Cooperative Routing for Collision Minimization in Wireless Sensor Networks

by

© Fatemeh Mansourkiaie

A dissertation submitted to the School of Graduate Studies
in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

Faculty of Engineering and Applied Science
Memorial University of Newfoundland

May 2016

St. John's, Newfoundland

Abstract

Cooperative communication has gained much interest due to its ability to exploit the broadcasting nature of the wireless medium to mitigate multipath fading. There has been considerable amount of research on how cooperative transmission can improve the performance of the network by focusing on the physical layer issues. During the past few years, the researchers have started to take into consideration cooperative transmission in routing and there has been a growing interest in designing and evaluating cooperative routing protocols. Most of the existing cooperative routing algorithms are designed to reduce the energy consumption; however, packet collision minimization using cooperative routing has not been addressed yet. This dissertation presents an optimization framework to minimize collision probability using cooperative routing in wireless sensor networks.

More specifically, we develop a mathematical model and formulate the problem as a large-scale Mixed Integer Non-Linear Programming problem. We also propose a solution based on the branch and bound algorithm augmented with reducing the search space (branch and bound space reduction). The proposed strategy builds up the optimal routes from each source to the sink node by providing the best set of hops in each route, the best set of relays, and the optimal power allocation for the cooperative transmission links. To reduce the computational complexity, we propose two near optimal cooperative routing algorithms. In the first near optimal algorithm, we solve the problem by decoupling the optimal power allocation scheme from optimal route selection. Therefore, the problem is formulated by an Integer Non-Linear Programming, which is solved using a branch and bound space reduced method. In the second near optimal algorithm, the cooperative routing problem is solved by decoupling the transmission power and the relay node selection from the route selection. After solving the routing problems, the power allocation is applied in the selected route. Simulation results show the algorithms can significantly reduce the collision probability compared with existing cooperative routing schemes.

Acknowledgements

As the formal part of my education comes to an end, it is a great pleasure to acknowledge several individuals who have had contributed to who I am today.

I would like to offer my sincere thanks to my supervisor Dr. Mohamed H. Ahmed for his continued and valuable guidance. I greatly appreciate the time he has spent contributing to this research and to my professional development. Without his guidance and persistent help this dissertation would not have been possible. The financial support provided by my supervisor, the Faculty of Engineering and Applied Science, the School of Graduate Studies is duly acknowledged.

A significant part of my education was in Iran and my foundations were laid in schools at the city of Tehran. I would like to thank my elementary school teachers, my math teachers at secondary and high schools, my B.Sc. project supervisor, and my M.Sc. thesis supervisor.

The final word of acknowledgement is reserved for my parents for their unconditional support, to my husband for his love, patience and unwavering belief in me, without their continuous support and encouragement, this dissertation would not have been possible.

Co-Authorship Statements

I, Fatemeh Mansourkiaie, hold a principal author status for all the manuscript chapters (Chapter 2 - 5) in this dissertation. However, each manuscript is co-authored by my supervisor, whose contributions have facilitated the development of this work as described below.

- Paper 1 in Chapter 2: Fatemeh Mansourkiaie and Mohamed H. Ahmed, "Cooperative Routing in Wireless Networks: A Comprehensive Survey," IEEE Communications Surveys and Tutorials, vol. 17, no. 2, pp 604-626, Apr. 2015.

  I was the primary author and with my supervisor contributed to the idea, its formulation and development, and refinement of the presentation.

- Paper 2 in Chapter 3: Fatemeh Mansourkiaie and Mohamed H. Ahmed, "Joint Cooperative Routing and Power Allocation for Collision Minimization in Wireless Sensor Networks," submitted to IEEE Wireless Communication and Networking Conference, Apr. 2016.

  I was the primary author and with my supervisor contributed to the idea, its formulation and development, and refinement of the presentation.

- Paper 3 in Chapter 4: Fatemeh Mansourkiaie and Mohamed H. Ahmed, "Per-Node

Traffic Load in Cooperative Wireless Sensor Networks," under review, IEEE Communications Letters.

I was the primary author and with my supervisor contributed to the idea, its formulation and development, and refinement of the presentation.

- Paper 4 in Chapter 5: Fatemeh Mansourkiaie and Mohamed H. Ahmed, "Joint Cooperative Routing and Power Allocation for Collision Minimization in Wireless Sensor Networks with Multiple Flows," IEEE Wireless Communications Letters, vol. 4, no. 1, pp. 6-9, Feb. 2015.

  I was the primary author and with my supervisor contributed to the idea, its formulation and development, and refinement of the presentation.

- Paper 5 in Chapter 6: Fatemeh Mansourkiaie and Mohamed H. Ahmed, "Optimal and Near-Optimal Cooperative Routing and Power Allocation for Collision Minimization in Wireless Sensor Networks," under review, IEEE Sensors Journal.

  I was the primary author and with my supervisor contributed to the idea, its formulation and development, and refinement of the presentation.

