diversity order d has an error probability at high SNR acting as $P_{out}(SNR) \approx SNR^{-d}$ (see Figure (2.2)) [9].

Hence, in a high SNR scenario, a method with higher diversity order will exceed the one with lower d. However, schemes with the same diversity order may have dissimilar
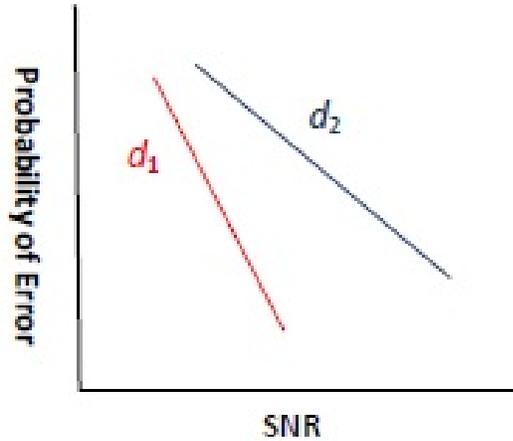
Figure 2.2: Diversity order vs. Probability of Error

properties in low SNR regime. Therefore, to prevent from misleading conclusions, this metric has to be used with other performance metrics [10].

Bit Error Probability

The bit error rate and symbol error rate (SER) are important metrics for measuring the performance of communication systems. The bit error rate or bit error ratio (BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval. BER is a unitless performance measure, often expressed as a percentage. The probability of bit error, P_e relates to the value of the BER. The BER can be considered as an approximate estimate of the bit error probability. This estimate is accurate for a long time interval and a high number of bit errors.

2.2 Energy Efficiency in Cooperative Communication

Cooperative communication can be used as a means to enhance the network performance, due to its ability in mitigating multi-path fading through spatial diversity [2]. In comparison

with current forms of space diversity using multiple antennas, cooperative communication can present more resiliency via relaying among the nodes. The power-saving problem can be tackled from different layer perspectives ranging from physical layer to network layer. At the physical layer, devising energy efficient communication methods for the wireless medium is the most important objective. One such method is the so-called cooperative communication [1], [6]. Designing cooperative medium access control (MAC) in wireless networks has also gained much attraction in recent years [11–13]. The protocols of this area are based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), which can be classified into two main categories: virtual hop cooperative such as CoopMAC and automatic repeat request like C-ARQ [14], [15]. The goal at the network layer is to find energy efficient routes with minimum transmission power in an end-to-end setting [16–18].

2.2.1 Physical Layer Approaches

Much works [19–21] have been done at the physical layer to reduce required transmission power from a source node to a destination node by choosing a transmission scheme that requires the minimum amount of transmit power. At this layer, user cooperation appears in the form of cooperative diversity, which can boost the capacity of network and acquire diversity gain through user's antennas to build a virtual antenna array. For instance, in [22] the authors propose a new form of spatial diversity in which diversity gains are achieved via the cooperation of mobile users. The capacity and outage probability of the cooperative diversity is also studied in their work. In order to take advantage of cooperative diversity, there are a variety of approaches at the physical layer such as Store-and-Forward (SF), Amplify-and-Forward (AF), Decode-and-Forward (DF), and Coded Cooperation (CC), which are discussed in [1], [11].

Moreover, cooperative communication by the use of relays has the capability to alleviate fading through obtaining spatial diversity and present flexibility in addition to traditional MIMO communication. Scaglione et al. [6] introduced three schemes of cooperative diversity: fixed relay, selected relay, and incremented relay. The fixed relay protocol includes

Amplify-and-Forward and Decode-and-Forward methods, whereas selected relay and incre-mented relay protocol dynamically manage cooperative schemes on the basis of feedbacks between the cooperative user, sender and receiver. In [23] and [24], relay-selection meth-ods in Decode-and-Forward cooperative systems were analyzed. The authors in [25] have provided symbol error rate performance analysis for the decode-and-forward multi-node scheme. By having an information theoretic look at the cooperative communication, they analyze the transmission power needed to obtain a desired end-to-end rate. Similarly, a decentralized relay-assignment algorithm for wireless communications has been offered in [26]. Most of these papers, however, put more emphasis on diversity of a single, isolated link. Even when such a link is regarded to be part of a larger network, routing issues and the effect of interference from other nodes usually remains unnoticed.

2.2.2 Network Layer Approaches

The problem of energy-saving in the network layer is to find the best possible routes that minimize transmission power in an end-to-end setting. As a result routing strategies also has gained interest to enhance network performance. Typical routing protocols usually consider ad-hoc networks as a graph of point-to-point or multiple links (Figure (2.3)), in order to convey data between nodes in a multi-hop manner. In other words, it is the exploitation of cooperative communications in a multi-hop structure. The cooperative multiple access control (MAC) and routing protocols were devised to decrease the energy consumption in the network [12]. Initially, cooperative nodes exchange control messages with neighboring nodes to reach an optimal transmit power. And then, they send their signal at the same time but different pseudo noise (PN) sequences which are set at the initial stage. In [27], authors proposed route searching algorithms to reduce overall power usage with cooperation via nodes . By the use of cooperative communication, we can extend the radio range, and accordingly facilitate connectivity in wireless networks [6]. It is proven that the cooperative network can be completely connected with high probability.
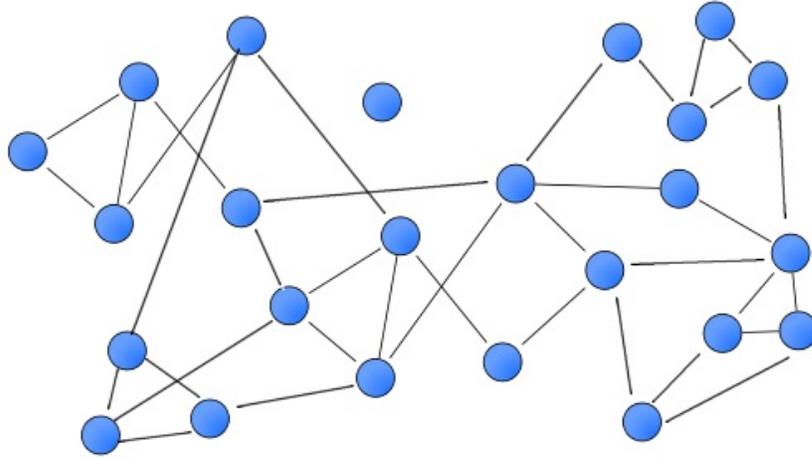
Figure 2.3: A simple graph of network

Unlike wired networks, the concept of a link has not been well defined in wireless communications. However, the same perception of link that is taken from wired networks are often confined by Wireless networks. That is, simultaneous transmissions of multiple nearby transmitters result in interference generating a collision [6]. On the contrary, in cooperative communication a link can derive from multiple transmitters, and concurrent transmissions when synchronized, do not result in collision. Therefore, we note that multi-hop communication in wireless networks is a particular case of cooperative communication.

2.2.3 Cross Layer Approaches

Although there has been significant research on energy efficient routing and cooperative communication, separately, only recently a few works have addressed network layer routing and physical layer cooperation problems together, which is known in the literature as cross-layer design. The cross-layer design (which is referred to designing protocols based on their layer dependencies) is an efficient technique in the energy limited cooperative communication [28], [29]. Generally, the objective of this type of designs is to locate the most power-optimal end-to-end routes. In this design, upper layers are provided with the physical information about the wireless medium to deliver scheduling, routing, resource allocation,

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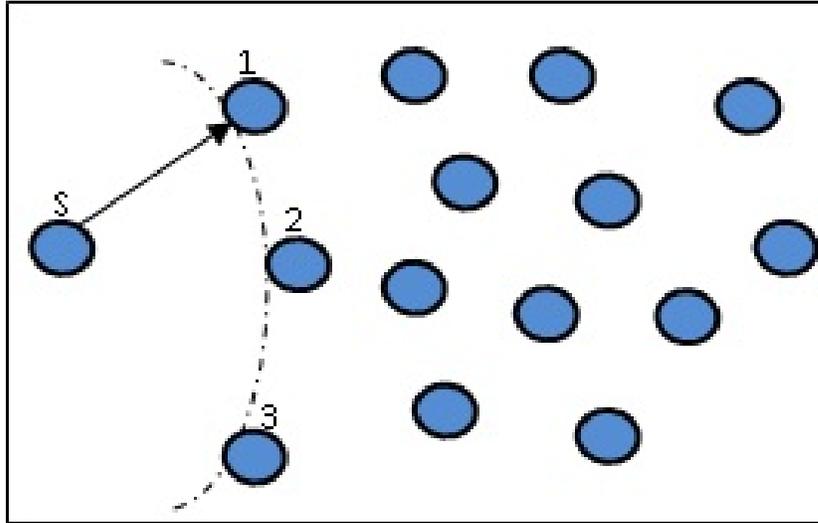
Figure 2.4: Wireless broadcast advantage

and flow control algorithms. Routing algorithms, which are established upon the cooperative communication, are known as cooperative routing. It is the idea of cooperation used at the network layer, that every node has the role of a data source or a relay to forward data packets for the rest of the nodes in the network.

Devising cooperative routing algorithms is a motivating research area and can reach to remarkable power savings. The cooperative routing takes advantage of two facts: wireless cooperative advantage and wireless broadcast advantage. As it is depicted in Figure (2.4), in the broadcast mode, signal transmitted by each node is received by more than one node within the transmission range, while in the cooperative mode many nodes send the same data to the same destination [4]. Figure (2.5) shows the cooperative transmission.

By the use of cooperative routing, we can achieve higher energy saving than non-cooperative shortest path routing. Besides, cooperative transmission considerably moderates the scalability issues in wireless networks.

Geographic routing and also opportunistic routing are another sorts of novel cooperative routing algorithms have been offered in recent years. As an example, in [30], the source broadcasts the location of itself and its destination via packets. When other nodes receive such packets, can select whether to forward the packets or not by calculating the distance
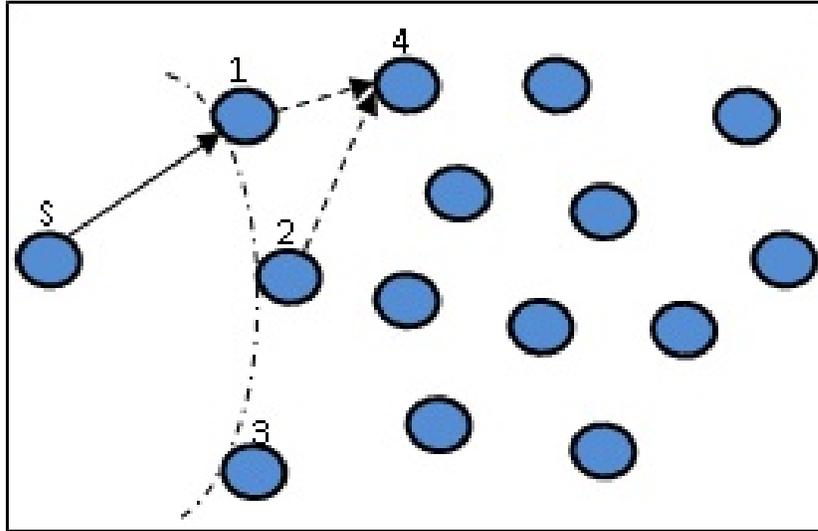
Figure 2.5: Wireless cooperative advantage

between the destination and themselves. This method assumes that the nodes are aware of their location and the location of their destination in the fading-free wireless networks (e.g. they are equipped with GPS receiver).

Another new routing method, which is discussed in [31], called opportunistic routing, where sources transmit packets with a list of particular priority of destinations. Nodes with the highest priority forward the packets while others discard them. Therefore, this design picks the best located node currently reachable and the priority hereby indicates the best positioned node to the destination.

Finally, the authors in [32] devised three cooperative routing algorithms, that is, relay-by-flooding, relay-assisted routing, and relay-enhanced routing. In the relay-by-flooding, the message is reproduced by flooding and multiple hops. The relay-assisted routing uses cooperative nodes of an existing route and the relay enhanced routing adds cooperative nodes to an existing route.
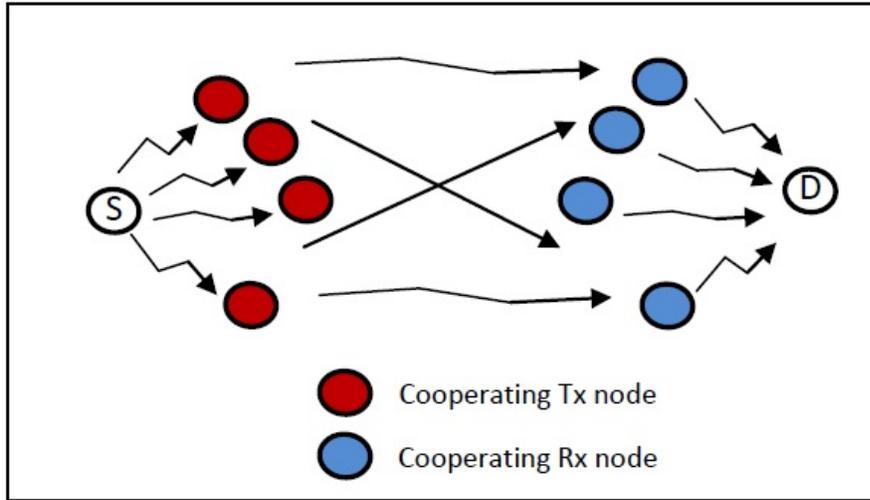
Figure 2.6: Illustration of virtual MIMO communication scheme

2.3   An Overview of Cooperative Communication

It has been proven that Multiple-Input-Multiple-Output (MIMO) techniques [19], [20] for point-to-point communication links, which use several antennas at the transmitter as well as the receiver, have remarkable improvements in quality (bit error rate) and data rate. These techniques can be exploited to enhance the network performance of ad-hoc networks. However, employing MIMO techniques in such networks is sometimes constrained due to size, cost and hardware restrictions mainly in size-limited devices. This gives rise to the concept of virtual MIMO communication in which a couple of single antenna network nodes form virtual antenna arrays and cooperatively do the transmission or reception of data. As a result, by the aid of cooperation nodes, which are belong to diverse locations of a wireless network, can form cooperative MIMO links that can achieve diversity and coding gains comparable to those of multi-antenna MIMO systems [1], [20]. This method is mostly named as cooperative communication. However the idea is to make these virtual arrays to imitate a MIMO system and hence obtain better performance. Figure (2.6) shows a schematic representation of such a method.

Relay as transitional nodes are present in close neighborhood to either the source or destination. They form the basis for cooperative communication, where they cooperate
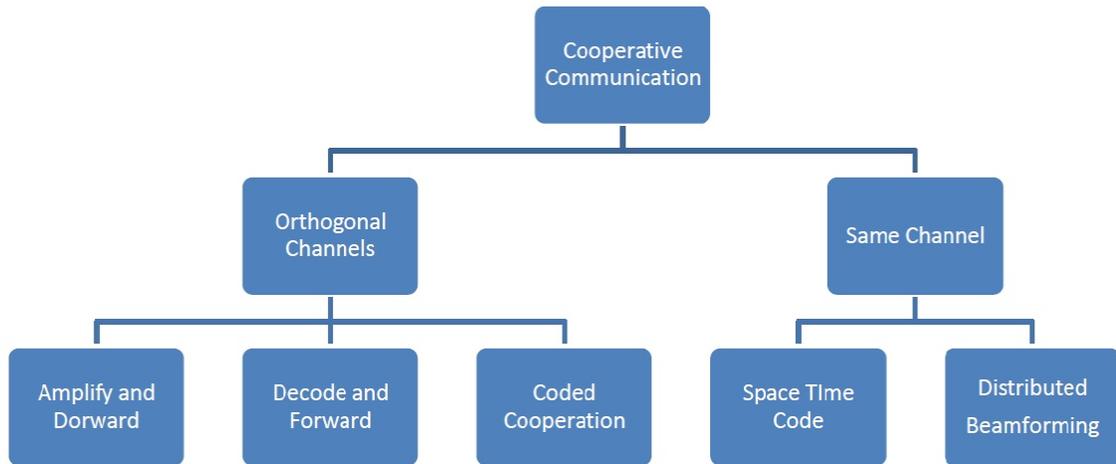
Figure 2.7: Various types of cooperative communications

with each other for transmission. The very first work in this area was done by Cover and El Gamal [33]. A feasible rate for relay networks is proposed based on accessible region for additive white Gaussian noise (AWGN) channels. The performance of cooperative diversity in a fading wireless environment was explored afterwards with various cooperative methods [2], [1]. When several nodes are concerned in cooperation, two types of cooperative protocol can be taken into account for the cooperating signals. The first category is that cooperative nodes use orthogonal signal to evade interference. Dissimilar frequency bands, different time slots or distinct spreading codes for each cooperating node are examples of orthogonal signal proportions. There are three fundamental cooperating methods in this category determined by the forwarding structure of the cooperating signal; amplify-and-forward, decode-and-forward, and coded cooperation. On the other hand, all cooperating nodes can transmit at the same time through the same signal dimension. Distributed beamforming and space time code use the same signal dimension. In the distributed beamforming cooperating nodes alter their frequency, phase, and timing offsets to get the coherent signal summation at the destination. These approaches are shown in Figure (2.7).