______________________________ ______________________

Fatemeh Mansourkiaie Date

Contents

List of Figures

List of Tables

List of Abbreviations

AF .... Amplify and Forward

AFCR .... Adaptive Forwarding Cluster Routing

AODV .... Ad hoc On-Demand Distance Vector

ARQ .... Automatic Repeat Request

AWGN .... Additive White Gaussian Noise

BER .... Bit Error Rate

BnB .... Branch and Bound

BS .... Base Station

CAMCD .... Cooperating Along Minimum Collision Direct Path

CAN .... Cooperation Along the Minimum Energy Non-Cooperative Path

CASNCP .... Cooperative Along the Shortest Non-Cooperative Path

CASP .... Cooperating Along the Shortest Path

CASPO .... Opportunistic Cooperation Along the Shortest Path

CCR .... Contention-aware Cooperative Routing

CLCR .... Cross-Layer Cooperative Routing

CM .... Cluster Membership

CMPR .... Cooperative Multipath Routing

CPLNC .... Cooperative Physical Layer Network Coding

CSI .... Channel State Information

CSMA-CA .... Carrier Sense Multiple Access with Collision Avoidance

CSP .... Cooperative Shortest Path

CT .... Cooperative Transmission

CTNCR .... Cooperative Routing along Truncated Non-Cooperative Route

CTS .... Clear to Send

DCF .... Distributed Coordination Function

DF .... Decode and Forward

DSRP .... Dynamic Source Routi

DT .... Direct Transmission

EBCR .... Energy-Balanced Cooperative Routing

EECRWSN .... Energy Effective Cooperative Routing in Wireless Sensor Network

EP .... Equal Power Allocation

HTS .... Helper ready To Send

K-OPT .... K-Receiver Optimal Cooperation

KR-CASPO .... K-Receiver Cooperation Along the Shortest Path

KT-CASPO .... K-Transmitter Cooperation Along the Shortest Path

MAC .... Medium Access Control

MCCR .... Minimum Collision Cooperating Routing

MCN .... Minimum Collision Non-Cooperative

MILP .... Mixed Integer Linear Programming

MINLP .... Mixed Integer Non-Linear Programming

MISO .... Minimum Input Single Output

MPCR .... Minimum Power Cooperative Routing

MPSDF .... Minimum Power Selected Decode-and-Forward

MRC .... Maximum Ratio Combination

MTE .... Minimum Total Energy

NACK .... Negative Acknowledgement

OC .... Optimal Combining

PACR .... Power Aware Cooperative Routing

PC .... Progressive Cooperative

PDR .... Packet Delivery Ratio

QoS .... Quality of Service

RA .... Relay Acknowledgement

RB .... Relay Broadcast

RREQ .... Route Request

RS .... Relay Start

SC .... Selection Combining

SIR .... Signal Interference Ratio

SNER .... Source Node Expansion Route

SNR .... Signal to Noise Ratio

TOCR .... Throughput Optimized Cooperative Routing

TSE .... Travelling Salesman Extension

WSN .... Wireless Sensor Network

Chapter 1

Introduction

1.1 Background

Wireless Sensor Networks (WSNs) are networks of tiny sensor nodes connected with wireless links. These sensor nodes can sense, measure, and gather information from the environment, and based on some local decision process, they can transmit the sensed data to a sink node. In most application scenarios, WSN nodes are powered by limited batteries, which are practically non-rechargeable, either due to cost limitations or because they are deployed in difficult-to-access areas and hostile environments. Therefore, energy constraint is one of the main challenges in designing wireless sensor networks. Moreover, similar to all other wireless networks, wireless sensor networks suffer from the effect of fading which results in a higher probability of transmission errors than that in wired media. In addition, collisions can be a major source of increased latency and packet retransmission. A source node, s, will cause a collision to another node, n, if s is sending while n is simultaneously receiving (from another node, m), provided that the interference from s at n is high enough to cause a collision. When collisions occur on energy constrained wireless networks, such as wireless sensor networks, extra latency and retransmissions equate to excessive energy consumption. Therefore, reducing collision probability can increase the overall lifetime of the wireless sensor network.

In WSNs, cooperative diversity has been proposed as an effective technique to improve the robustness of wireless links [1–4]. The information is transmitted over channels that are affected by uncorrelated fading using cooperative diversity.

Cooperative diversity exploits the neighboring nodes antenna in order to relay the packets of transmitting nodes to the intended destination. Combining multiple copies of the same signal at the destination node leads to several advantages such as better signal quality, reduced transmission power, better coverage and higher capacity [5–7].

The idea behind cooperative communication is shown in Figure 2.1. This figure shows two sensor nodes (nodes s and l) communicating with the same destination node (node d). Each sensor node has one antenna and cannot individually generate spatial diversity. However, it may be possible for one node to receive the signal of the other nodes, in which case it can forward the data to the destination node. Because the fading paths from the two sensor nodes are statistically independent, this generates spatial diversity.

Various relaying techniques of cooperative communication, such as amplify-and-forward (AF), decode-and-forward (DF), selection relaying and incremental relaying, have been described in [8]. In the amplify-and-forward protocol, each relay first amplifies the received signal (including the desired signal and added noise) and then forwards it to the destination. AF suffers from the noise amplification problem, which can degrade the signal quality, particularly at a low Signal-to-Noise Ratio (SNR). In order to avoid the noise amplification problem, the decode-and-forward (DF) technique removes the noise

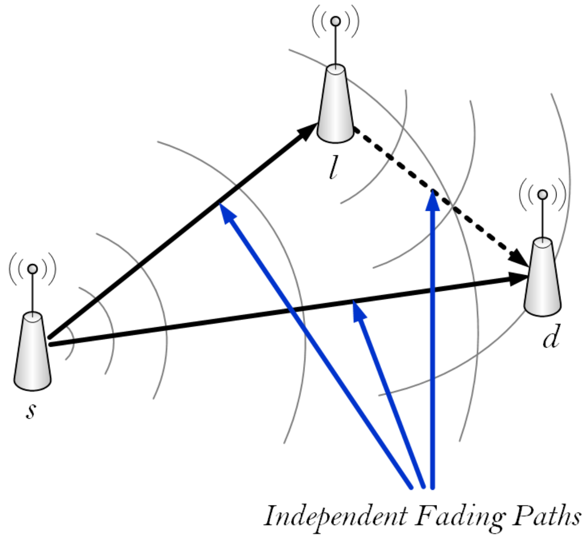


Figure 1.1: Cooperative Communication

by detecting and decoding the received signals and then regenerating and re-encoding the signal to be forwarded to the destination.

Other types of relaying techniques have also been proposed in the literature such as Incremental Relaying [9] and Best Relay Selection [10]. In Incremental Relaying, the technique tries to limit the cooperation based on some required conditions. This can be done by exploiting a feedback signal from the destination about the success or failure of the direct transmission [9]. In the case of unsuccessful detection, one or more relays forward the signal to the destination. Otherwise, the relays do nothing and the source can send another signal. Therefore, the additional resource needed for relaying will be used only if the direct transmission is not successful. When multiple relays are available, the best-relay selection is used to improve the resource utilization. In this case, the best relay that maximizes the SNR, is selected only to forward the signal to the destination [10]. Incremental Relying and Best Relay selection techniques achieve maximum diversity order with high power and bandwidth efficiencies. Such techniques like incremental relaying and best-relay selection can be used with AF, DF or any other relaying method.

In [1], cooperative diversity employs space-time coding, which is the 2×2 Alamouti scheme, using cooperative relaying. This scheme is shown to improve link quality significantly, and as a result, it reduces the packet dropping rate at the receiver and improves the network throughput. In [2,3] a cooperative MAC protocol has been proposed to facilitate the use of cooperative diversity with adaptive relay selection in WSNs using signal forwarding (by the relays) and Maximum Ratio Combining (MRC) at the destination. As shown in both references, the proposed MAC protocol is able to improve the links robustness, and therefore increases the throughput gain and reduces the packet dropping rate significantly.

Routing algorithms which take into consideration the availability of cooperative transmission at the physical layer are known in the literature as cooperative routing algorithms. In other words, cooperative routing makes the use of cooperative diversity from the physical layer to benefit the network layer by improving the performance of routing. Therefore, cooperative routing is a cross-layer design approach that combines the network layer and the physical layer to transmit packets through cooperative links. This cross-layer design approach effectively enhances the performance of the routing protocols in wireless networks.

In traditional multi-hop routing, messages are transmitted through multiple radio hops and routing protocol is a concatenation of traditional hops. These traditional routing protocols choose the best sequence of nodes between the source and the sink, and forward each packet through that sequence using a single direct signal. In contrast, cooperative routing takes the advantage of the broadcasting transmission to transmit the message in each hop through relay nodes as well. Therefore, cooperative routing allows multiple nodes along a path to coordinate together to transmit a message to the next hop as long as the combined signal at the receiver node satisfies a given Signal-to-Noise Ratio (SNR) threshold value. The receiver node in each hop selects the best of received signals (direct or relayed), or combines them to produce a stronger signal.

For signal combining in cooperative routing, traditional diversity combining techniques such as Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), and Selection Combining (SC) can be used by each receiver node along the path. Brennan described the aforementioned techniques in [11]. In MRC, the received signals from all cooperators are weighted and combined to maximize the instantaneous SNR. It is known that MRC is optimal and maximizes the total SNR in noise-limited links with Gaussian noise. However, the main drawback of the MRC technique is that it requires full knowledge of the channel state information [8]. EGC is a simplified sub-optimal combining technique, where the destination node combines the received copies of the signal by adding them coherently. Therefore, the required channel information at the receiver node is reduced to the phase information only. SC is even simpler and the combiner simply selects the signal with larger SNR. Although, SC removes the overhead of estimating the channel state information, its performance is ultimately degraded compared to MRC and EGC [8].

1.2 Research Motivation

As mentioned before, in addition to the energy constraint in wireless sensor networks, another main fundamental limiting factor is the collision probability [12]. In some situations, for instance upon the detection of an event in wireless sensor networks, the data exchange in certain areas spots may become intensified, resulting in a high packet collision probability. A high packet collision rate causes a packet loss and leads to retransmission. Retransmission increases the packet delay and energy consumption.

Packet collision in general wireless ad hoc network is usually addressed by the use of Distributed Coordination Function (DCF). DCF provides a 4-way handshaking technique, known as Request-To-Send/Clear-To-Send (RTS/CTS) mechanism. RTS/CTS mechanism is basically designed to reduce the number of collisions by reserving the channel around both the sender and the receiver to protect transmitted frame from corruption caused by collision [13]. However, this method presents several problems when used in wireless sensor networks. These problems include the following:

- the energy consumption related to a RTS/CTS packets exchange is significant,
- because data frames in wireless sensor networks are usually small and collision may occur for RTS/CTS packets same as data frames, it does not make a significant difference in collision probability if the technique is used or not,
- it may lower the network capacity due to the exposed node problem [14],
- it cannot be used for broadcasting frames.

Transmission collision in a wireless sensor network can be minimized by reducing the collision probability. This can be achieved through the use of cooperative diversity techniques. Cooperative diversity is beneficial for WSNs since the size and power constraints restrict sensor nodes from possessing more than one antenna [15].

Although the merits of the cooperative communications in the physical layer have been well-explored, the impact of the cooperative communications on the design of the higher layers, such as routing protocols, has not yet been well-developed.

Routing is a key factor which plays an important role to the network performance, particularly in WSNs. Due to the restricted communication range and power budget, packet forwarding in sensor networks is usually performed through multi-hop data transmission. Therefore, routing in wireless sensor networks is crucial and challenging.

Routing protocols need to be redesigned for cooperative communication in wireless networks because of three reasons. First, when cooperative communication is supported in the physical layer, a link is no longer composed of one sender and one receiver. There may be multiple nodes acting as the senders or as the receivers simultaneously. Therefore, the definition of a traditional link which contains only two nodes (one sender and one receiver) should be revised. With the revised link definition, routing, which is constructed based on the concept of links, cannot remain unchanged. Second, cooperative diversity introduces new aspects to the typical traffic load of the nodes in WSNs. A relay node in a cooperative link not only receives traffic load from the transmitter node, but also forwards the traffic load to the destination node. Third, with the introduction of cooperative communication, the collision probability between multiple links is different. Therefore, a new routing protocol should consider the differences in cooperative communication.

1.3 Thesis Contribution

This dissertation presents the following novel contributions to the optimal cooperative route selection for minimizing the collision probability in WSNs.

- We propose a novel and accurate mathematical model to analyse the per-node traffic load in a cooperative link of WSNs.

- We show the accuracy of the proposed per-node traffic load analytical model by verifying the agreement between the analytical results and simulation.

- We employ the proposed analytical model of per-node traffic load in cooperative transmissions and we formally define and formulate the collision problem in WSNs.

- We present a Mixed Integer Non-Linear Problem (MINLP) model for optimizing the cooperative routing selection to minimize the collision problem subject to the outage probability constraint.

- We solve the optimization problem by enhancing the Branch and Bound (BnB) algorithm and developing a *BnB Space Reduction* algorithm. The obtained solution applies a joint optimization approach to power allocation, relay node assignment, and path selection which are the main optimization issues in cooperative routing.

- We also propose two near-optimal algorithms by decoupling the optimization variable decisions from the other optimization parameters. In the first near optimal cooperative routing, optimal power allocation and relay selection is decoupled from the routing decision. In the second near optimal cooperative routing, optimal transmission power is decoupled from the other optimization variables.