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2.3.1 Relaying Methods

2.3.2 Decode and Forward

In this method, the cooperating node decodes the received signal from the source during the first time interval and retransmits the decoded signal to the destination in the next time interval. This method is depicted in Figure (2.8). The receiver at the destination uses information retransmitted from multiple relays and the source to make decisions. It is likely that a cooperating node decodes symbols incorrectly resulting in transmission error. Faultless restoration at the relays may involve retransmission of symbols or use of forward error correction (FEC) based on the quality of the channel between the source and the relays. This may not be appropriate for a delay limited networks. Although this method is somehow simple and flexible to channel conditions, it suffers from unsuccessful detection, which leads to an unfavorable error at the destination. We should note that, when this method is implemented in our algorithms discussed in the following chapters, have an advantage of canceling the noisy information received by the relay.
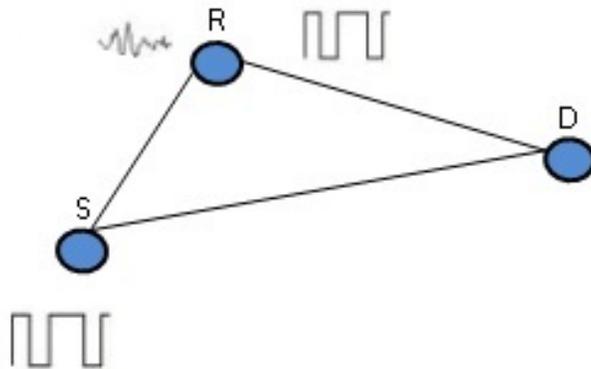
Figure 2.8: Decode and Forward method

2.3.3 Amplify and Forward

As you can see in Figure (2.9) at the first time slot, the cooperating node receives the signal transmitted by the source but do not decode them. At the next time interval, the cooperating node amplifies and retransmits the received attenuated version of the signal to the destination. The destination combines both signals sent by the source and the relay to attain diversity from two independent channels. The destination needs to have channel state information between sources and relay to properly decode the symbols sent from the source. To this end, pilot signals must be sent over the relays which call for extra bandwidth. Apart from that, analog signals sampling, amplification and retransmission is not a trivial task for real-time applications. AF also has the drawback of noise amplification, with the chance of augmenting the errors made by the source as a result of an operating relay.
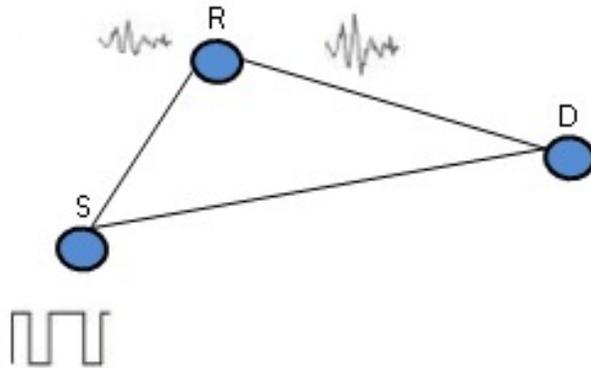
Figure 2.9: Amplify and Forward method

2.3.4 Coded Cooperation

Another method (Figure (2.10)) in which cooperation and coding are used together, is called coded cooperation [34]. In this method, user's code word is sent via different fading paths. The most crucial aspect of coded cooperation is that all of this is done automatically

without any communications between the users. The users data is divided into blocks and CRC code is added to each block. Moreover, data is encoded into a codeword which is devided to two segments; N_1 and N_2 bits [1]. Generally, in this framework, various channel coding approaches can be exploited. For instance, the code may be a block of convolutional code or a combination of both.
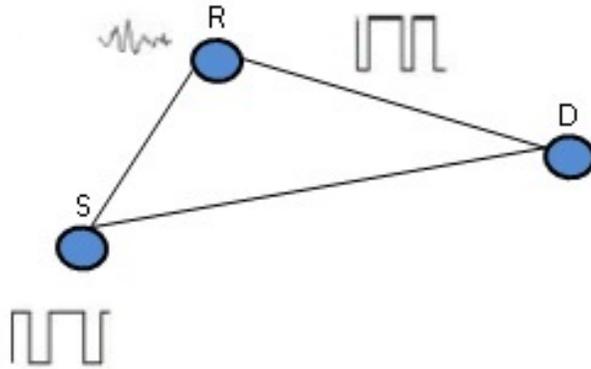
Figure 2.10: Coded Cooperation method

We have also another forwarding method, which is called Demodulate and Forward. In this method the relay node demodulates the received data and forward it toward the destination.

In [35] the authors measure the performance of AF and DF and show that these methods are very dependent on the relay position. For instance, DF demonstrates better results when the relay is closer to the source. Similarly, AF has better performance the relay is closer to the destination. On the other hand, Coded cooperation, can be used for all channels, and always obtains better rate than the direct transmission. As far as the implementation is concerned, DF is more complex because of the decoding necessity. AF implementation may also be tricky due to dealing with analogue data.
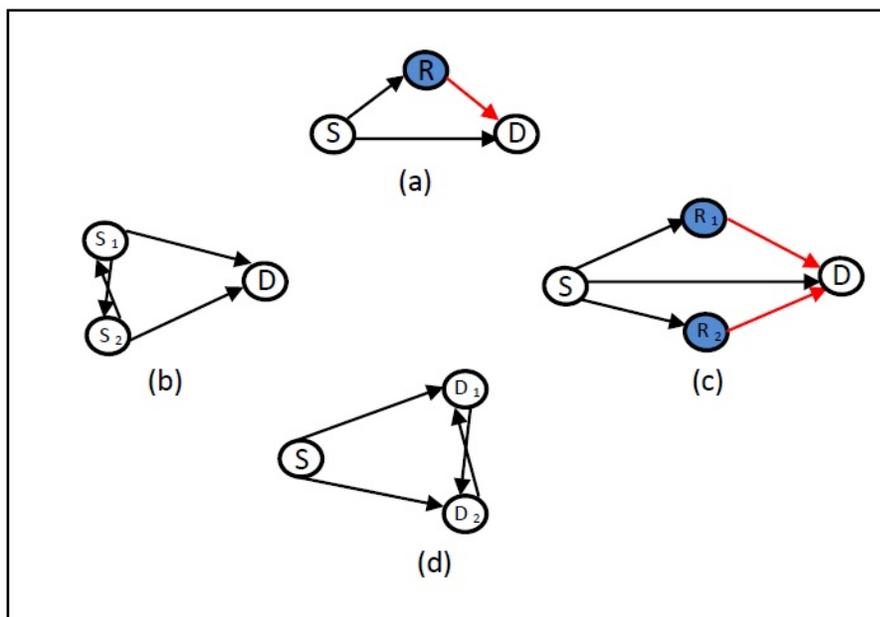
Figure 2.11: Relays architectures

2.3.5 Relaying Architectures

Figure (2.11) shows various relaying architectures as explained in [33]. Figure (2.11(a)) is the original relay architecture in the cooperative communication, which is also called "single-relay model". We mostly use this model in our analysis. In the figure S is the source, R is the relay and D is the destination terminal. The source broadcasts the signal to both the relay and destination. The relay then retransmits the information to the destination. When the source and the relay cooperate to transmit information at the same time to the destination our first case is changed to a multiple access channel as shown in Figure (2.11(b)). Moreover, when the relay and the destination cooperate we will have a broadcast problem as shown in Figure (2.11(c)). Figure (2.11(d)) shows a simple case of parallel relaying using two branches of relays.

2.4 Related Work and Issues

The existing literature in this area can be categorized into two groups, as follows. The first group assumes a static network in which perfect channel state information is obtainable; in this case, nodes are capable of cooperatively transmit to a receiver. A prominent example is the work presented in [36], where optimal power allocation and routing are formulated. Whereas there have been lots of works (as we discussed above) in this type of cooperation recently, the synchronization necessities for such are burdensome in mobile ad-hoc networks.

In the second category, cooperative routing decisions are made without channel state information. For instance, in [37] authors consider a set of neighboring nodes, which cooperatively transmit with equal power. Whereas the first type (i.e., cooperative beamforming) encounters major implementation issues, present solutions in the second category (i.e., equivalent power allocation) suffer from being optimal.

The cooperative routing problem has been recently investigated in the literature. In [4], [38] authors focus on the theoretical analysis in routing and cooperative diversity in order to reach an ideal end-to-end rate. For Instance, in [4] two cooperative routing algorithms, namely Minimum Power Cooperative Routing (MPCR) and also Cooperation Along the Shortest Non-Cooperative Path (CASNCP) are proposed, which rely on establishing the routes based on well-known shortest path algorithms. In [36], Khandani et al. present one of the earliest works in this area, where they formulate the energy utilization in a static cooperative wireless network. They consider the energy efficient approaches, which support broadcast and cooperative communication-aware routing and propose a couple of weighted heuristic algorithms (Cooperation Along the Minimum Energy Non-cooperative Path (VAN-L) and Progressive Cooperation (PC-L)) from a single source to a single destination. In their work, Multiple-Input Single-Output (MISO) technique is also taken into account, and substantial energy savings obtained. However, since they assume there is only one flow in the network, the relations between various neighboring flows have not been examined. In [39], Li et al. prove that the problem of using cooperative radio transmission model to find

the most energy efficient route from a source to destination is NP-complete. Then, they propose a cooperative algorithm called Cooperative Shortest Path (CSP), which minimizes the power transmitted by the last L nodes added to the route.

In this work, we assume that only fading distribution is known at the transmitters, and jointly formulate optimal power allocation and cooperative routing. In particular, a general cooperation method is considered in which multiple transmitters cooperatively convey data to a receiver by the use of relays. However, distributed receiver cooperation is inherently onerous and ineffective. Hence, receivers independently receive and decode transmitted data. Receivers that are successful in such decoding can then join the transmitting set or used as relays.

In those protocols, however, only one relay will be selected to forward the data packet to the destination and additional information is required for the node selection procedure such as inter-node loss rates and geographic distance. Furthermore, those approaches limit the potential performance gain by restricting the number of the forwarding nodes to one even when multiple neighboring nodes can be involved in cooperation.

Chapter 3: Minimum-Energy Cooperative Routing Strategies in Wireless Ad-hoc Networks

3.1 Introduction

In this section, we study the problem of minimum energy routing with cooperative MIMO communication in a static wireless network (such as a wireless ad-hoc network). We use cooperative MIMO concept in a limiting form, in which there is no communication among the receivers, i.e., no coding gain from MIMO. It is due to the fact that distributed decoding drastically raises the complexity of the physical layer communication, and causes extensive signaling overhead. As an alternative, in this chapter, we focus on power gain of cooperative MIMO in an environment similar to multiple parallel MISO transmissions. It means that the receiving set must not be a single node as in MISO techniques considered by Khandani et al. [1].

Our goal is to find routes that are energy efficient while assuring minimum end-to-end throughput. We consider cooperative communication in a wireless network, and formulate the cooperative link cost (in terms of transmission power) between a set of transmitting and receiving nodes as an optimization problem. Since there is not a straightforward form for the optimal solution we derive a sub-optimal answer for the power allocation problem; two heuristic algorithms of polynomial complexity, namely, Optimal Restricted Cooperative (ORC) and Optimal Cumulative Cooperative (OCC), to find energy efficient routes. To evaluate the performance of the proposed algorithms, some comparisons are performed with those algorithms offered by Khnadani et al. [1] through simulations. In particular, we show the energy savings of up to 50% can be achieved with our heuristic algorithms.

3.1.1 System Model

Consider a static wireless network that is modeled as an undirected graph with N nodes (devices), where each node has a single omni-directional antenna. We assume that each node can regulate its transmission power so as to manage its transmission radius. The energy cost for transmission from node i to node j (for example node 2 to node 3 in Figure (3.1)) is proportional to $d_{ij}\alpha$, where d_{ij} is the distance between nodes i and j and α takes the value between 2 and 4, depending on the specifications of the transmission medium. The precise transmit power at each step is determined based on the decision of a node to transmit directly to the adjacent node or transmit cooperatively using a neighboring node as a relay. All nodes in the network are assumed to have full knowledge of the location and residual energy of every other node in the network. The channel coefficients are independent complex Gaussian random variables with zero mean and unit variance and are assumed to be constant over a complete frame transmission. The noise terms are modeled as zero-mean, complex Gaussian random variables with equal variance N_0.

Channel Model

In this work, a time-slotted wireless channel is considered between each pair of transmitting and receiving nodes, assuming that the channel is completely characterized by the channel coefficient gain. The channel coefficient reflects the different effects of the channel such as symbol synchronicity, multi-path fading, shadowing, and path loss between two nodes. In our free space propagation model, this parameter is inversely relative to the square of the distance between the communicating nodes. The model for the discrete-time received signal at each non-transmitting node j is as follows:

$$y_j[t] = \sum_{i=1}^{N} g_{ij}x_i[t] + n_j[t] \tag{3.1}$$
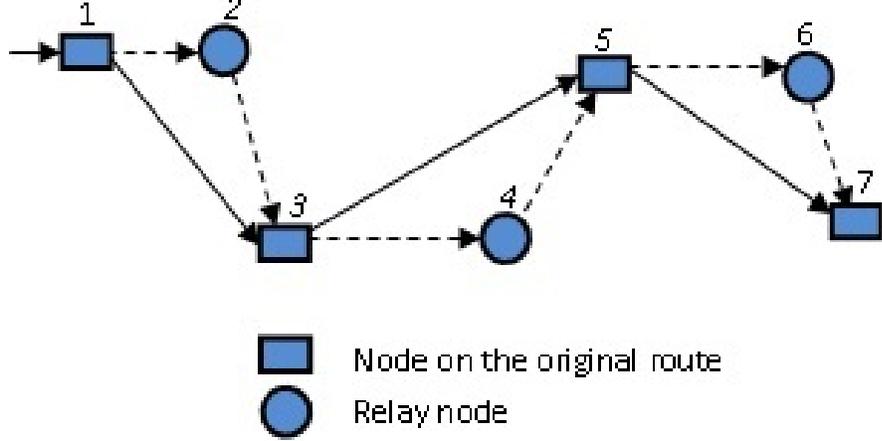
Figure 3.1: Cooperative routing model

where $y_j[t]$ is the received signal at node j in time-slot t, N is the number of transmitters, g_{ij} is the channel coefficient between the transmitting node i and the receiving node j, $x_i[t]$ is the signal transmitted by node i, and $n_j[t]$ models the additive noise and other interference received at node j. The transmission power of transmitter i is denoted by P_t and the received power level at node j is given by $P_r = g_{ij}^2 P_t$. Furthermore, each node has a bound on its maximum transmit power denoted by P_{max}. For simplicity, the time-slot index t in the rest of this discussion is skipped. It is assumed that the data can be decoded appropriately if the received Signal-to-Noise Ratio (SNR) is higher than a minimum threshold SNR_{min}, and if not, no data is received. Moreover, we also assume that the information is encoded in a signal that has unit power and that we can regulate magnitude of the signal by multiplying a scaling element s_i, so that the transmitted power by node i would be s_i^2. Finally, the noise power at node j is denoted by P_{nj}.

Cooperative Routing Model

Figure (3.1) shows a rigid route (1-3-5-7) in an ad-hoc network, where source node 1 transmits data to destination 7 through two intermediate nodes 3 and 5. The nodes 2, 4, and 6 are three relays.