- We illustrate that the MINLP solution serves as a benchmark for evaluating the quality of the solutions obtained by any sub-optimal algorithm for this problem.

- We evaluate the effect of each of the optimal routing parameters separately, by developing addition routing algorithms, in which one optimization variable is used while the other parameters are not employed.

- We show that the proposed algorithms (optimal and near optimal) find good solutions which help to reduce collision probability compared to the existing cooperative routing algorithms.

1.4 Thesis Outline

In this section, we outline the organization of this thesis and give a brief overview of each chapter.

In Chapter 2, we present a comprehensive survey of the existing cooperative routing techniques, together with the highlights of the performance of each strategy. We also provide a taxonomy of different cooperative routing protocols and outline the fundamental components and challenges associated with cooperative routing objectives. Moreover, the design requirements of cooperative routing protocols are discussed to provide an insight into the objectives of routing protocols. We compare existing cooperative routing algorithms and lay the groundwork for further research.

Most of the proposed cooperative routing techniques are designed for single-flow networks and packet collision caused by multiple flows has not been taken into account. In Chapter 3, packet collision probability is mathematically formulated and a sub-optimal cooperative routing algorithm to minimize collision probability is proposed. In this chapter, the problem is formulated assuming that the average per-node traffic load follows the Poisson arrival process (this assumption is improved in Chapter 5, using the mathematical analysis obtained in Chapter 4).

In Chapter 4, we present a new and detailed analytical model for calculating the per-node traffic load in cooperative WSNs. Cooperative routing introduces a new aspect to the typical per-node traffic load in multiple-flow networks. A relay node in a cooperative link not only receives traffic load from the transmitter node, but also forwards the traffic load to the destination node. To the best of our knowledge, there is no analytical model which can accurately characterize the per-node traffic load in a cooperative wireless network. Analysing the per-node traffic load in cooperative system helps to provide important insights into designing efficient cooperative routing protocols.

The analytical model of the traffic load is employed in Chapters 5 and 6 to minimize the collision probability using cooperative routing. We propose the Minimum Collision Cooperative Routing (MCCR) algorithm by combining cooperative transmission, optimal power allocation, and route selection in Chapter 5. The proposed algorithm in Chapter 5 is a sub-optimal routing due to the following reasons; (1) the optimal power allocation technique is decoupled from the optimal route selection and (2) a suboptimal approach is employed in the relay node selection and relay nodes are selected as the node closest to the middle point of the transmitter and receiver nodes of each link.

In Chapter 6, we obtain the optimal solution by formulating the problem as a large-scale Mixed Integer Non-Linear Programming problem. To solve the optimization problem, we also propose a solution based on the branch and bound algorithm augmented with reducing the search space (branch and bound space reduced). To reduce the computational complexity of the optimal solution, we propose a near-optimal cooperative routing algorithm in Chapter 6. In the near-optimal algorithm, we solve the problem by decoupling the optimal power allocation scheme from optimal route selection. Finally in Chapter 7, we summarize the contributions presented in this dissertation and discuss several potential extensions to our work.

REFERENCES

[1] L. Liu and H. Ge, "Space-time coding for wireless sensor networks with cooperative routing diversity," in *Proc. Asilomar Conference on Signals, Systems and Computers*, vol. 1, Nov. 2004, pp. 1271–1275.

[2] M. Gokturk and O. Gurbuz, "Cooperative MAC protocol with distributed relay actuation," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC'09)*, April 2009, pp. 1–6.

[3] ——, "Cooperation in wireless sensor networks: Design and performance analysis of a MAC protocol," in *Proc. IEEE International Conference on Communications (ICC '08)*, June 2008, pp. 4284–4289.

[4] T. ElBatt, S. Krishnamurthy, D. Connors, and S. Dao, "Power management for throughput enhancement in wireless ad-hoc networks," in *Proc. IEEE International Conference on Communications (ICC '00)*, June 2000, pp. 1506–1513.

[5] J. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[6] T. Himsoon, W. Siriwongpairat, Z. Han, and K. J. R. Liu, "Lifetime maximization by cooperative sensor and relay deployment in wireless sensor networks," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC'06)*, April 2006, pp. 439–444.

[7] A. Bletsas, A. Khisti, and M. Win, "Opportunistic cooperative diversity with feedback and cheap radios," *IEEE Trans. Wireless Commun.*, vol. 7, no. 5, pp. 1823–1827, May 2008.

[8] M. H. Ahmed and S. S. Ikki, *To Cooperate or not to Cooperate? That is the Question!* John Wiley and Sons, Ltd, 2011, pp. 21–33.

[9] J. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[10] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, March 2007.

[11] D. G. Brennan, "Linear diversity combining techniques," *Proc. IEEE*, vol. 91, no. 2, pp. 331–356, Feb. 2003.

[12] W. Ye and J. Heidemann, "Medium access control in wireless sensor networks," USC/Information Sciences Institute, Tech. Rep. ISI-TR-580, Oct. 2003.

[13] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, March 2000.

[14] A. Koubaa, R. Severino, M. Alves, and E. Tovar, “Improving quality-of-service in wireless sensor networks by mitigating ”Hidden-Node Collisions”,” *IEEE Trans. Ind. Informat.*, vol. 5, no. 3, pp. 299–313, Aug. 2009.

[15] N. Shastry, J. Bhatia, and R. Adve, “Theoretical analysis of cooperative diversity in wireless sensor networks,” in *Proc. IEEE Global Telecommunications Conference, (GLOBECOM ’05)*, vol. 6, Dec. 2005, pp. 3269–3273.

Chapter 2

Cooperative Routing in Wireless Networks: A Comprehensive Survey

2.1 Abstract

Cooperative diversity has gained much interest due to its ability to mitigate multipath fading without using multiple antennas. There has been considerable research on how cooperative transmission can improve the performance of the physical layer. During the past few years, the researchers have started to take into consideration cooperative transmission in routing and there has been a growing interest in designing and evaluating cooperative routing protocols. Routing algorithms that take into consideration the availability of cooperative transmission at the physical layer are known as cooperative routing algorithms. This paper presents a comprehensive survey of the existing cooperative routing techniques, together with the highlights of the performance of each strategy. This survey also provides a taxonomy of different cooperative routing protocols and outlines

the fundamental components and challenges associated with cooperative routing objectives. Existing cooperative routing algorithms are compared to lay the groundwork for further research.

2.2 Introduction

Cooperative communication has emerged as a promising approach for mitigating wireless channel fading and improving reliability of wireless networks by allowing nodes to collaborate with each other. Nodes in cooperative communication help each other with information transmission by exploiting the broadcasting nature of wireless communication [1–3]. In a cooperative transmission scheme, neighboring nodes are exploited as relay nodes, in which they cooperate with the transmitter-receiver pair to deliver multiple copies of a packet to the receiver node through independent fading channels. The idea behind cooperative transmission is shown in Fig. 2.1. This figure illustrates a simple cooperative transmission scheme where two nodes (one source node and one relay node) are communicating with the same destination node. Each node has one antenna and does not individually have spatial diversity. However, it may be possible for one node to overhear and receive the other, in which case it can forward the data to the destination node. Because the fading paths from the two nodes are statistically independent, this generates spatial diversity. Combining multiple copies of the same signal at the destination node leads to several advantages, including a better signal quality, reduced transmission power, better coverage, and higher capacity [4–6].

Cooperative Communication at the Physical Layer: During the past decade, there have been numerous studies (e.g., [7–10]) on cooperation communication at the physical

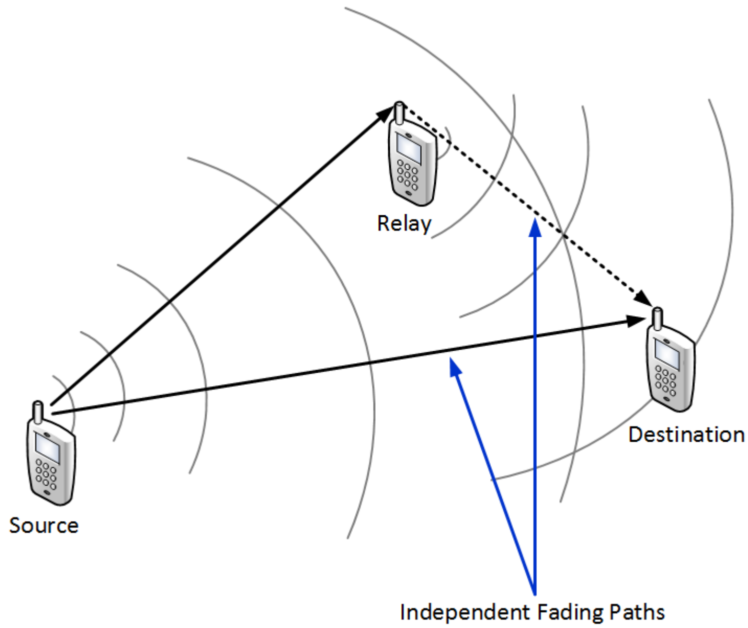


Figure 2.1: Cooperative Communication.

layer. The key idea behind cooperative communication at the physical layer is sharing the physical layer resources and cooperating to forward each node's packet to the intended destination node. Cooperative communication at the physical layer involves decisions about: 1) cooperative and relaying schemes such as amplify-and-forward, decode-and-forward, and coded cooperation; 2) the transmission power allocation for each node to satisfy the Quality of Service (QoS) requirements of the network; and 3) the relay selection schemes of the network.

Cooperative MAC Protocols: Cooperative Medium Access Control (MAC), which is used to facilitate cooperative transmission in the physical layer, has also attracted much attention. Modified Distributed Coordination Function (DCF) is most commonly used in the literature to develop cooperative MAC protocols (e.g., proposed cooperative MAC protocols in [11–18]). The DCF scheme uses handshaking methods to reserve the channel and alleviate collision problems [19]. For the cooperative handshaking, additional control signalling packets such as HTS (Helper ready To Send) in [11]; cRTS (cooperative Request To Send) in [12]; RS (Relay-Start), RA (Relay-Acknowledgement), and RB (Relay-Broadcasting) in [13] are introduced. The additional signalling packets are used to select the relay nodes, indicate the presence of relay nodes and willingness for the cooperative transmission, and demonstrate the availability of channel (i.e., check whether the channel is not busy) for the relay nodes.

Cross-Layer Cooperative Communication: With better understanding of the cooperative communication in the physical layer and the cooperative MAC protocols, it has become critically important to study how the performance gain of cooperative communication in the physical and MAC layers can be reflected to upper layers (such as the network layer), ultimately improving the performance using cooperative routing and cross-layer cooperative protocols [20–22]. A routing algorithm that takes the advantages of cooperative transmission in the physical layer is known as cooperative routing. Cooperative routing is a cross-layer design approach that combines the network layer and the physical layer to transmit packets through cooperative links. This cross-layer design approach effectively enhances the performance of the routing protocols in wireless networks.

In the past few years, significant progress has been made on the design and development of cooperative routing protocols. These cross-layer routing protocols optimize various aspects of cooperative communication. Cooperative routing is a promising approach to improving energy efficiency (or saving power) and QoS; it saves energy by reducing path loss and combining multiple copies of the same packet at the receiver node. Path loss is reduced by shortening the link length, which generates less interference due to the lower transmission power. Moreover, optimal power allocation at the transmitter and relay nodes (using power allocation techniques) can further reduce the energy (or power) consumption.

In traditional multi-hop routing, messages are transmitted through multiple radio hops and the routing protocol is a concatenation of traditional hops. These traditional routing protocols choose the best sequence of nodes between the source and the sink, and forward each packet through that sequence using a single direct signal. In contrast, cooperative routing takes the advantage of the broadcasting transmission to transmit the message in each hop through relay nodes as well. Therefore, cooperative routing allows multiple nodes along a path to coordinate together to transmit a message to the next hop as long as the combined signal at the receiver node satisfies a given Signal-to-Noise Ratio (SNR) threshold value. The receiver node in each hop selects the best of received signals (direct or relayed), or combines them to produce a stronger signal.

In this chapter, a comprehensive survey of the existing cooperative routing algorithms is presented and the important aspects, requirements, challenges, and aims to design cooperative routing algorithms are discussed. In this paper, we provide a taxonomy of different cooperative routing protocols and we analyze various algorithms within the groups with common characteristics. We also briefly discuss the most significant and well-cited cooperative routing algorithms and compare the performance of the algorithms.