It observes that node 2 is not included on the route, but it is the neighbor of nodes 1 and

3 and can be used as one of the relays of node 1. The same regulation enforces involving nodes 4 and 6. Figure (3.1) also reveals the model of cooperative routing, where a source or a middle node in a centralized behavior selects one relay among all of its neighbor nodes. The source or intermediate node sends a data packet to its next hop and a duplicate to relay. The relay receives and forwards the packet to the next hop of the source or intermediate node that acts equally on the packet until the packet reaches the destination. For the rest of the nodes on the fixed route, the situation is the same. Meanwhile, nodes only choose one best relay, which is a straightforward model of uni-hop cooperative routing.

Figure (3.2) is also a simple model of cooperative routing. At each transmission slot, all nodes that have received the information cooperate to send the information to the next node along the best route. Explicitly, in first transmission slot, the source node S transmits to the next hop which is node 1, and then in the second transmission slot, node S and 1 can cooperatively send the information to the second hop, node 2, and then in the next step, node S, 1 and 2 cooperate to transmit information to the third hop, node 3, and so on, until the destination node D is reached.
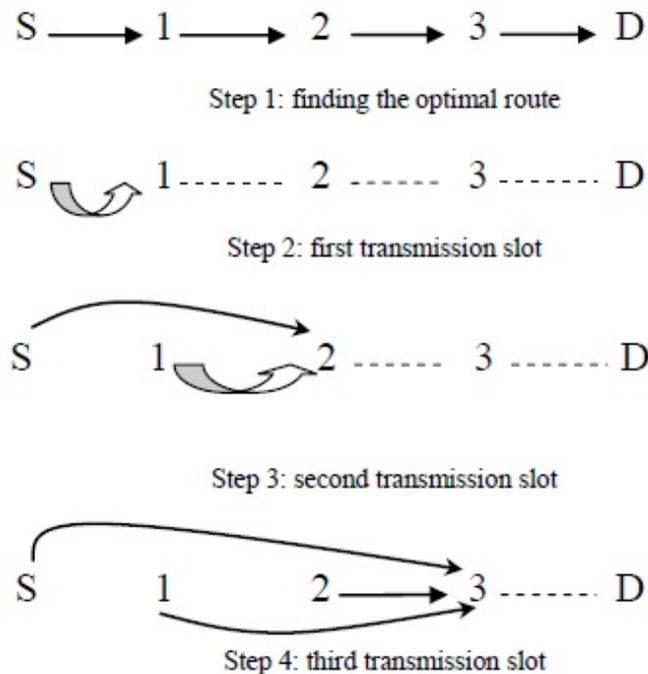
Figure 3.2: Cooperative routing procedures

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Link Cost Formulation

In this subsection, our goal is to find the optimal power allocation required for a successful transmission from a set of m transmitting nodes $T = \{t_1, t_2, \ldots, t_m\}$ to a set of n receiving nodes $R = \{r_1, r_2, \ldots, r_n\}$. The link cost (LC) is determined as the summation of the transmission power over all nodes in the transmitting set T, that is:

$$LC = \sum_{t_i \in T} s_i^2 \tag{3.2}$$

We construct a vector called g_j as the vector of channel gains between transmitting nodes in T and a receiver r_j from R, and also vector S as the power scaling factor for nodes in T, as follows:

$$g_j = \begin{bmatrix} g_{1j} \\ g_{2j} \\ \vdots \\ g_{mj} \end{bmatrix}, \quad S = \begin{bmatrix} g_{1j} \\ g_{2j} \\ \vdots \\ g_{mj} \end{bmatrix} \tag{3.3}$$

Considering these two vectors, the received signal at receiver r_j can be rewritten as:

$$y_j = g_j^T S + n_j \tag{3.4}$$

In order to have an error-free transmission, the received SNR should be greater than SNR_{min} for all the nodes in R. Thus, the following inequality should be held:

$$(g_j^T S)^2 \geq SNR_{min} P_{n_j} \tag{3.5}$$

where P_{n_j} is the noise power at receiver r_j. There is also a bound on the maximum power transmitted by each node, which can be written as:

$$s_i^2 \leq P_{max} \quad \text{for all } t_i \in T \tag{3.6}$$

We are concerned with minimizing the transmission power for a successful transmission from T to R. According to equations mentioned above, allocation problem is now an optimization problem with $m + n$ constraints. In order to solve this problem, we can easily rewrite them as follows:

$$\mathbf{y} = G^T S + \mathbf{n} \tag{3.7}$$

where, y and n are as follows:

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, \qquad \mathbf{n} = \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_n \end{bmatrix} \tag{3.8}$$

and $G = [g_1, g_1, \ldots, g_1]$.

Remember that y_j and n_j are the received signal and the additive noise at receiver r_j, correspondingly. After that, subject to the restrictions on the received signal powers at the receivers, and the maximum power on every transmitter, we describe our transmit power minimization problem as the following quadratic program formulation:

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$$
r_d = \begin{cases} minf(s) = \dfrac{1}{2}S^T Q_s \\[2mm] G^T S \geq b, \\[2mm] S \leq p \end{cases}
\tag{3.9}
$$

where, Q, b and p are as follows:

$$
Q = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}, \qquad b = \begin{bmatrix} \sqrt{SNR_{min}P_{n1}} \\ \sqrt{SNR_{min}P_{n2}} \\ \vdots \\ \sqrt{SNR_{min}P_{nm}} \end{bmatrix},
\tag{3.10}
$$

$$
p = \begin{bmatrix} \sqrt{P_{max}} \\ \sqrt{P_{max}} \\ \vdots \\ \sqrt{P_{max}} \end{bmatrix}
\tag{3.11}
$$

Various mathematical methods such as the simplex method, active set method or lagrangian multipliers can be exploited to solve the optimization problem defined in (3.9). However, there may not be any applicable answer to the power allocation problem.

Approximate Link Cost Formulation

It is helpful to solve the optimization problem (3.9) in a way that can be written in a closed form. Such a closed-form solution gives some perception into the power allocation problem by which we will be able to verify a property of MIMO links (specifically, as the transmitting set becomes larger the link cost becomes smaller).

When we consider the set of receiving nodes as an essential node, the problem of power allocation will be concentrated to a MISO scenario instead of MIMO one. In order to solve

the power allocation problem for MISO, we need to calculate the channel gains between the transmitters and the essential node. To compute channel gains, assume a typical transmitter has to transmit at its maximum power with the intention that the total power from ti and other transmitters received at any node r_j is larger than the minimum SNR level. Naturally, a receiver with larger channel coefficient requires less transmit power in order to decode the received signal correctly. We estimate this by assuming that the transmitter t_i sees all receivers r_j equivalently. In other words, node t_i considers that all nodes r_j have the smallest channel coefficient among all $g_{ij}s$ for all receivers in the R. Let g^* denotes the channel coefficient vector between transmitters and the other nodes . Based on the above discussion, the resulting vector for the channel coefficient is:

$$g^* = \begin{bmatrix} ming_{1j} \\ ming_{2j} \\ \vdots \\ ming_{mj} \end{bmatrix}, \tag{3.12}$$

The new optimization problem based on (3.12) is rewritten as:

$$\begin{cases} min \sum_{t_i \in T} s_i^2 \\ (s^T g^*)^2 \geq SNR_{min} P'_n \\ s_i^2 \leq P_{max} \quad \text{for all } t_i \in T \end{cases} \tag{3.13}$$

where P'_n is the largest noise factor of the essential node. Using Lagrangian multipliers technique, the solution to this optimization problem is described as:

$$S_i = \frac{g_i^*}{|g^*|^2}\sqrt{SNR_{min}P_n'} \tag{3.14}$$

where g^* is i-th entry of the channel gain vector. The link cost is then given by:

$$LC = \sum_{t_i \in T} s_i^2 = \frac{SNR_{min}P_n'}{\sum_{t_i \in T}(g_i^*)^2} \tag{3.15}$$

A few interpretations are important to mention here. First, based on equation (3.14), the transmitted signal level is relative to the channel attenuation. In addition, based on equation (3.15) the cooperative cost is smaller than each point-to-point cost. This conclusion is intuitively reasonable and proves the energy saving caused by the wireless cooperative benefit.

3.2 Cooperative Route Selection

In the previous section, we formulated the transmission cost for cooperative communication between two sets of nodes. In this section, we develop optimal algorithms to discover the least cost route in an arbitrary wireless network.

3.2.1 Optimal Route Selection

In this subsection, we find an optimal cooperative route from a source to a destination in an arbitrary network. The optimal routing algorithm is multi-hop naturally and chooses a cooperative link in every time-slot. The transmitting and receiving sets, in every time-slot k, are denoted by T_k and R_k correspondingly. Starting from the source node, the primary transmitting set, T_0 is simply $\{s\}$, and a route is found as soon as the receiving set at some time-slot k contains the destination node d. Considering the transmitting and receiving sets in previous time-slots, the transmitting set in time slot $k+1$ can be determined in different

algorithms. For instance, all nodes that have the data from preceding transmissions can cooperate in the next transmission (Cumulative Cooperative) or simply a subset of all nodes that already have the data take part in the transmission (Picky Cooperative). There is also another way, which just the receiving nodes in previous time-slot cooperate in the next transmission (Restricted Cooperative). We now use the link cost specified in previous section to formulate the total cost of a cooperative route. The goal is finding a route to minimize the total power P_t. The answer to this problem specifies an optimal transmission strategy at every time slot, and determines the least cost route in the network.

Having built the basic numerical tools, inspired form [36] we now present an uncomplicated example that illustrates the advantage of cooperative routing. Figure (3.3(a)) shows a simple network with four nodes. The arcs characterize links and the arc labels are point-to-point link costs. Figure (3.3(b)) shows the equivalent cooperation graph for this network. This graph can be used to illustrate the states of optimal routing problem, where a state is the set of nodes that have received the data until now. Links between the nodes in the cooperation graph stand for potential transitions between the states. The cost is calculated according to link cost formulation discussed in the previous section (the dashed links cost is zero since all go to the last node). The optimal cooperative route is the shortest path between node s and the last node in the cooperation graph. There are five different paths between the source and the destination in this graph, P_0 through P_5. P_0 is the non-cooperative minimum energy between s and d. And P_3 corresponds to the shortest path. Table 3.1 sorts the costs of these policies.

Figure (3.4) illustrates a network with 4×4 grid topology. For this network non-cooperative routing, the sequence of nodes passed from source s to destination d is $\{s, 1, 5, 6, 10, 11, d\}$. Moreover, if we consider the third algorithm, which is described above, the least cooperative cost is $(\{s\}, \{1, 4\}, \{5, 8, 9\}, \{10, 13, 14\}, \{d\})$. In a network with $n + 1$ node, can be proven that a typical shortest path algorithm (such as the Dijkstra's algorithm) will have exponential computational complexity. Besides, finding the cooperative route with the minimum power consumption is NP-complete. Hence, this would be intractable for
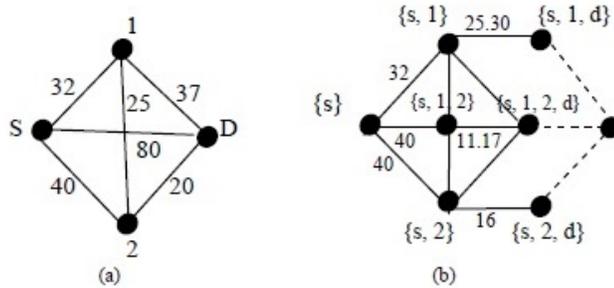
Figure 3.3: An example of cooperative routing algorithm. The graph in (b) is the cooperation graph equivalent to simple network in (a).

Table 3.1: Different transmission paths with the correspondent cost

1	Path	Cost
P_0	Non-Cooperative	60
P_1	$(\{s\}, \{s, 1\}, \{s, 1, d\})$	55.30
P_2	$(\{s\}, \{s, 2\}, \{s, 2, d\})$	56
P_3	$(\{s\}, \{s, 1, 2\}, \{s, 1, 2, d\})$	51.17
P_4	$(\{s\}, \{s, 2\}, \{s, 1, 2\}, \{s, 1, 2, d\})$	65.19
P_5	$(\{s\}, \{s, 1\}, \{s, 1, 2\}, \{s, 1, 2, d\})$	58.55

large networks. In the next subsection, we will develop sub-optimal cooperative routing algorithms that have polynomial complexity and perform reasonably efficient compared with the optimal cooperative routing algorithm discussed here.

3.2.2   Sub-optimal Route Selection

In optimal cooperative routing in the preceding subsection, we were looking for a set of receivers that minimize the total transmission power. To devise such a heuristic routing algorithm, we consider the largest set of transmitting nodes. We name this approach the selfish approach because the transmitting set meanly selects receiving nodes in order to build the largest possible receiving set. In every time-slot k, the largest receiving set is chosen with the intention that the power restrictions expressed in the other section for a successful cooperative transmission are fulfilled. We can also use one of the three algorithms described above along the selfish approach. We will assess the performance of these algorithms through

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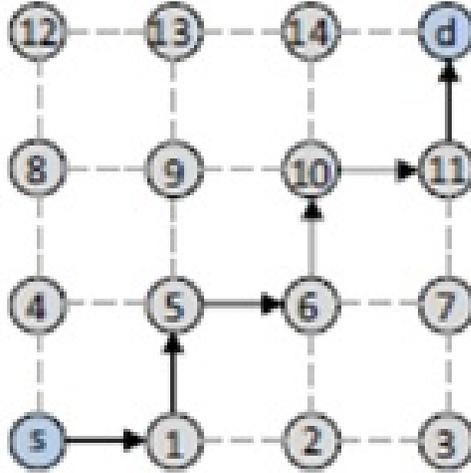
Figure 3.4: A standard grid topology with 16 nodes.

simulations in the next section. The simulation results indicate that the selfish algorithms perform comparatively efficient to the optimal algorithms although with considerably lower complexity. For instance, considering the network shown in Figure (3.4), we have evaluated the minimum cost route by the selfish restricted cooperative algorithm; the sequence of receivers is $(\{1, 4\}, \{2, 5, 6, 8, 9\}, \{3, 7, 10, 11, 13, 14, d\})$. Inquiring all probable nodes for addition in the receiving set, in time-slot k, takes $O(n)$ time. Since the maximum length of a route is $O(n)$, the complexity of finding a route with the selfish algorithms is $O(n^2)$. Thus, selfish routing algorithms are drastically quicker than the optimal ones, which have complexity of $O(2^{2n})$ for a network with n nodes.

3.3 Performance Evaluation

In this section, the routing algorithms discussed in previous sections are simulated to estimate their performance numerically in some example networks. In the next subsections, we present our simulation results and compare the performance of different algorithms in terms of energy consumption. For the simulations, we consider a wireless network with $N \times N$ grid (Figure (3.4)). We chose two nodes s and d positioned at the lower left and the upper right corners of the grid, respectively, and find cooperative and non-cooperative routes. We then calculate the total amount of energy consumed on each route using different routing algorithms. The performance measure of concern in evaluating different routing algorithms is the total energy consumed to send out data from source to destination. We choose the optimal non-cooperative routing algorithm, i.e., Dijkstra's algorithm, as the baseline for comparing cooperative algorithms. Hence, energy savings of a cooperative routing algorithm α is:

$$E_S(\alpha) = \frac{E_{nc} - E_\alpha}{E_{nc}} * 100 \tag{3.16}$$

where E_α and E_{nc} denotes the total transmission energy consumed by cooperative and non-cooperative algorithms respectively. We compare the effectiveness of the optimal algorithms with the algorithm proposed in [36]. We also compare the performance of our sub-optimal algorithms with the optimal on top of the sub-optimal algorithms proposed in [36].

Figure (3.5) shows the total energy cost for the two optimal cooperative algorithms ORC (Optimal Restricted Cooperation), OCC (Optimal Cumulative Cooperation) and ONC (Optimal Non-cooperative Routing. The total energy cost is the end-to-end link cost for a routing algorithm as defined above. As illustrated in the figure, the total energy cost is decreased by using the new schemes. Distinctively, it shows that the bigger the network is the superior the drop in energy cost. As estimated, OCC consumes less energy than ORC

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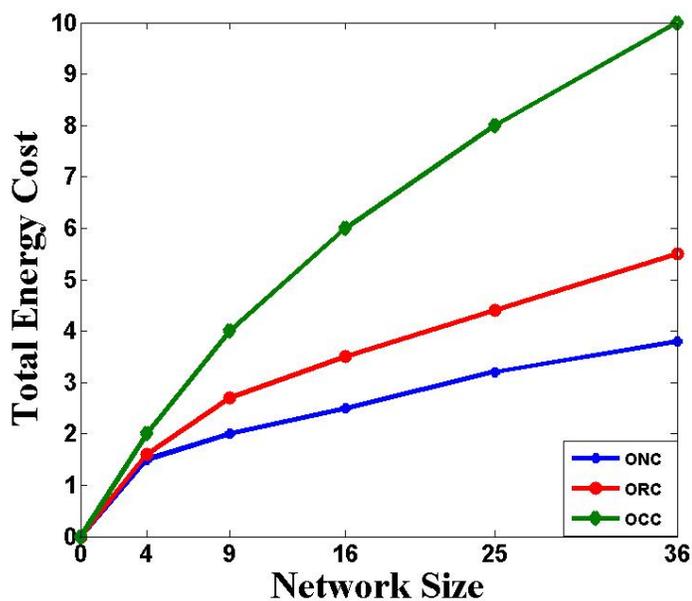
Figure 3.5: Total energy cost of optimal cooperative routing algorithms

due to the rising number of transmitters in the algorithm.