The remaining part of this chapter is organized as follows: In Section 2.3, a background of cooperative routing is given. Section 2.4 provides a taxonomy of state-of-the-art cooperative routing schemes and classifies the existing cooperative routing algorithms in terms of 1) optimality, 2) objective function, and 3) centralization. Section 2.5 discusses the optimality of cooperative routing algorithm. Section 2.6 explains the cooperative routing objectives and aims. The objectives include energy-efficiency, QoS parameters, and collision minimization. Section 2.7 presents a review on centralized and distributed cooperative routing algorithms. Section 2.8 provides a brief overview of some existing cooperative routing algorithms. The performance evaluation and comparison of the proposed cooperative routing algorithms and challenges are presented in Section 2.9, and finally, Section 2.10 concludes the chapter and presents some future research directions.

2.3 Background of Cooperative Routing

In general, a cooperative route is a concatenation of cooperative-transmission and direct-transmission links. Fig. 2.2 shows an example of cooperative routing. The direct-transmission (DT) block is represented by the link (a, b), where node a is the transmitter node and node b is the receiver node. The cooperative-transmission (CT) block is represented by the links $(i, j), (i, k)$, and (k, j), where i is the transmitter node, k is a relay node, and j is the receiver node. In cooperative transmission, in addition to the direct link from the transmitter node to the receiver node, one or more relay nodes can be used to relay the signal to the receiver node. Therefore, the definition of the traditional link, which includes only two nodes, should be revised. In order to facilitate cooperative communication, researchers need to address the requirements for designing cooperative systems. These requirements include making decisions about the cooperative transmission scheme, relay node selection, resource allocation, channel state information, and the cooperative routing metrics. In the entire chapter, we define the source node as the initial transmitter node and the destination node as the final receiver node.

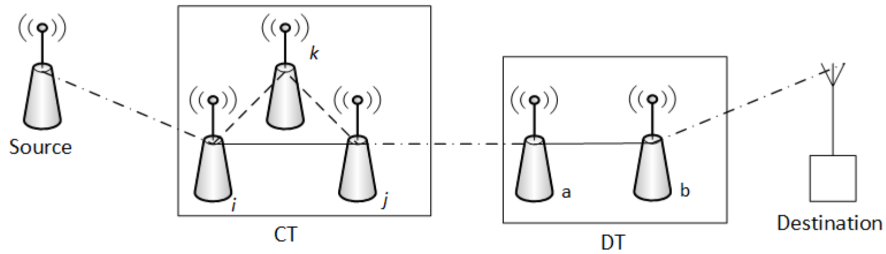


Figure 2.2: A sample cooperative route: Constructing the route using Cooperative Transmission (CT) and Direct Transmission (DT).

2.3.1 Cooperative Transmission Scheme

To make an effective routing decision, a transmitter node needs to determine whether cooperation on each link is necessary or not. If it is necessary, the node selects the optimal relay node(s). The main aspects of cooperative transmission include the relaying techniques and combining methods.

2.3.1.1 Relaying Techniques

Several relaying techniques are employed by cooperating relay nodes. These techniques vary in the performance, implementation complexity, and signal processing. Laneman *et al.* [23] introduced a number of relaying techniques: (1) fixed relaying scheme, such as Decode-and-Forward (DF) or Amplify-and-Forward (AF) and (2) adaptive relaying schemes, such as selection relaying and incremental relaying techniques.

The performance of fixed relaying algorithms (depending on whether the relay node decoded the received signal (Decode-and-Forward, DF) or only amplified (Amplify-and-Forward, AF)) was analyzed in [24]. The relative performance of each technique depends on the position of the relay. It is shown that DF outperforms AF if the relay node is closer to the transmitter node, and AF outperforms DF if the relay node is closer to the receiver node [24]. From a practical point of view, it is still debatable which scheme is easier to implement. DF may offer higher complexity because of the decoding requirement at the relay node. On the other hand, AF may be problematic in terms of data storage in analogue format [25].

Fixed relaying techniques need twice the time to transmit a data packet from the source to the destination node compared to the direct transmission technique. As a result, the throughput of the fixed relaying schemes can be degraded compared to that of the direct transmission. In addition, when the destination node can correctly decode the data packets transmitted from the source in the first time slot, the channel resource of the second time slot exploited by the relay node is wasted. To combat these problems, adaptive relaying methods that effectively use the channel resources are proposed in [1]. The authors described two adaptive relaying protocols: selection relaying and incremental relaying. Selection relaying allows transmitter nodes to select a suitable relay node based on the measured SNR. With the incremental relaying technique, the source node sends its signal to the destination node, using a direct link. If the destination node is unable to detect the signal using the direct link, the relay node forwards the signal to the destination node (provided that the relay node was able to detect the signal). If the relay node is unable to detect the signal, it will remain silent. Selection relaying and incremental relaying can be used with either AF or DF.

2.3.1.2 Combining Techniques

For signal combining in cooperative routing, traditional diversity combining techniques such as Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), and Selection

Combining (SC) can be used by each receiver node along the path. Brennan described the aforementioned techniques in [26]. In MRC, the received signals from all cooperators are weighted and combined to maximize the instantaneous SNR. It is known that MRC is optimal and maximizes the total SNR in noise-limited links with Gaussian noise. However, the main drawback of the MRC technique is that it requires full knowledge of the channel state information [27]. EGC is a simplified sub-optimal combining technique, where the destination node combines the received copies of the signal by adding them coherently. Therefore, the required channel information at the receiver node is reduced to the phase information only. SC is even simpler and the combiner simply selects the signal with larger SNR. Although, SC removes the overhead of estimating the channel state information, its performance is ultimately degraded compared to the MRC and EGC [27]. In addition to the aforementioned combining techniques, Optimal Combining (OC) is proposed for the interference-limited links in the literature [28, 29]. With Optimal Combining, signals received from the transmitter and relay nodes are weighted to maximize the Signal Interference Ratio (SIR) at the receiver node. However, OC requires the instantaneous Channel State Information (CSI) of all interferers to be known at the receiver, and hence, demands significant system complexity [30].