Figure (3.6) shows the energy savings of different cooperative routing algorithms for different network sizes. We observe that OCC (a MIMO technique) significantly outperforms CAN (a MISO technique), and achieves energy savings of close to 55% for a network with 36 nodes (relatively small network). Interestingly, ORC performs almost the same as CAN although one might expect a better performance. The reason is that CAN is inherently a progressive routing algorithm, which achieves low energy consumption by employing a large transmitting set in every step of routing toward the destination.
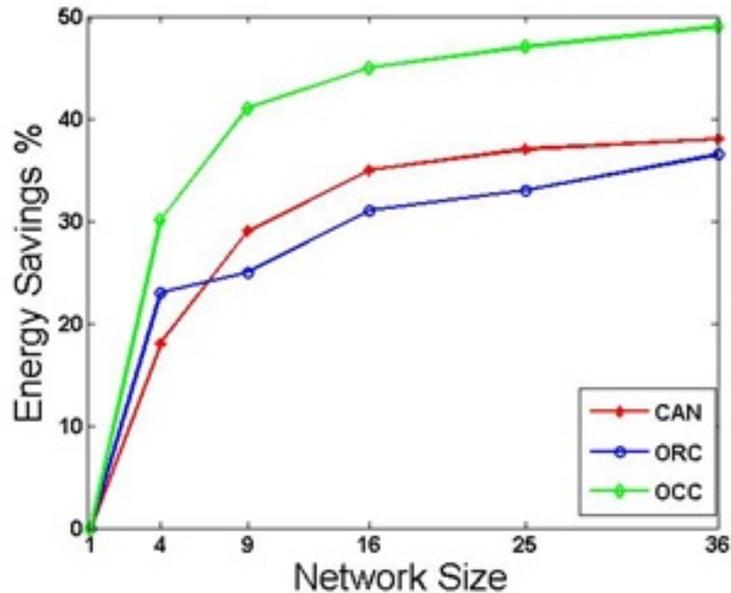
Figure 3.6: Energy savings of optimal cooperative routing algorithms

3.4 Conclusion

In this section, we investigated the problem of finding the minimum energy route in an arbitrary wireless network. We considered a cooperative technique for transmission at physical layer, and formulated the cost of a cooperative link between a set of transmitters and receivers as the lowest transmission power essential for successful decoding at every node in the receiving set. This is a general formulation of a cooperative link, which includes point to point, point to multi-point, multi-point to point and multi-point to multi-point transmission techniques measured by other researchers. We focused on the optimal transmission from a source to destination through sets of nodes that may perform as cooperating relays. Essential to the routing problem was the understanding of the optimal power allocation for a transmission from a set of source nodes to a set of destination nodes. We demonstrated solutions to this problem, and used these as the basis for solving the minimum energy cooperative routing problem. However, general shortest algorithms are not mathematically manageable and are not suitable for large networks. For a regular grid topology, we analytically achieved the energy savings due to cooperative transmission, representing

the advantages of the cooperative routing scheme. For general topologies, we proposed two heuristics and showed significant energy savings (close to 50%) based on simulation results.

Chapter 4: An Outage-Aware Power Saving Cooperative Routing Algorithm in Wireless Networks

4.1 Distributed Energy-Efficient Cooperative Routing in Wireless Networks

In this section we consider the general case of larger networks, in which we aim to propose a cross-layer design of cooperation-based routing algorithms that minimize the end-to-end transmission power while guaranteeing a desired outage.

Although most of prior work in this area address the combined optimization of the routing and power allocation, only a few employ end-to-end outage probability as a performance evaluation metric in cooperative communication. Moreover, majority of proposed algorithms are established on a single shortest path between source and destination. In this manner, benefit of cooperation-based routing is confined to only one path which might be far from being optimal. This motivates us to propose an approach to take various shortest paths into consideration in order to fully utilize the advantage of cooperative transmission. In this dissertation, we develop the relations between the transmitted power and link outage behavior in cooperative wireless communication to find energy cost-effective routes. One of the the main contribution of this dissertation is the proposed Outage-aware K-shortest Cooperative Routing (OKCR) algorithm, which is capable of finding the most optimal energy efficient route, given the preferred Quality-of-Service (QoS) requirements defined by outage probability at the destination. It is shown that OKCR obtains energy saving of 51.92% over non-cooperative, and of 43.18% with respect to CASNCP algorithm [4], which uses the shortest-path route in cooperative communication and employs the combination of cooperative and point-to-point modes in a single-relay model. The results of this chapter is

presented in [40] .

In the next section, we explain the cooperative system model, and form the transmission cost on the basis of outage probability. In the performance analysis section, our proposed algorithm is described in detail. The performance of different energy saving algorithms is discussed through simulation and results are demonstrated in simulation results section. Finally, we conclude the chapter in the last Section.

4.1.1 Network Model and Transmission Modes

In this section, we describe the network model and formulate the minimum-power routing problem. Then, we present the direct transmission and cooperative transmission modes.

Let us consider a general wireless network consisting of N nodes uniformly distributed between the source and the destination, which is modeled as an undirected graph. The energy costs for transmission from one node i to j is relative to the propagation distance and path attenuation model. Each node is assumed to have an omni-directional antenna, which allows them to communicate with each other. Notably, cooperative routing is performed hop-by-hop between any source-destination pair with the intention of reducing the transmission power, and at the same time assuring a particular outage probability. We assume time-slotted scheme, i.e., each node transmits in its individual time slot.

To be more specific, by the use of Decode-and-Forward (DF) strategy, in every time slot one relay is selected to receive the signal from the source, do the decode and re-encode procedure and then retransmit it toward the destination. The optimal path can be a mixture of cooperative transmissions and point-to-point transmissions. Therefore, we consider two types of transmissions similar to those in [4] direct transmission and cooperative transmission Figure (4.1). The route can be considered as a flow of any number of these two transmission modes, and the total power of each route is the summation of the transmission powers along the route.

Let $h_{s,d}$, $d_{s,d}$, and n_d represent the channel coefficient, distance, and additive noise between any two nodes in the network, respectively. For the direct transmission between
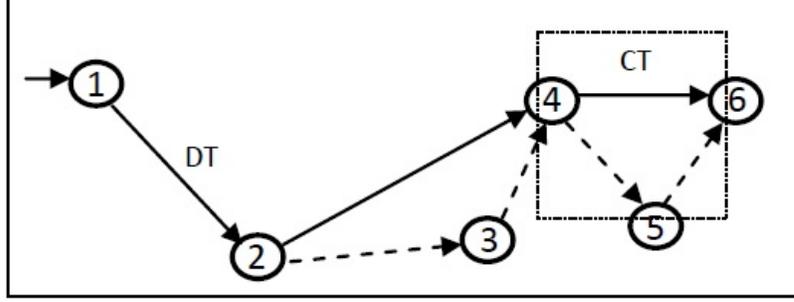
Figure 4.1: Cooperative Transmission (CT) and Direct Transmission (DT) modes.

nodes s and d , the received signal is:

$$r_d = \sqrt{\rho} h_{s,d} x_s + n_d$$

$$\rho = \frac{1}{d^k} p_t$$

(4.1)

where p_t is the transmission power, x_s is the information transmitted by the source and k is the path loss exponent. ρ is also the average signal to noise ratio.

For the cooperative transmission in Figure (3.7), we consider a moderated version of the decode-and-forward relaying cooperative scheme, offered in [2]. The sender sends its data in the current time slot. Due to the broadcast nature of the wireless medium, both the receiver and the relay receive the transmitted symbol. The received symbols at the receiver and the relay can be modeled as:

$$y_{s,d} = \sqrt{\rho} h_{s,d} x_s + n_d \qquad (4.2)$$

and

$$y_{s,r} = \sqrt{\rho} h_{r,d} x_s + n_d \qquad (4.3)$$

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We assume that the receiver and the relay decide that the received symbol is properly received if the received signal-to-noise ratio is greater than certain threshold [4]. In general, the relay can transmit with a power that is different from the sender power. However, this complicates the problem of finding the minimum-power formula, as will be derived later. For simplicity, we consider that both the sender and the relay send their data employing the same power.

Throughout this chapter, flat quasi-static fading channels are considered, hence, the channel coefficients are assumed to be constant during a complete frame, and may vary from a frame to another. We assume that all the channel terms are independent complex Gaussian random variables with zero mean and unit variance. Finally, the noise terms are modeled as zero-mean, complex Gaussian random variables with equal variance N_0. In this section, we formulated the minimum-power routing problem and we defined two main transmission modes. In the next section, we derive the closed-from expressions for the transmission power in both direct and cooperative transmission modes required to achieve the desired throughput.

4.1.2 Link Analysis

The wireless channel is characterized by its attenuation factor which is defined as:

$$\chi = \sqrt{\frac{1}{d^k}} h_{i,j} \tag{4.4}$$

where k is the path attenuation exponent and d is the distance between transmitter and receiver. Additionally, $h_{i,j}$ represents channel coefficient. It is assumed that the channel between the links follow Rayleigh fading distribution. For that reason the resulting channel gain is exponential. For the point-to-point link model the mutual information is:

$$I_P = \log(1 + SNR_p) \tag{4.5}$$

where the received transmission power to noise ratio SNR_p is denoted below:

$$SNR_p = \frac{P_t}{N_0}\chi_{x,z}^2 \tag{4.6}$$

Since, the noise is modeled as zero-mean complex Gaussian random variable with variance N_0. The outage event for the chosen transmission rate R_0 can be written as below:

$$P_{o-direct} = Pr(I_P \leq R_0) = \Theta(\delta d_{xz}^k)$$

$$\delta = \frac{(2^{R_0} - 1)N_0}{p_t} \tag{4.7}$$

$$\Theta(x) = 1 - \exp(-x)$$

For the cooperative transmission during the first time slot, the destination signal is the same as (4.1). Established upon the classic DF cooperative diversity scheme [2], source has to repeat the transmission when the relay is not capable of decoding the information (source-relay channel quality is not good enough). On the contrary, when the relay is able to decode and replicate the information appropriately, diversity gain is achieved through cooperative communication. Thus, link quality is a vital factor in system performance. The receiver in the second time slot satisfies:

$$r_d = \begin{cases} \sqrt{\frac{1}{d_{s,d}^k}p_t}h_{s,d}x_s + n_d, & |\chi_{s,r}^2| < \delta \\ \sqrt{\frac{1}{d_{r,d}^k}p_t}h_{r,d}x_r + n_d, & |\chi_{s,r}^2| \geq \delta \end{cases} \tag{4.8}$$

In this case, when we have retransmission of information by the use of relay, the mutual information can be written as below:

$$
I_C = \begin{cases} \log(1 + SNR_p), & |\chi^2_{s,r}| < \delta \\ \log(1 + SNR_c), & |\chi^2_{s,r}| \geq \delta \end{cases} \tag{4.9}
$$

where SNR_c is the received cooperative ratio:

$$
SNR_c = \frac{P_t}{N_0}(\chi^2_{x,z} + \chi^2_{r,z}) \tag{4.10}
$$

Then, the total outage for the cooperative link is written as:

$$
P_{o-cooperative} = Pr(I_C \leq R_0) = P_r * P_{o-direct} + (1 - P_r) * Pr(SNR_c < \delta) \tag{4.11}
$$

and the source-relay link outage event is similar to (4.8):

$$
P_r = \Theta(\delta d^k_{xr}) \tag{4.12}
$$

After substituting (4.12) and approximate exponential functions in (4.11) we reach to:

$$
P_{o-cooperative} = \delta^2 d^k_{xz}(d^k_{xr} + d^k_{rz}) \tag{4.13}
$$

We can use (4.13) in order to minimize the total transmission power of the cooperative link meeting end-to-end outage probability which can be expressed as:

$$
\begin{cases} min \quad p_t \\ s.t. \quad P_{outage} < Q(target\ outage) \end{cases} \tag{4.14}
$$

Using the above condition, OKCR minimum transmission power is shown as:

$$P_{t-min} = \sqrt{\frac{d_{xz}^k(d_{xr}^k + d_{rz}^k)}{Q}(2^{R_0} - 1)N_0} \qquad (4.15)$$

4.1.3   Cooperative Route Selection Algorithm

After characterizing the cooperative transmission cost in previous section, we describe in detail the proposed distributed algorithm OKCR to discover the best power-optimized route in a random wireless network while guaranteeing a predefined requirement for outage probability on every link. Table 4.1 outlines this algorithm elaborately. By employing OKCR we somehow identify the least energy-cost route while exploiting the advantage of cooperation. Generally, the K-shortest paths algorithms provide us with a list of the routes which are sorted by length. By the use of Yen's K shortest paths algorithm [41], which is implemented in a distribute way; the previously mentioned formulas are utilized to build the new cost functions necessary for finding the minimum-power route. Although there are other algorithms to find K shortest paths, the Yen's algorithm is more efficient than others and has less computational complexity. The Yen's algorithm works as follows. First, by the use of Dijkstra's algorithm [42] the shortest path is discovered, and then for each node in the shortest path, except the destination node, another shortest path is calculated. Simply, the new dissimilar path is added to the root path to construct a complete path from source to destination [43].

It is worth noting that the distance between nodes and also link outage are essential factors in the cooperative cost calculation. Accordingly, distance estimations between relays can be incorporated in the "HELLO" packets (which are periodically broadcasted between nodes). The proposed algorithm is implemented as follows. First, it generates K different shortest paths. Then, for each of these paths locates the best possible relay based on the cooperative cost calculation. Next, selects the most optimum path based on the total transmission power. We constrained the relaying procedure to just one best individual relay due to the fact that increasing the number of relays may not be necessarily improves the

performance.

Table 4.1: OKCR algorithm

Step 1: Apply Yen's non-cooperative K-Shortest paths algorithm to discover K paths that have the shortest lengths from the source node to the destination node
Step 2: In each optimal path, the cooperative link cost is calculated based on (4.10) to nominate the best possible relay as the next hop.
Step 3: When the minimum cost obtained using a specific relay, the source takes that potential relay to cooperatively facilitate the transmission toward the destination.
Step 4: After constructing all the cooperative links over each path, the path that requires less total power is chosen.

4.2   Simulation Results

In this section, our results are presented to demonstrate the power saving capability of our OKCR routing algorithm in comparison with other cooperation-based power saving schemes. The simulations are based on a $100m \times 100m$ square random network, in which N nodes are uniformly distributed (which is depicted in Figure (4.2) with 40 nodes). We choose the first and the last nodes as source and destination, respectively. The path loss exponent is $k = 2$, $R_0 = 0.2$ b/s/Hz and end-to-end outage of 0.001. Results are averaged over 1000 random network topologies.
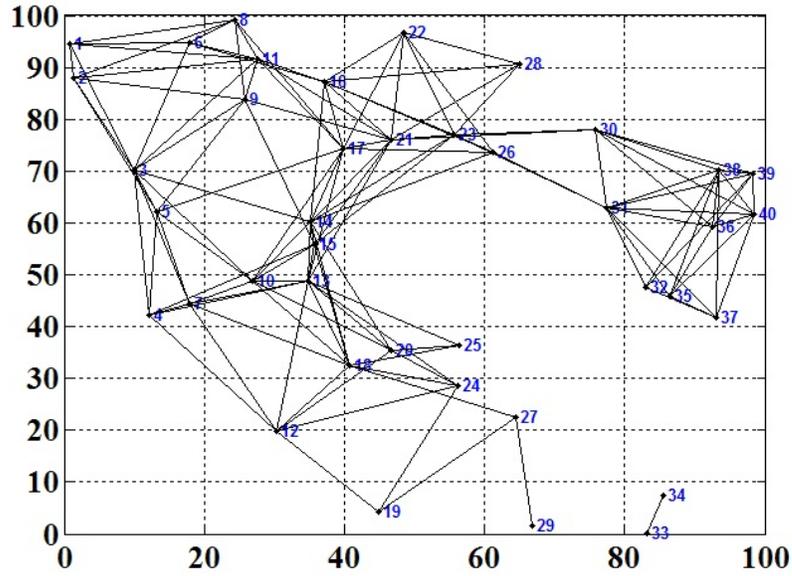
Figure 4.2: A $100m \times 100m$ square random wireless network consists of 40 nodes
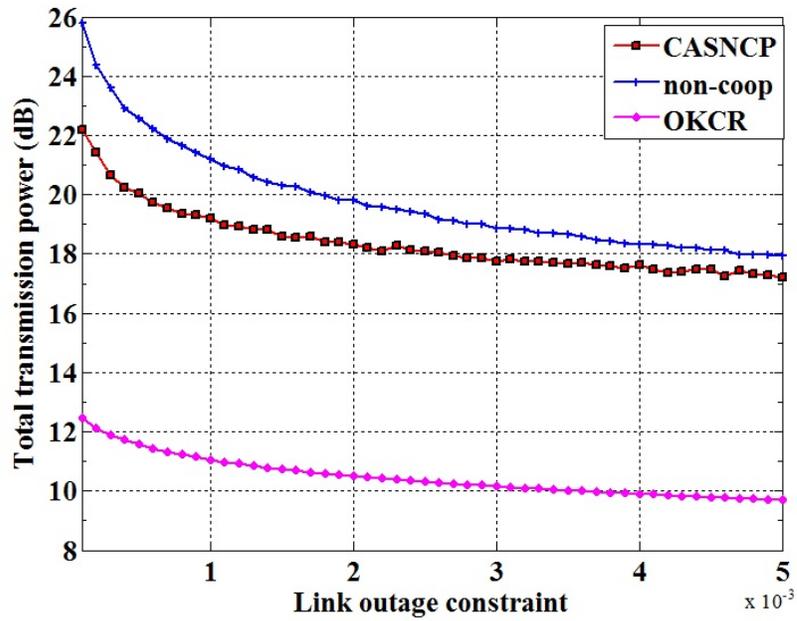
Figure 4.3: Total transmission power vs. link outage probability for $N = 100$, $K = 2$ and $R_0 = 0.2$ b/s/Hz in a $100m \times 100m$ random network.

Figure (4.3) shows the total transmission power versus link outage limit for various routing algorithms with equal total number of nodes. We anticipate the enhancement of the power efficiency from the analytical power measurements mentioned in the above sections. Besides, the procedure of finding the best relay (the one that is closer to the destination) plays an important role in the power reduction process. In fact, the simulation results validate this considerable progress.
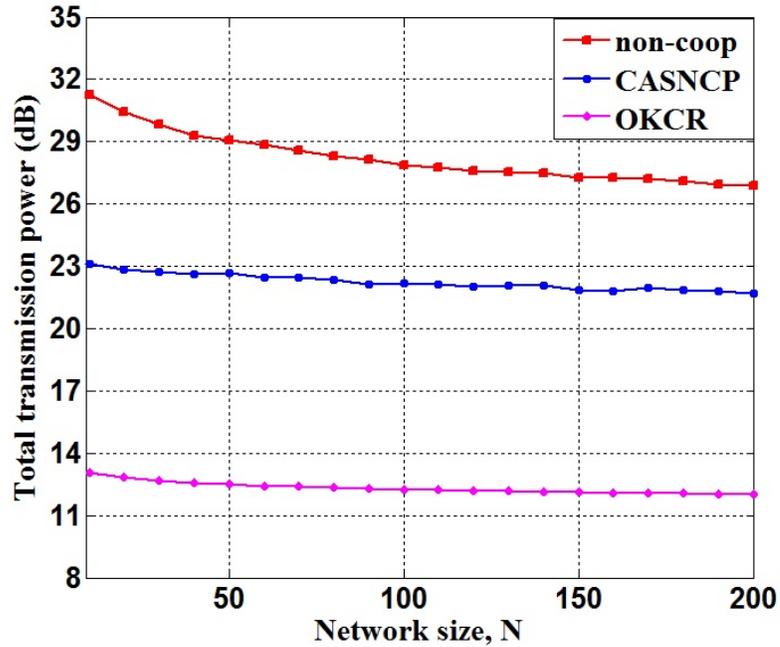
Figure 4.4: Total transmission power vs. link outage probability for $N = 100$, $K = 2$ and $R_0 = 0.2$ b/s/Hz in a $100m \times 100m$ random network for different number of paths as used by K-shortest paths algorithm.

Figure (4.4) illustrates the total power consumption with the similar setting as Figure (4.3) for different number of nodes. As illustrated, the total power decreases with network size scaling. Apparently, when the number of nodes increases their compactness goes up as well which leads to power reduction. In addition, our proposed power efficient routing algorithm outperforms CASNCP [23] exploits just one shortest path between source and destination.

In Figure (4.5), we plot the total power consumption with respect to different number

of paths which is designated as K. The higher the numbers of paths in use, the higher the needed total transmission power. The reason is that after a certain point there is no significant change in the arrangement of the network. As we can see in Figure (4.3), $K = 3$ outperforms other Ks. As a result it can be used as an optimum number of paths in the K-shortest paths algorithm.
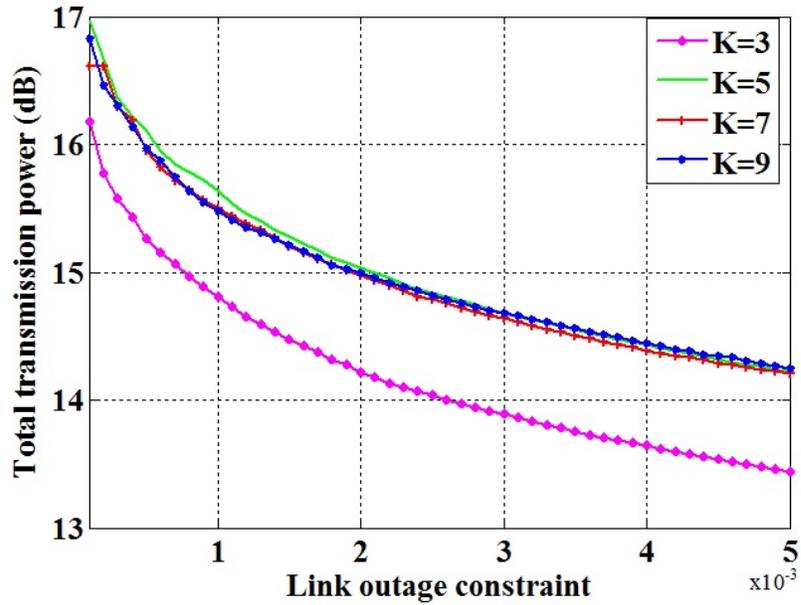
Figure 4.5: Total transmition power vs. the number of nodes for the desired outage of 0.001, $K = 2$ and $R_0 = 0.2$ b/s/Hz in a $100m \times 100m$ random network.

4.3 Conclusion

In this work, we have generalized the relay-selection problem to a broad routing problem. Specifically, we have explored the effect of the cooperative communications on the minimum-power routing problem in wireless networks. For a specified source-destination pair, the optimum route requires the minimum end-to-end transmission power while assuring predefined target outage. We have proposed a cross-layer design of routing method, called, Outage-aware K-shortest paths Cooperative Routing (OKCR) algorithm, which builds the typical shortest-path route then applies a cooperative-communication protocol upon the established route. We have shown that for random networks of N nodes, OKCR obtains energy saving of 51.92% in comparison with non- cooperative algorithms and of 43.18% over CASNCP which is one of the prominent cooperative routing algorithms in the literature.

Chapter 5: Minimum Outage Routing in Cooperative Multi-hop Networks

In this chapter, we focus on a multi-hop decode-and-forward wireless network with multiple relays located between the source and the destination. We employ end-to-end outage probability as the performance metric to study the relation between cooperation and routing. We are mainly concerned with establishing an optimal path(s) between the source and the destination with the goal of minimizing outage.

To be specific, an efficient sub-optimal routing algorithm is devised to choose the best path among all possible paths between the source and the destination. In this method, the network is divided into a number of clusters, and at each cluster all possible paths are established from the source toward temporary destinations within the local relay cluster. The best path is the one with minimum outage probability, which is selected at each hop distributively. Although, this method improves the outage performance significantly, the channel state information requirement increases with the number of nodes. To reduce the amount of overhead needed, a simpler realization of the same algorithm is implemented with less complexity level. By the use of a relay selection method based on channel gains, at each hop l relays are selected to forward the information toward the destination. To reflect the effects of fading and path loss, a practical channel model is also considered, and the performance comparison with other known algorithms in the area, is carried out. The results of this chapter is presented in [44] .

In the following sections, we first explain the system model. Our proposed methods along with the details of relay selection criteria are presented next. The performance evaluation of the proposed algorithms is done through simulation and is presented in the last section.
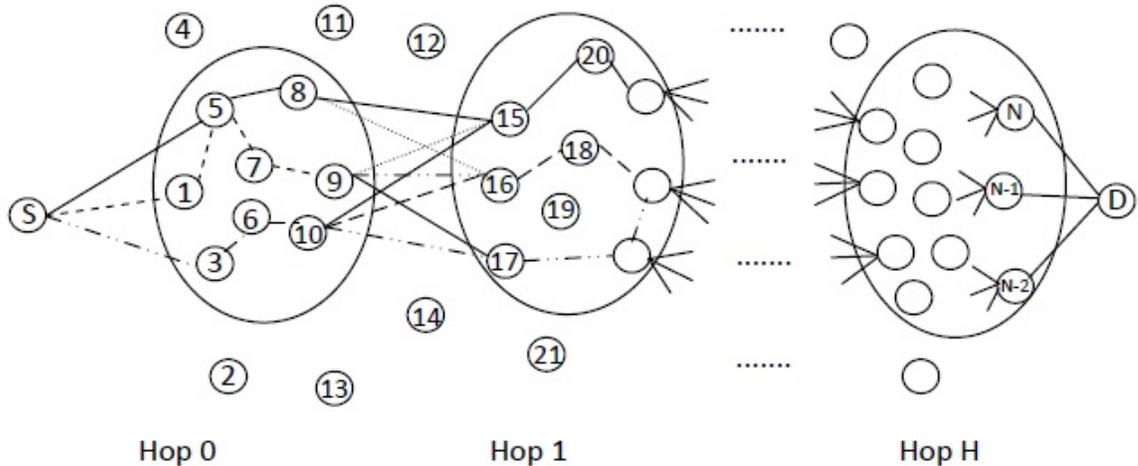
Figure 5.1: A simple H cluster cooperative network

5.1 System Model

As illustrated in Figure (5.1), we consider a general wireless network with $N+2$ uniformly distributed nodes consists of a source S, a destination D and a set of N potential relays. Each node is assumed to have an omni-directional antenna. There are H relay clusters established by the active source at each hop based on well-known position-based methods [45]. Time-slotted scheme is adopted, i.e., each node transmits in its own time slot. In every time slot, only one relay uses Decode-and-Forward (DF) strategy to carry out the decoding, re-encoding and retransmission procedure. For the channel gain between nodes i and j, we assume a complex Gaussian random variable with zero mean and variance $\sigma_{i,j}^2$. Typically, this reflects the effect of path loss, shadowing, and Rayleigh fading. Furthermore, the noise is modeled as zero-mean complex Gaussian random variable with variance N_0. For simplicity, we assume all nodes have the same constant power, P_t. Finally, the average SNR from node i to node j, can be defined as

$$SNR_{i,j} = \sigma_{i,j}^2 \frac{P_t}{N_0 W} \tag{5.1}$$

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where W is the bandwidth in Hz and $\sigma_{i,j}^2$ is modeled as

$$\sigma_{i,j}^2 = d_{i,j}^{-\alpha} \tag{5.2}$$

resulting from path loss and distance. Here, we use end-to-end outage as our performance metric. We assume that each link is in outage if the SNR at the receiver is lower than a threshold. The outage probability at link l is denoted as P_{out}^l, and total outage probability for path t is

$$P_{out}^t = 1 - \prod_{l=0}^{L}(1 - P_{out}^l) \tag{5.3}$$

Furthermore, the probability of outage for link l is calculated as

$$P_{out}^l = Pr(SNR_{i,j} < \xi_{th})$$

$$= 1 - \exp(-\frac{\xi_{th}}{SNR_{i,j}}) \tag{5.4}$$

$$\simeq \frac{\xi_{th}}{SNR_{i,j}}$$

where ξ_{th} denotes the required SNR threshold based on the desired rate R_0 in bps/Hz and modeled as

$$\xi_{th} = (2^{R_0} - 1) \tag{5.5}$$

Then, by replacing (5.4) into (5.3), we have

$$P_o^t = 1 - \prod_{l=0}^{L}(1 - Pr[SNR_{i,j} < \xi_{th}])$$

$$= Pr[\min_{l=0,...,L} SNR_{i,j} < \xi_{th}] \tag{5.6}$$

As we can see, the outage probability at each path is restricted by the worst link.

5.2 Optimal Routing Strategy

In this section, the proposed routing algorithms and their outage behavior are described in detail. Then, we present our simulation results to demonstrate the capability of these strategies.

5.2.1 Outage Analysis of the Sub-optimal Routing Algorithm

We consider H hops, at each hop there is a relay cluster reachable by the active source. All possible paths are established from the source to temporary destination nodes within the current relay cluster. Note that, these particular temporary destination nodes are selected as the closest nodes among the other nodes to the main destination.

In general, let $SNR_{i,j}^t$ denote the SNR of each link at path t, which $t \in \{1, ..., K\}$, $i, j \in \{1, ..., L\}$. According to (5.3), inspired by [46], we can say the end-to-end outage of each path is always bounded by the minimum SNR, SNR_{min}^t of links. In other words, the minimum outage between all paths is calculated by choosing the largest SNR_{min}^t. In the sub-optimal algorithm, we first generate K paths (K is the number of all possible paths) toward the selected nodes in the relay cluster. Then, for each path one link is chosen, which has the minimum SNR among all the links. Finally, the best path is selected as the one with the largest minimum SNR. When the largest minimum SNR is below the threshold, the outage occurs. Hence, the outage probability for each hop is written as below

$$P_{out}^h = Pr[\max_{i=1,...,K} \min_{j=1,...,L} SNR_{i,j}^t, h < \xi_{th}] \tag{5.7}$$

As a result, the total probability of outage in the network is the maximum of the outage

calculated at each hop, which is given by

$$P_{out}^{total} = 1 - \prod_{h=0}^{H} \{1 - P_{out}^h\} \tag{5.8}$$

If we replace (5.7) into (5.8), since H clusters are independent, the total outage is equal to

$$P_{out}^{total} = \prod_{h=0}^{H} Pr[\max_{t=1,...,K} \min_{j=1,...,L} SNR_{i,j}^t, h < \xi_{th}] \tag{5.9}$$

The Outage probability at each hop in (5.7) is not easy to solve. This probability is almost similar to the end-to-end outage of optimal routing calculated in [46] with definite number of relays and hops in the entire network. Inspired by their work and approximating exponential functions, the outage probability for each hop is given by

$$P_{out}^h \simeq (\frac{\xi_{th}}{SNR_{S,S+1}, h})^a + (\frac{\xi_{th}}{SNR_{D-1,D}, h})^b$$

$$- (\frac{\xi_{th}^{2ab}}{(SNR_{S,S+1}, h)^{ab}(SNR_{D-1,D}, h)^{ab}}) \tag{5.10}$$

$$+ O((\frac{\xi_{th}}{SNR})^c)$$

where a, b are the number of links in the first and last hop, respectively. The source and the destination are denoted here by S and D. The last element shows the effect of intermediate hops with c representing the number of links in between. Moreover, SNR is the average signal to noise ratio without considering the effects of path loss and shadowing. By replacing (5.10) into (5.9), the total end-to-end outage probability for our proposed routing algorithm is given by

$$P_{out}^{total} \simeq \prod_{h=0}^{H} [(\frac{\xi_{th}}{SNR_{S,S+1}, h})^a + (\frac{\xi_{th}}{SNR_{D-1,D}, h})^b$$

$$- (\frac{\xi_{th}^{2ab}}{(SNR_{S,S+1}, h)^{ab}(SNR_{D-1,D}, h)^{ab}}) \tag{5.11}$$

$$+ O((\frac{\xi_{th}}{SNR})^c)]$$

It can be implied that, the total outage probability is mostly relying on the first and last hop channel gains. The reason is that, all paths share the links in the first hop. Similarly, all paths have the same bottleneck in the last hop. Therefore, the number of paths in between which is changed by the number of hops, play an important role in the outage performance in low SNR scenarios.