2.3.2 Relay Node Selection

Relay node selection is crucial for the performance of cooperative routing because a good quality relay node yields a higher diversity gain. Therefore, optimal relay node selection potentially enhances the system performance and achieves the cooperative routing objectives such as energy efficiency, throughput, and packet delivery ratio. The relay node selection strategies in terms of the optimal number of relay nodes and optimal relay node location are briefly described below.

2.3.2.1 Optimal number of relay nodes

Intuitively, exploiting more relay nodes will lead to a higher diversity gain and better performance. However, more relay nodes need more resources (such as more time slots) and cause a larger interference area (containing the set of nodes that would cause interference at the receiver, if they also transmitted [31]), which may reduce the cooperation gain. Without a central controller, more coordination overhead is involved in selecting more relay nodes. Due to the protocol overhead, the energy efficiency of cooperative transmission degrades with the increase of the number of relay nodes. The authors in [14] demonstrated that there is a direct relationship between the interference area and the number of relay nodes; the interference area affected by cooperation is enlarged proportionally to the number of relay nodes. Therefore, the overall throughput performance may degrade. It is proved in [32,33] that selecting only the single best relay node accomplishes the same diversity gain as that of multi-relay cooperation.

2.3.2.2 Optimal relay node placement

In addition to the number of relay nodes, the potential gain of a cooperative route depends on the location of the relay nodes. The best relay node is the one that can enhance the objective performance to the maximum extent. The definition of the best relay node depends on the application scenario. For instance, in [34], in which the routing objective is the energy efficiency, if the minimum energy consumption of a cooperative-transmission link corresponds to a certain relay node, that specific node is selected as the best relay node for the transmitter node. For links with a single relay node, Wang *et al.* [35] showed how game theory [36] can be used to select the best cooperative relay node. For links with multiple relay nodes (i.e., multi-relay based cooperative links), the authors in [37] proved that the optimal performance is achieved when all the cooperative nodes appear to be at the same distance from the destination node. In addition, Astaneh and Gazor in [38] demonstrated that, for the DF relaying scheme, the best location for the relay node is in the vicinity of the midpoint between the transmitter-receiver pair in each link.

2.3.3 Resource Allocation in Cooperative Communication

When a feedback channel in cooperative links is available, adaptive resource allocation can make significant performance enhancement by adapting transmission parameters to the channel characteristics. The existing resource allocation strategies of cooperative links can be divided into two categories: optimal resource allocation and equal resource allocation.

Optimal resource allocation has been addressed in many studies, such as [39–42], and the authors have dealt with various aspects of resource allocation, in terms of power [42], bandwidth [40], and time [41]. The optimization techniques and heuristic decision making algorithms are employed to allocate optimal resources to the transmitter and relay nodes. For instance, the Lagrangian method is used in [21, 37, 42–44] to allocate optimal transmission power of transmitter and relay nodes. Moreover, authors in [40] employed Stackelberg differential game models (described in [36]) as the heuristic decision making algorithms to allocate joint bandwidth and the power of the transmitter and relay nodes in the cooperative-transmission links.

Although equal resource allocation strategies are not optimal, the simplicity of the equal resource allocation algorithms make them more suitable for implementation [45,46].

2.3.4 Channel State Information (CSI)

In order to adapt to the channel statistics, most of the existing cooperative schemes take the availability of CSI at transmitter nodes into consideration to evaluate the effectiveness of cooperation and to coordinate the relay node selection. In a cooperative link, the receiver nodes utilize the available CSI for coherent reception, and the transmitter nodes can utilize the available CSI for power control, signal combining, and relay selection. To estimate a channel coefficient, a pilot message is usually sent out by the transmitter nodes, and then the receiver nodes exploit the known pilot message to estimate the channel coefficient.

The majority of the work on cooperative communication has focused on the scenarios in which the CSI is available at the transmitter and receiver nodes in the form of accurate estimates for the fading coefficients. However, because of the errors that can occur in the channel estimation, a perfect CSI is hard to obtain practically. A central unit can be used to collect the accurate CSI of all links, to schedule the transmission, and to coordinate the cooperative behaviours (e.g., [42, 43, 47]). However, the centralized policies are not efficient in large networks or in networks where the traffic is relatively low. Therefore, the authors in [48–50] developed distributed algorithms that require far less CSI and yield a performance nearly as good as the centralized cooperative transmission with CSI, while outperforming the direct transmission.

The performance of cooperative communication in the presence of imperfect CSI is investigated in the literature, such as [51–53]. The relay selection and power allocation in the consideration of CSI imperfection are performed in [51] by means of the correlation coefficient of the estimated channel gain and its actual values. It is shown in [53] even though the transmitter nodes have imperfect CSI, cooperative transmission can significantly improve the overall system performance compared to the direct transmission.

2.3.5 Network Coding in Cooperative Diversity

Network coding is an efficient technique that allows intermediate nodes to encode and combine incoming packets instead of only copying and forwarding them. Network coding has been recognized as a promising technique to increase system throughput, and also is the basis for many bandwidth and energy-efficient transmission schemes in wireless networks [54–56]. While there are many papers, such as [57], addressing network coding in cooperative diversity, there are only a few papers discussing the network coding in cooperative routing (e.g. [7]). In [7], the cooperative Physical Layer Network Coding (CPLNC) scheme (physical layer network coding is discussed in [58]) is applied to an optimal non-cooperative shortest path route. After choosing the shortest path route, the first symbol is transmitted non-cooperatively between the source and the destination node. If CPLNC consumes less power than non-cooperative transmission for the given hop, from the second symbol onwards, for each group of three consecutive nodes along the route, the first two nodes transmit cooperatively to the third node. Simulation results in [7] proved that the network coding in cooperative routing outperforms the conventional network coding in terms of energy saving gains.

2.3.6 Cooperative Routing Metrics

A routing metric is a function of the routing objective(s) and demonstrates the cost values used by routing protocols to determine whether one particular route should be chosen over another. Therefore, the routing cost metric, which affects the path selection and resource consumption, is a crucial element of the routing protocol design. To perform cooperative routing, a metric calculation is performed for each cooperative link, including the potential relay node in an available cooperative transmission scheme. According to the various applications of the cooperative networks, the routing metrics include energy consumption (e.g., [42]), throughput (e.g., [59]), packet delivery ratio (e.g., [60]), and collision probability (e.g., [61]).