5.2.2 Relay Selection Algorithms

To gain higher diversity, relay selection plays an essential role in cooperative communication, which is a challenge of how to choose the best relay(s). Various relay selection strategies have been designed in the literature [24, 47, 48].

Most of these works have focused on cooperative diversity for single-hop communication. When single-hop approach is applied in a multi-hop network, routing becomes very important. In recent years, several routing algorithms [49–51] are devised within the area of multi-hop cooperative communications. The key idea is that every node can be a relay to forward data toward the destination. The objectives of such protocols are generally confined to optimizing energy consumption [36, 39, 52], maximizing network throughput [53] or lifetime [54, 55].

5.2.3 Relay Selection Criteria

Before describing our L-relay ad-hoc routing method, we introduce two alternative criteria for relay selection. These criteria have the advantage of not requiring the source to have instantaneous CSI of the channels between the relays and the destination. These methods are first introduce in the work of Tarokh et al. [56]. As you can see in Figure (5.2), We consider a wireless network with $N + 2$ terminals: a source s, a destination d and a set of N candidate relays $R = 1, 2, \cdots, N$. We assume that the N candidate relays are uniformly distributed in a circle of radius d_0 centered at the source node. Among these, R denotes the set of selected relays. Assuming flat-fading, let h_{sd}, h_{si}, and h_{id} denote the wireless channel coefficients from the source to the destination, from the source to relay i, and from relay i to the destination, respectively. These coefficients represent the impacts of both path loss and Rayleigh fading. The path loss is equivalent to the distance between transmitter and receiver and also path loss exponent. The Rayleigh fading component is modeled as a zero mean complex Gaussian random variable with variance $1/2$ per real dimension. We assume that the source terminal has instantaneous channel state information (CSI) of h_{sd} and h_{si}, which it can measure directly. However, the source has no instantaneous CSI of h_{id}, but only has the distribution of these channel coefficients.

Best Expectation Method

In the cooperative transmission, the channel capacity between the source and relay i is written as [56]:

$$C_{si} = \log_2(1 + \frac{P|h_{si}|^2}{\eta^2})$$

(5.12)

where η^2 is the variance of noise at the receiver side and P is the transmission power. The channel capacity for the cooperative group and the destination is denoted as:

$$C_{sAd} = \log_2(1 + \frac{P|H_{sAd}|^2}{\eta^2}) \tag{5.13}$$

where H_{sAd} is the channel matrix between the cooperating group and the destination. In this method, the set of relays are chosen to maximize the equation:

$$S_{Best-Expectation} = C_{Si} + E\{C_{sAd}\} \tag{5.14}$$

Therefore, this method selects the best relays based on the source-relay capacities.

Best-m Method

A simpler method can be considered which is needless of the number of relay calculation. In other words, the source itself decides the optimal number of relays for cooperation without any dependency on the particular network realization. In this method, the relays are selected according to the following criterion:

$$S_{Best-m} = \arg \max_{|S|=m, S \subset R} (S_{si}) \tag{5.15}$$

Since, this method is also easier to implement, we use it as a base for our relay selection criteria. To implement this method we can use the following algorithm [56]:

Table 5.1: Best-m algorithm

1: Sort $|h_{si}|$, $i \in R$ in decreasing order such that $|h_{si}| \geq |h_{si}| \geq |h_{si}| \dots |h_{si}|$, where $r_n \in R$ and $1 \leq n \leq N$
2: Include the relay node $r_1, r_2, \dots, r_m$ into set S_m

This algorithm easily chooses m relays with the best source-to-relay channels. The number of relays depends on the total number of relays N, the relay distribution and also the channels between relays, but it is not dependent on the particular network realization [56].
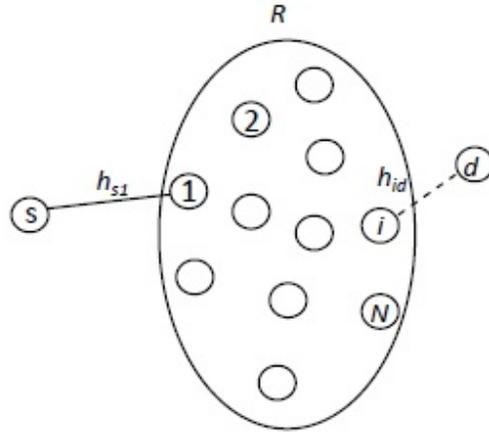
Figure 5.2: Wireless multi-hop network for relay selection

5.2.4 Outage Analysis of the L-relay ad-hoc Routing Method

Although, the outage performance is improved by the use of our sub-optimal strategy, its complexity and overhead will increase when we have a large number of nodes. To have a less complex strategy, in this section, we introduce another realization of the previous algorithm in which a relay selection method is employed at each relay cluster. As opposed to the sub-optimal strategy, the amount of channel information in the L-relay ad-hoc strategy is significantly decreased.

Figure 5.3: L-relay ad-hoc routing strategy cooperative network model

As we can see in Figure (5.3), at each hop, l relays are selected to forward the packet to l nodes within the relay cluster. The best relays are simply chosen based on the best source-to-relay channels. The nodes which receive the relays information at each cluster, are also selected as the closest nodes among the the other nodes to the destination. Hence, at hop $h \in \{0, ..., H\}$, l relays are chosen form the set $R_m = \ar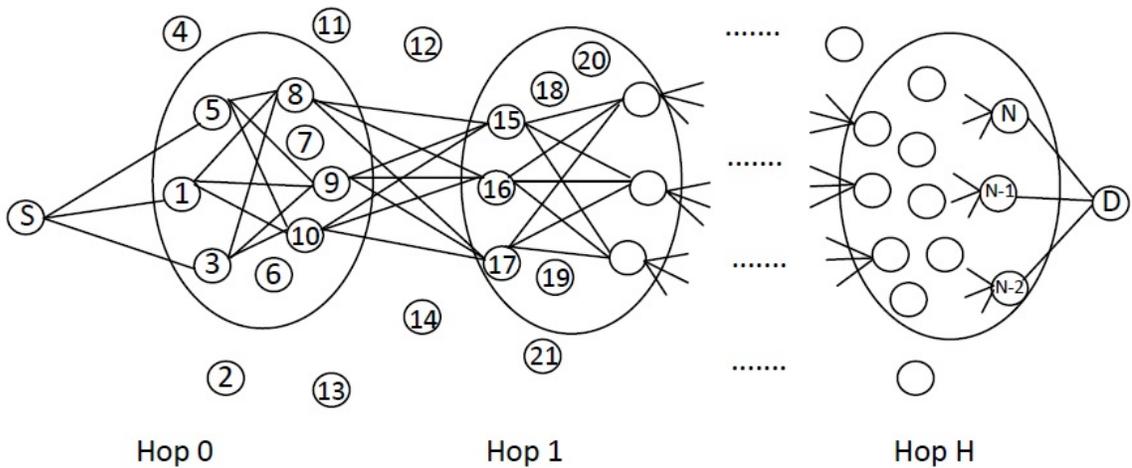g\max_{i=1,...,R}\{h_{sr_i}\}$, where h_{sr_i} denotes the channel between the source and relay i. Then, after we generate all possible paths between the relays toward their destinations at each relay cluster, the best path is selected as the one with the largest minimum SNR. When the largest minimum SNR is below the threshold, the outage occurs. Hence, the end-to-end outage probability is written as below

$$P_{out}^{L-relay} = 1 - \prod_{h=0}^{H}\{1 - P_{out}^h\} \tag{5.16}$$

where P_{out}^h is the outage at each hop. To calculate the outage at each hop, we can use equation (5.10) considering the fact that the end-to-end outage is limited by the links in the first and the last hop. In each intermediate cluster, we have outage, if all the selected relays SNR are below the threshold.

As opposed to the sub-optimal algorithm, with this simple assumption, we can easily calculate the outage at each intermediate cluster by dividing the network to C sub-clusters in which the links are independent. There are $3l$ paths between two consecutive sub-clusters. Therefore, the outage probability at each intermediate sub-cluster after approximating exponential function, can be written as

$$P_{out}^{sub} \simeq (\frac{\xi_{th}}{SNR_{c,c+1}})^{3l} \quad, for \quad c \in \{1, ..., C\} \tag{5.17}$$

where $S = 2(H - 1)$ denotes the number of sub-clusters. At the first and last hop, which we have just l links, the outage probability is similar to the sub-optimal algorithm and is

calculated as $(\frac{\xi_{th}}{SNR_{S,S+1}})^l$ and $(\frac{\xi_{th}}{SNR_{D-1,D}})^l$, respectively. Hence, the total outage probability

for the L-relay ad-hoc algorithm is

$$P_{out}^{L-relay} \simeq (\frac{\xi_{th}}{SNR_{S,S+1}})^l + (\frac{\xi_{th}}{SNR_{D-1,D}})^l$$

$$- (\frac{\xi_{th}^{2l^2}}{(SNR_{S,S+1})^{2l^2}(SNR_{D-1,D})^{2l^2}})$$

$$+ \prod_{c=1}^{C}(\frac{\xi_{th}}{SNR_{c,c+1}})^{3l} \tag{5.18}$$

5.2.5   Implementation Issues

As mentioned above, we assume that channel gains between nodes remain unchanged for a long period of time. Thus, our methods can be used for constructing the routes between the source and the destination using only nearby available channel state information. Although, our approaches can be used when a central controller is available, their system overhead is significantly reduced in comparison with other multi-hop routing strategies in the literature. The reason is that, in the sub-optimal algorithm, we choose only one relay as a local destination in each cluster to receive the information of other nodes and then all possible paths are generated toward that particular node. In this way, we confine the channel state information requirement to the local hop. In addition, only one central controller is needed at each hop. Whereas, in the optimal solution introduced in [46], the source needs the CSI of all links globally. Thus, the complexity of this solution will increase drastically in large networks.

In some applications, centralized implementation can be done easily when a central controller is accessible. In this way, the proposed algorithms can be employed efficiently. However, the availability of a central controller in some other applications, such as sensor networks is problematic. This necessitates a distributed implementation for the proposed algorithms. To implement our methods in a decentralized form, we can use a back-off

timer method introduced in [47] for each relay. In this scheme, relays start their timers before forwarding their information. The duration of the timers is set based on the channel gain information. The relay with the best channel gain has the lowest timer value among others and obviously that relay starts its transmission first. As soon as it starts sending the information, other relays refrain from transmission by going trough a random back-off time.

Although, the proposed sub-optimal algorithm can considerably improve the outage performance with less complexity than the optimal solution in [46], its algorithmic complexity is still high. To achieve a better complexity level, the L-relay ad-hoc method is proposed, which picks the best relays at each hop to forward the information toward the destination. For the first and last hop, l links connect the source and the destination to the rest of the network, as a result, $2(l-1)$ comparisons are needed. At each relay cluster, $3l$ paths are also established with the length of 2 and the number of comparisons is $(2H-3)(3L-1)$. Hence, by the use of L-relay ad-hoc strategy better complexity is achieved.

Moreover, collecting position information of nodes might be another practical issue. In greedy geographical routing, each node is aware of its position and forwards the packet to its neighbor, that is geographically closest to the destination [45]. To address this issue in our methods, the positions of neighboring nodes are collected via regular HELLO messages. Considering the fact that, the distance between relay clusters is in proportion with the network diameter, each node collects its neighbor nodes information within this particular range. Therefore, the neighbors updates are limited within each relay cluster as opposed to being broadcasted in the entire network, which reduces the resulting overhead to an agreeable level.

5.3   Simulation Results

In this section, our results are presented to demonstrate the advantage of our methods comparing to other multi-hop routing strategies. The simulation is based on a square random network with a diagonal of 160m and $N+2$ uniformly distributed nodes. Results are
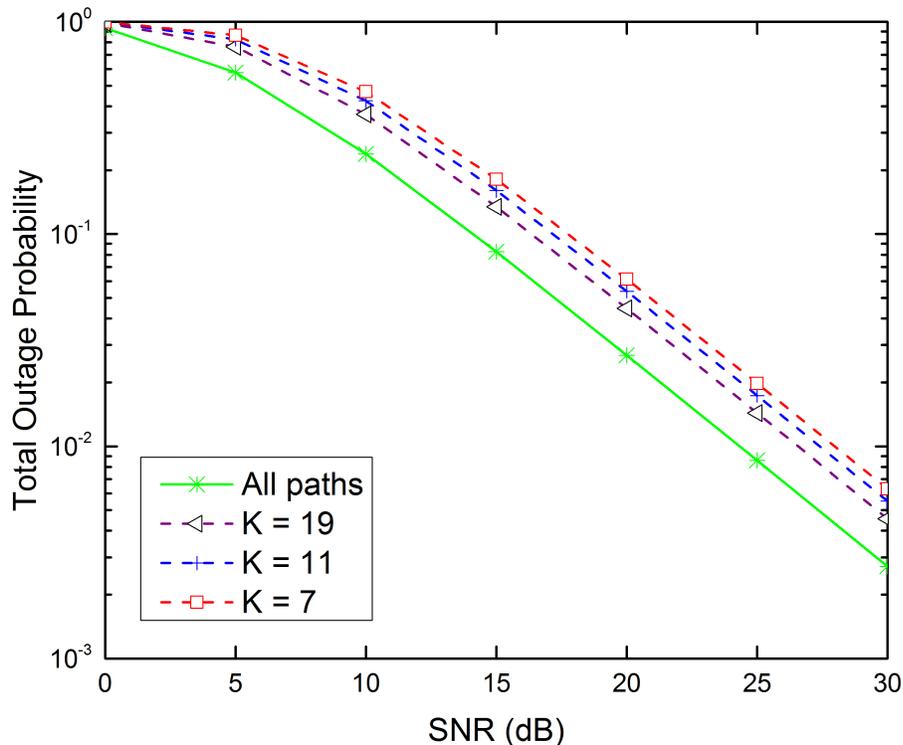
Figure 5.4: Total outage probability vs. SNR, for the Sub-optimal strategy with different numbers of paths, $R_0 = 2$ bps/Hz

averaged over a large number of runs. We examine the total outage probability performance for the source and the destination located at the bottom left corner and the top right corner of this area. We consider the effects of path loss and flat Rayleigh fading for the channel. The path loss exponent is $\alpha = 2$ and the SNR threshold ξ_{th} is determined based on the parameter R_0, the desired transmission rate. The distance between relay clusters is in proportion with the network diameter, which is $1/4$ in our simulations.

To evaluate the performance of our proposed methods, comparisons are presented with the optimal routing strategy which is denoted as "Global optimal" in our plots and also "ad-hoc" routing discussed in [46]. In the optimal strategy all paths between the source and the destination are established and then the best path is chosen with regards to outage

Figure 5.5: Total outage probability vs. SNR, for the Sub-optimal strategy with different number of nodes, $R_0 = 2$ bps/Hz

performance. The ad-hoc strategy chooses one relay at each hop to forward the information. The best relay is selected as the one with maximum received SNR. It is worth mentioning that, for the last two hops, the authors consider a joint optimization which requires CSI of the last two links.

In the simulation results depicted in Figure (5.4), we can observe that, the outage performance for the sub-optimal strategy increases by employing more paths at each hop. This result is consistent with the fact that, when we have more paths, although the more channel state information is needed, the probability of finding the most optimal path on the basis of outage is increased as well.

Figure (5.5) depicts the total outage probability for different number of nodes in the
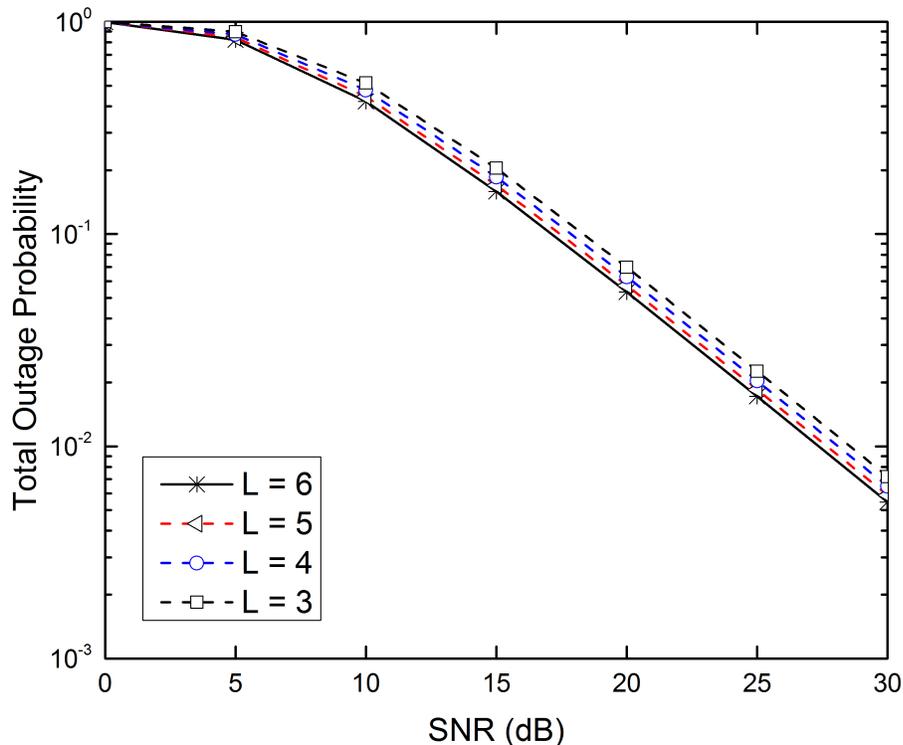
Figure 5.6: Total outage probability vs. SNR, for the L-relay ad-hoc strategy with different numbers of relays, $R_0 = 2$ bps/Hz

Sub-optimal strategy. As we expected from our analysis, it can be observed that, when the nodes density increases, the number of paths between the source and the destination goes up as well, which leads to better outage performance. In other words, the nodes compactness reduces the distance between neighbors, as a result, more paths are generated guaranteeing the lower outage probability in the network.

In Figure (5.6) the outage probability is depicted for different number of relays employed at each hop in the L-relay ad-hoc method. As we can observe, the outage performance increases by utilizing more relays at each cluster. However, the impact of relays on the performance is confined by the fact that, unlike the Sub-optimal strategy, limited number of paths are established between the current source and its local destination. Hence, the
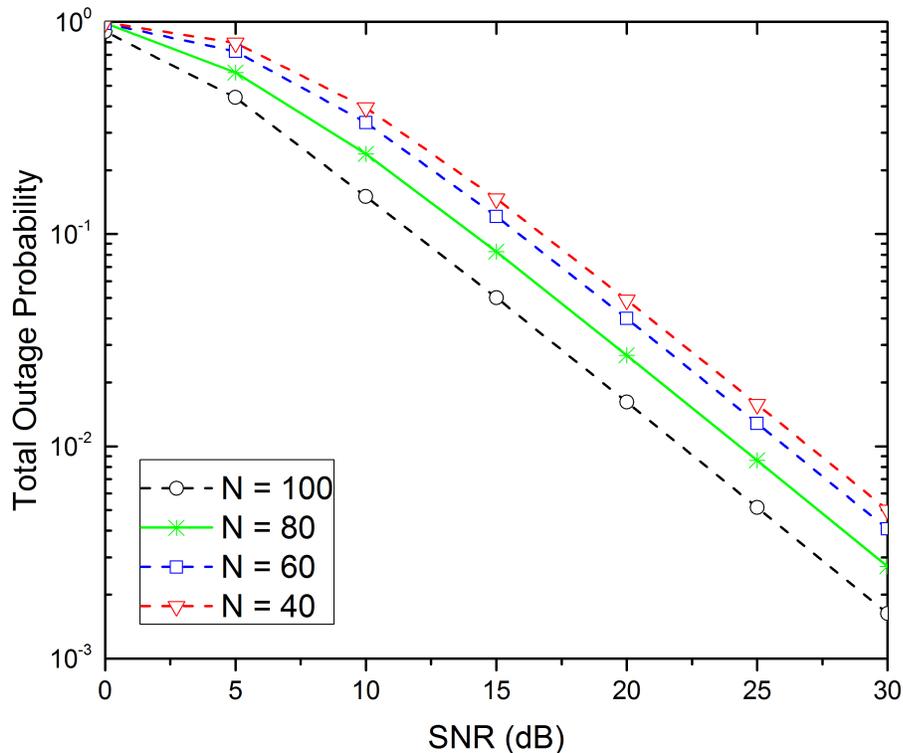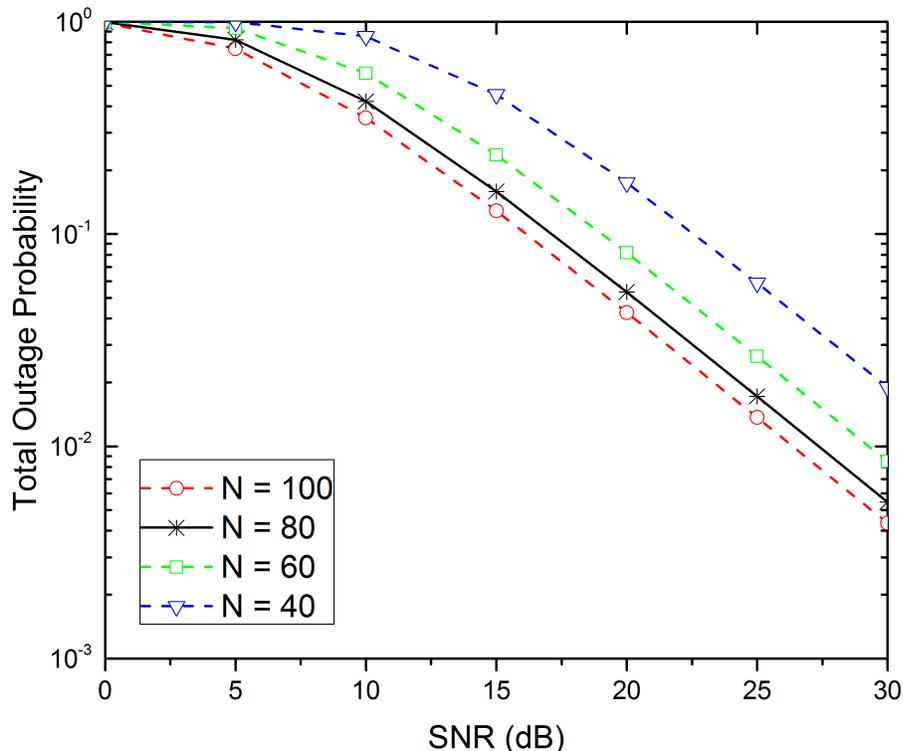
Figure 5.7: Total outage probability vs. SNR, for the Sub-optimal strategy with different number of nodes, $R_0 = 2$ bps/Hz

outage performance is not effected considerably by increasing the number of relays.

With an increase in N, the performance of the L-relay ad-hoc method will improves. As shown in Figure (5.7), when the number of nodes in the network increases, normally, the number of relays in each relay cluster increases as well. For the L-relay ad-hoc strategy, this increase means choosing better relays at each hop on the basis of channel quality, which leads to superior cooperative diversity and clearly performance improvement.

The outage probability for our proposed methods are depicted in Figure (5.8), with different number of hops. This figure shows the effect of hops on the outage. The outage probability will increase for the Sub-optimal routing, when more hops are employed. Similarly, the performance of L-relay ad-hoc gets close to ad-hoc routing with more hops.
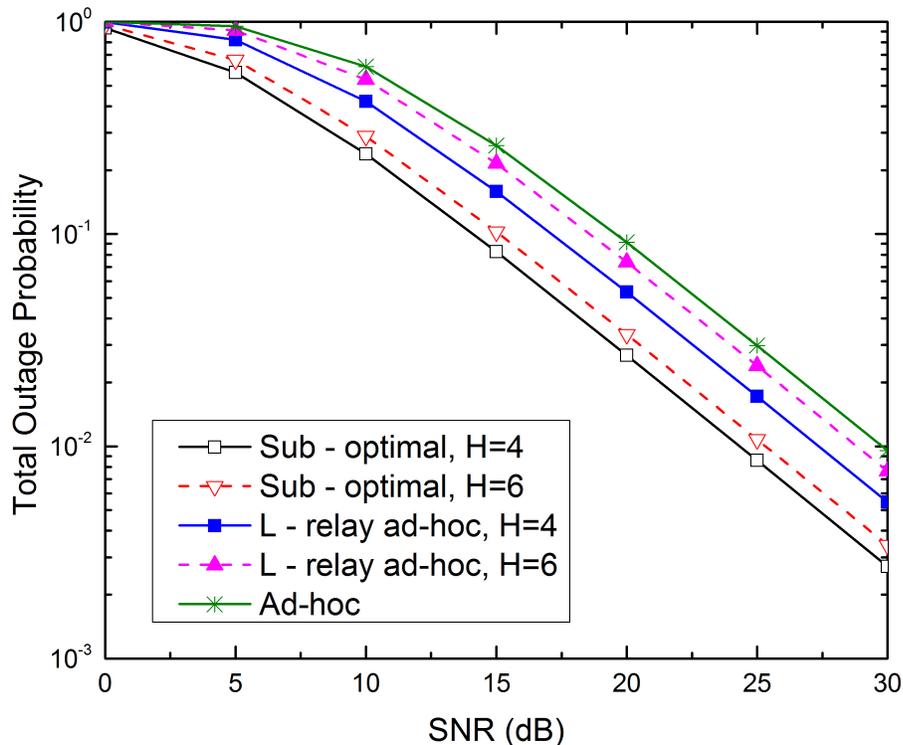
Figure 5.8: Total outage probability vs. SNR, with different number of hops, $R_0 = 2$ bps/Hz

The reason is that, adding the number of hops will decrease the number of relays in each relay cluster, and as a result, it closes to the typical node-by-node approaches like ad-hoc strategy.

Figure (5.9) presents the total end-to-end outage probability for different routing strategies. Simulation results are shown when we have 80 nodes and $R_0 = 2$bps/Hz. It can be seen that, Global optimal strategy outperforms the other strategies due to its global information of all the links in the network. The proposed Sub-optimal algorithm performs closely to the Global optimal strategy with limited amount of links channel information. The results validate the outage performance analyses in which more number of paths at each hop leads to outage performance enhancement. Moreover, L-relay ad-hoc method, which considers l relays at each hop, performs better than ad-hoc strategy. As we discussed in the above

Figure 5.9: Total outage probability vs. SNR, for different routing strategies, $R_0 = 2$ bps/Hz

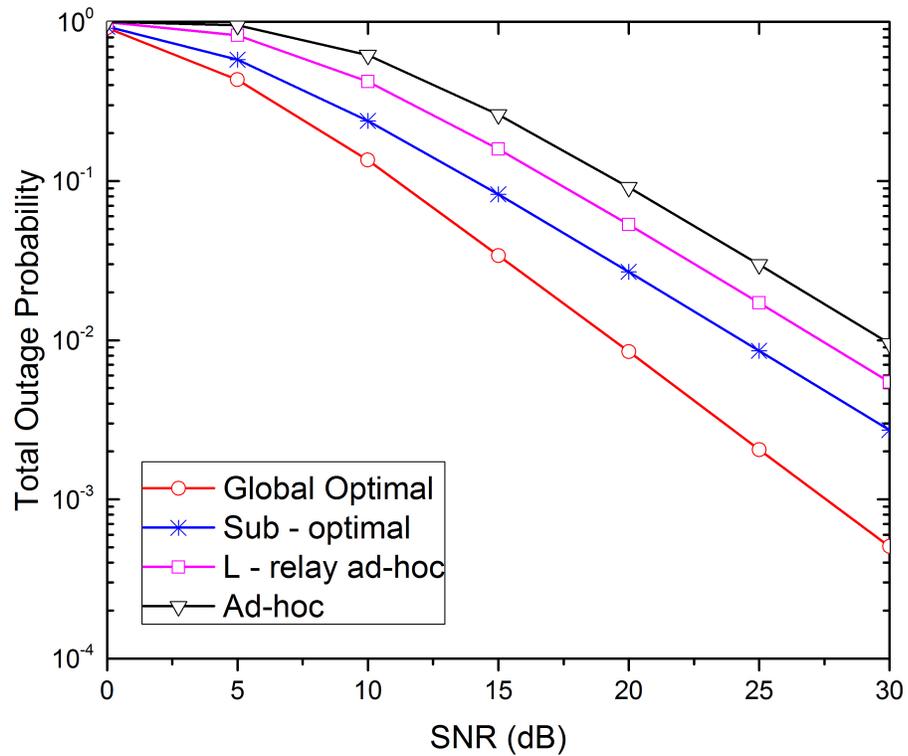sections, the results are consistent with the fact that choosing more relays at each hop will increase the performance gain. The ad-hoc strategy which chooses the best possible path on a hop-by-hop manner achieves the worst performance despite the fact that it needs the lowest amount of channel information.

5.4   Conclusion

In this section, we proposed a cooperative routing algorithm aiming at minimizing the end-to-end outage probability for multi-hop wireless networks. In the sub-optimal cooperative routing algorithm, the entire network is clustered into independent relay groups. We establish all possible paths between the active source and its local destinations, and then the best path with minimal outage probability is chosen. The advantage of this strategy over other optimal methods is the amount of CSI requirement at each hop. To reach a better complexity level while maintaining the performance, the L-relay ad-hoc realization of the same algorithm was proposed, in which the relay selection is done at each hop based on the channel quality. It also needs $(2H-3)(3L-1)$ comparisons to find the best path. To evaluate the performance of our proposed methods, practical conditions are considered to fully reflect the effect of path loss and fading. Simulation results show that, the sub-optimal routing strategy can perform better than its counterparts on the basis of end-to-end outage probability, due to its ability of exploiting diverse range of optimal routes throughout the network. On the other hand, the L-relay ad-hoc outperforms the ad-hoc algorithm while demonstrates an acceptable compromise between performance and overhead.

Chapter 6: Conclusions and Future Work

6.1 Conclusions

In this dissertation, we have developed and analyzed a cross-layer framework for utilizing the cooperative communication paradigm in wireless networks. In particular, we have developed new relay deployment and selection protocols across the network layers that can minimize the end-to-end outage, reduce the required transmission power needed to achieve a desired network throughput, maximize the lifetime of a given network and also mitigate the effect of channel estimation error and co-channel interference (CCI). More specifically, we have addressed the following problems.

In Chapter 3, we study the problem of minimum energy routing with cooperative MIMO communication in a static wireless network (such as a wireless ad-hoc network). We use cooperative MIMO concept in a limiting form, in which there is no communication among the receivers, i.e., no coding gain from MIMO. As an alternative, we focus on power gain of cooperative MIMO in an environment similar to multiple parallel MISO transmissions. It means that the receiving set must not be a single node. Our goal is to find routes that are energy efficient while assuring minimum end-to-end throughput. We consider cooperative communication in a wireless network, and formulate the cooperative link cost (in terms of transmission power) between a set of transmitting and receiving nodes as an optimization problem. Since there is not a straightforward form for the optimal solution we derive a sub-optimal answer for the power allocation problem; two heuristic algorithms of polynomial complexity, namely, Optimal Restricted Cooperative (ORC) and Optimal Cumulative Cooperative (OCC), to find energy efficient routes. To evaluate the performance of the proposed algorithms, some comparisons are done with those algorithms offered by Khnadani et al. [36] through simulations. In particular, we show the energy savings of up

to 50 % can be achieved with our heuristic algorithms.

In Chapter 4, we generalized the relay-selection problem to a broad routing problem. Specifically, we have explored the effect of the cooperative communications on the minimum-power routing problem in wireless networks. For a specified source-destination pair, the optimum route requires the minimum end-to-end transmission power while assuring pre-defined target outage. We have proposed a cross-layer design of routing method, called, Outage-aware K-shortest paths Cooperative Routing (OKCR) algorithm, which builds the typical shortest-path route then applies a cooperative-communication protocol upon the established route. We have shown that for random networks of N nodes, OKCR obtains energy saving of 51.92% in comparison with non- cooperative algorithms and of 43.18% over CASNCP which is one of the prominent cooperative routing algorithms in the literature.

In Chapter 5, we focused on realizable cooperative routing algorithms aiming at minimizing the end-to-end outage probability for multi-hop wireless networks. In the sub-optimal cooperative routing algorithm, the entire network is clustered into independent relay groups. We establish all possible paths between the active source and its local destinations, and then the best path with minimal outage probability is chosen. The advantage of this strategy over other optimal methods is the amount of CSI requirement at each hop. To reach a better complexity level while maintaining the performance, the L-relay ad-hoc realization of the same algorithm was proposed, in which the relay selection is done at each hop based on the channel quality. To evaluate the performance of our proposed methods, practical conditions are considered to fully reflect the effect of path loss and fading. Simulation results show that, the sub-optimal routing strategy can perform better than its counterparts on the basis of end-to-end outage probability, due to its ability of exploiting diverse range of optimal routes throughout the network. The L-relay ad-hoc also outperforms the ad-hoc algorithm while demonstrates an acceptable compromise between performance and overhead.

6.1.1 Power Optimization of Cooperative Link

In our theoretical analysis for calculating outage probability, we have assumed that the transmission power for the source node and the transmission power for the relay node, are equal. In case of different transmission power for the nodes, we have to solve the following optimization problem:

$$
\begin{cases}
min & P_s + P_r \\
s.t. & P_{outage} < Q \ \ (target \ outage)
\end{cases}
\tag{6.1}
$$

Furthermore, we can express outage probability in terms of data rate, distance and transmission power. The assigned bandwidth (B) is also an important factor, which needs to be taken into account. In this case, the transmission power can be expressed as $P = SNR * N_0 RB$. As a result, the general form of new cooperative outage probability will be expressed as follows:

$$
P_{o-cooperative} = \frac{(2^R - 1)^2 (N_0 RB)^2}{(P_x)^2} d_{xz}^k (d_{xr}^k + \frac{P_s}{P_r} d_{rz}^k)
\tag{6.2}
$$

6.1.2 Relay Arrangement in LTE-Advanced

Currently, there is an extensive attention in deploying relays and cooperative communication protocols into the fourth generation (4G) cellular systems, Long Term Evolution(LTE). Exploiting relays into cellular networks can encounter the shadowing effect, augment the coverage area, advance the total throughput, and lower the infrastructure implementation costs compared to that of the traditional base stations. For relay-oriented cellular networks, there are various motivating issues that need to be addressed. As an example, along with optimum location of the relays we have to determine how many relays must be deployed in each cell. On the other hands, the optimal number of relays is significantly important.

We will answer these questions by choosing an optimization metric. As an example, the

performance of the cell-edge users can be considered as the optimization basis. Three relay deployment strategies will be taken into account with the goal of remarkably enhancing the performance of the network.

6.1.3 Enhanced Distributed Heuristic Cooperative Algorithms

Most of existing cooperation-based routing algorithms are built on the shortest paths, which in this case the merits of cooperative communications at the physical layer may not be fully exploited. For this reason, we implement a new algorithm based on greedy geographical routing. At each hop one of the neighbor nodes in the transmission range that is locally closer to the destination selected for the next hop node. To do so, we will use the range extension factor based on the power efficiency and diversity gain. For the chosen next hop node, the best possible relay (i.e., a node which minimizes the total power for a given outage probability) in the transmission range is selected and a one-hop cooperative link from the current node to this node is established. To encounter the non-infrastructure nature of ad-hoc networks, we have to come up with a distributed manner for choosing the nodes among candidate relay nodes, without using a central node.

Appendix A: Performance Evaluation of Cooperative Communication

A.1 Effects of Fading

To illustrate the effects of fading, we have simulated a transmission over different channel characteristics. The most important factor in here is probability of error. This simulation, depicts the unfavorable effect on the signal quality due to fading. The Figure (A.1) also shows that the performance of the BPSK modulated signal is in general 3dB better than the one modulated with QPSK.
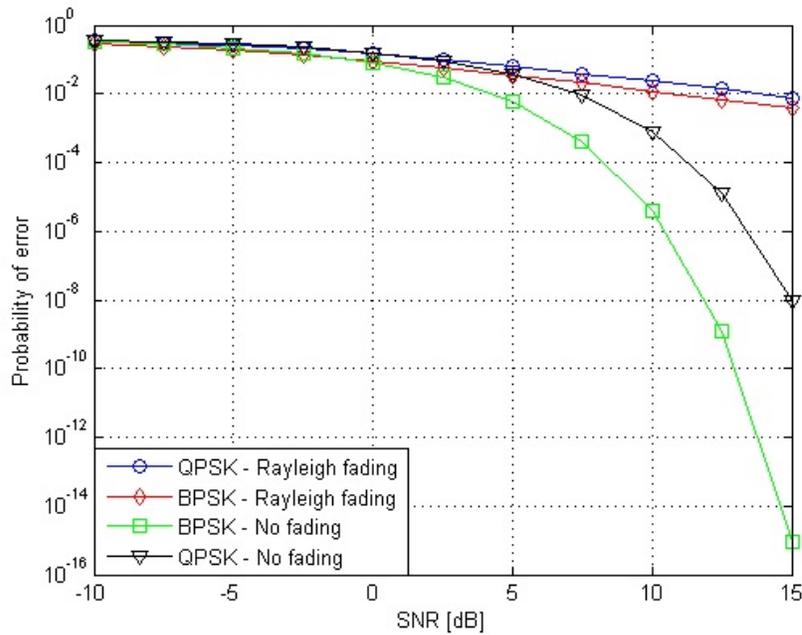

Figure A.1: Effects of Rayleigh Fading Channel

A.2 AF vs. DF Performance Evaluation

In Figure (A.2) the performance of Decode and Forward (DF) method is compared under different modulation scheme by the use of Maximum Ratio Combining scheme. MRC

achieves the best possible performance by multiplying each input signal with its corresponding conjugated channel gain. The drawback of such scheme in multi-hop environments is that it only take the last hop into account. This problem can be solved by using error correcting code. As we can see in the Figures, The diversity arrangement has to send the data twice and therefore requires twice the bandwidth of the single link transmission. To compensate for this effect, the single link channel is modulated using BPSK and the diversity arrangement uses QPSK.
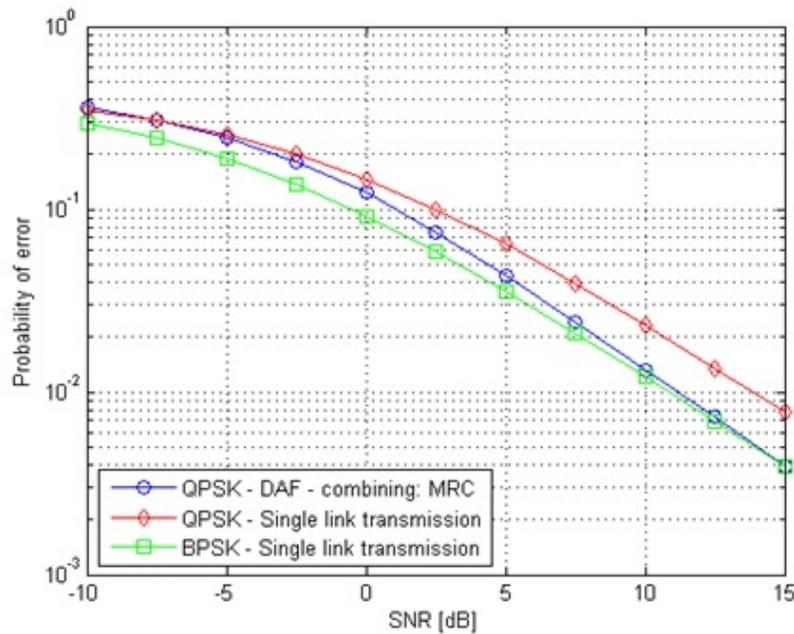

Figure A.2: Decode and Forward method using QPSK vs Direct transmission

To compare the benefits of using Amplify and Forward (AF) method. We show the performance of this method using Fixed Ratio Combining (FRC). In FRC instead of just adding up the incoming signals, they are weighted with a constant ratio, which will not change a lot during the whole communication. The ratio should represent the average channel quality and therefore should not take account of temporary influences on the channel due to fading or other effects. But influences on the channel, which change the average channel quality, such as the distance between the different stations, should be considered. The result of the simulation illustrated in Figure (A.3) shows that the best performance
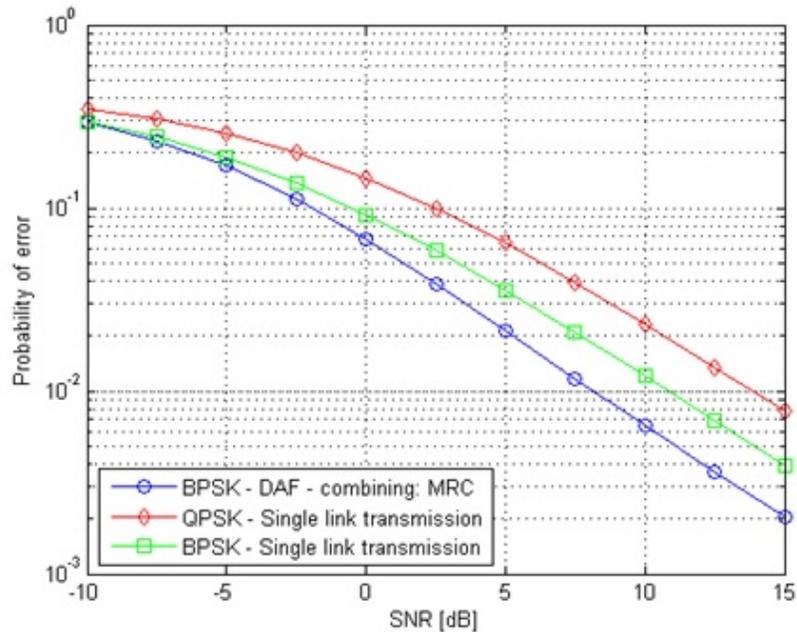
Figure A.3: Decode and Forward method using BPSK vs Direct transmission

using FRC is achieved with a ratio of 2:1. FRC with this ratio is now used to compare performances with one of the other combining types.

In Figure (A.4) and (A.5) the effect of different combining types using an AAF protocol can be seen. The BPSK single link transmission should demonstrate if there is any benefit at all using diversity, while the QPSK two senders link indicates a lower bound for the transmission. Using the equidistant arrangement, the aim is to get as close to the latter curve as possible or to get an even better performance.

The first pleasant result is that whatever combining type is used, the AAF diversity protocol achieves a benefit compared to the direct link. Even the equal ratio combining shows advantages. But compared to the fixed ratio combining, the performance looks quite poor. Otherwise you should call to mind that the equal ratio combining does not need any channel information, except the phase shift, to perform the combining. The fixed ratio combining on the other hand, needs some channel information to calculate the appropriate weighting.
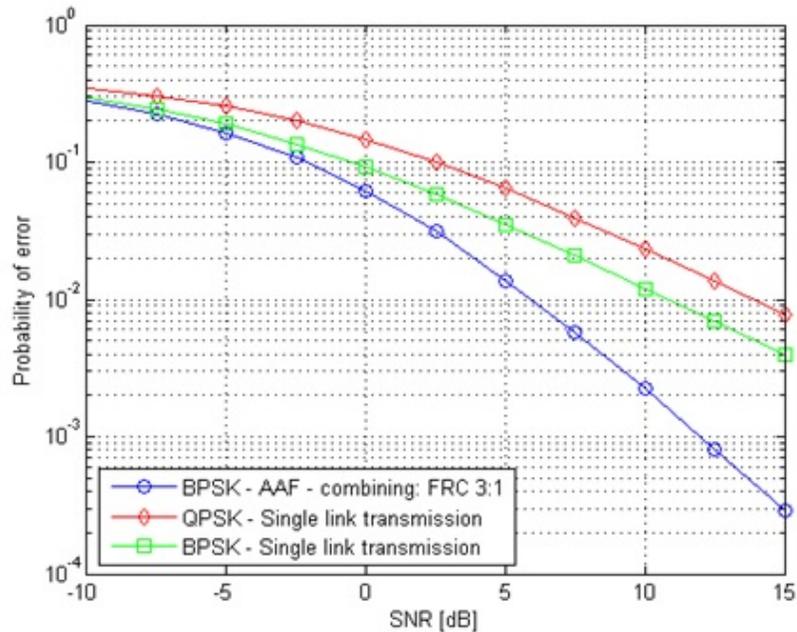
Figure A.4: Amplify and Forward method using BPSK vs Direct transmission

A.3 Lifetime Under Different Non-cooperative Protocols

Considering the network shown in Figure (5.2), network lifetime over the number of nodes (sensors) is plotted in Figure (A.6). As we can see, in non-cooperative mode, the random selection method performs worst, the best channel scheme outperforms the random selection scheme. MMRE scheme employing both CSI and REI has better performance than other methods, and as the node number increases, the performance gain escalates. The most residual energy method performance is very close to best channel performance due to similarity of the parameters they take to measure the lifetime. If we implement these methods with different modulation schemes, such as M-PSK or M-QAM, the latter one has better performance. When M increases, the transmission period of data packet decreases, which means more energy saving.
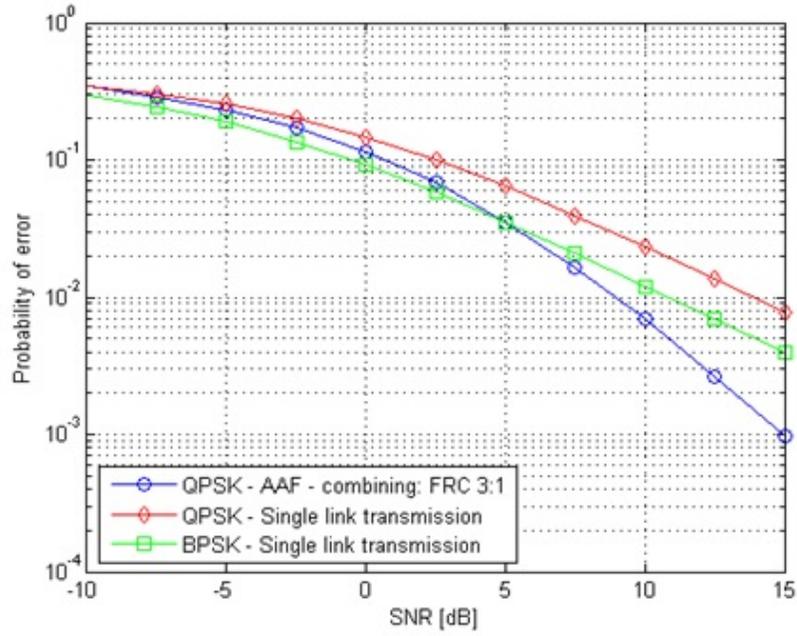
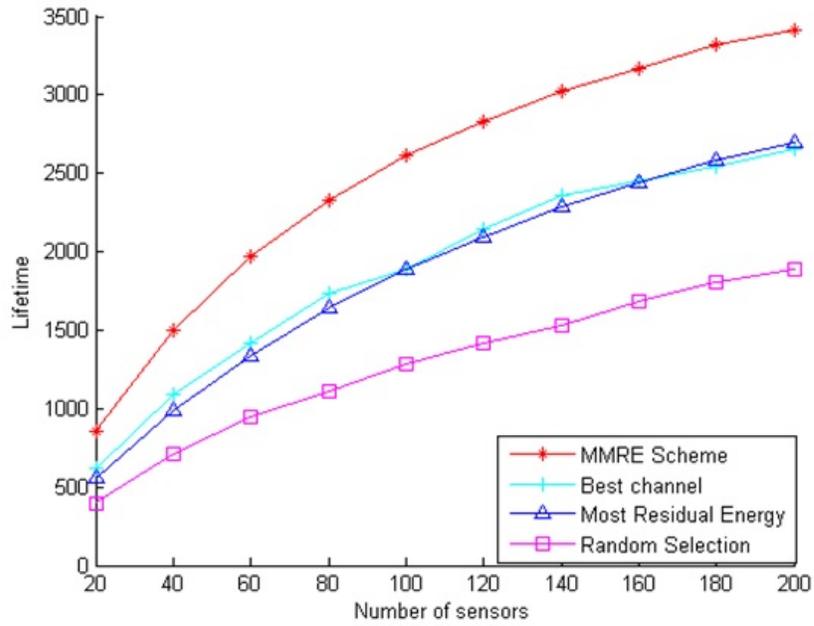Figure A.5: Amplify and Forward method using BPSK vs Direct transmission

Figure A.6: Lifetime under different non-cooperative protocols

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Curriculum Vitae

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