Most of the proposed cooperative routing algorithms, such as [42, 59], rely on the use of only a single cost metric. However, the single-metric approach is not adequate for future wireless networks for the following reasons: firstly, some applications might have multiple performance requirements that should be met simultaneously during the route discovery; secondly, developing new wireless communication technologies produces a wide range of wireless devices with different levels of constrained resources. Therefore, multi-metric cooperative routing algorithms are developed in the literature. For instance, in [60], cooperative routing metrics include throughput, packet delivery ratio, and energy efficiency. In other words, the algorithm in [60] decides what route is preferred based on the achievable throughput, packet delivery ratio, and energy efficiency. This is achieved by combining all these routing metrics in the routing cost function.

2.3.7 Cooperative Routing Applications

Each cooperative routing algorithm has a specific application in a given scenario and can be designed to allow the network to cope with the demands of a particular application. Thus, the performance of a cooperative routing protocol may vary dramatically with different network applications. It is very difficult to make a comprehensive cooperative routing suitable for all applications. Thus, cooperative routing is formulated according to the network application. For instance, in [43], cooperative routing is applied in a sensor network and problem formulation corresponds to the total remaining energy, which is the most important performance measure in WSNs due to the limited power supply. Therefore, the objective function is the remaining energy. WSNs play an important role in vast applications, such as environmental monitoring and target detection. In [62], the cooperative routing is formulated for rate maximization in a cellular network and each mobile station has the option of routing a tone signal in a cell through the other mobile stations in the cell.

2.4 Taxonomy of Cooperative Routing Protocols

In order to evaluate the state-of-the-art cooperative routing algorithms, first a taxonomy should be defined and various algorithms should be compared and analysed within the groups with common characteristics. Cooperative routing algorithms are classified based on three main characteristics: 1) optimality, 2) objective, and 3) centralization. The taxonomy of cooperative routing protocols is illustrated in Fig. 2.3.

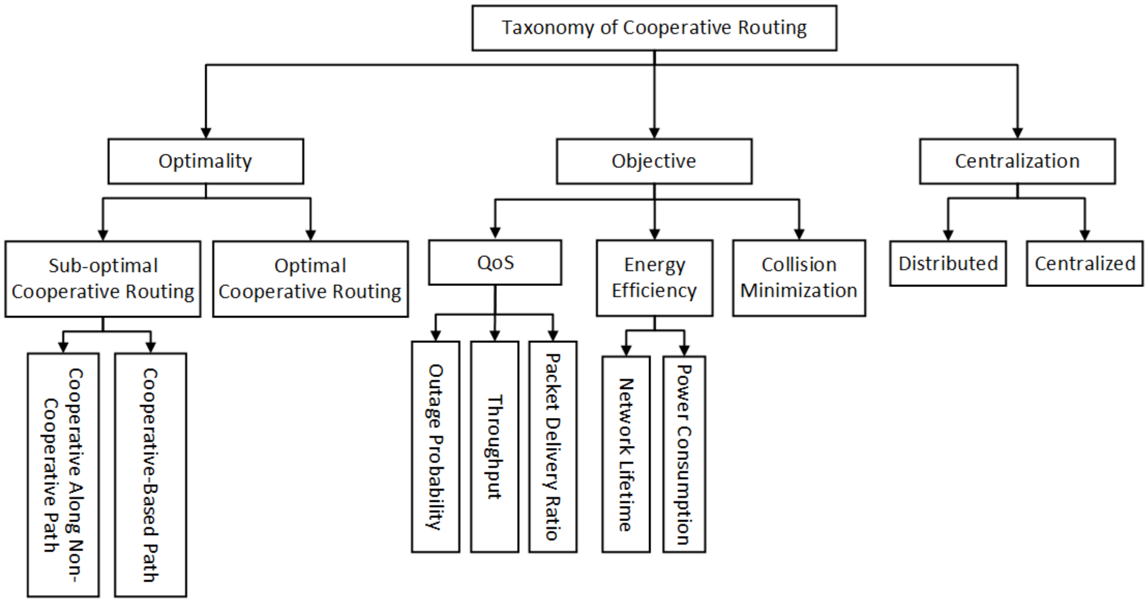


Figure 2.3: Taxonomy of Cooperative Routing.

2.4.1 Optimality

In this chapter the term optimality (or sub-optimality) of a routing algorithm is referring to the optimal (or sub-optimal) route in terms of achieving the routing objective(s). The objective function can be optimized depending on the application of the proposed algorithm. For instance, in [63], where cooperative routing is applied in WSNs, the routing objective is the energy consumption minimization. Therefore, an optimal cooperative routing algorithm is one with the minimum energy consumption. Finding the optimal cooperative route in a large arbitrary network is computationally intractable (as will be discussed later, in Section 2.9). While many efficient sub-optimal cooperative routing algorithms are proposed in the literature, only a few studies have focused on optimal cooperative routing. As Fig. 2.3 shows, sub-optimal cooperative routing algorithms can be divided into two categories. The first category of cooperation-based routing algorithms, namely *Cooperative Along Shortest-Path* (such as the proposed algorithms in [42, 43]), is implemented by finding the shortest-path route first, and then building the cooperative route based on the shortest path. The main idea of algorithms in this category is to use cooperative transmission to improve performance along the selected non-cooperative links. However, the optimal cooperative route might be completely different from the non-cooperative shortest path. Therefore, the merits of cooperative routing are not fully exploited if cooperation is not taken into account while selecting the route. The algorithms in the second category, *Cooperative-Based Path* (e.g., the proposed algorithms in [34, 45, 64, 65]), address the above problem by exploiting cooperative communication during the route selection process. However, the algorithms in this category are not optimal due to the following reasons: (1) they employ the sub-optimal approaches in the relay node selection [45], power allocation [34], or route selection [64] and (2) they utilize optimal relay node selection, resource allocation, and route selection but not jointly (as will be discussed in detail in Section 2.5), such as algorithm in [65].

2.4.2 Objective

The objective of cooperative routing is defined as the target of the cooperative routing algorithm. As Fig. 2.3 illustrates, the targets of cooperative routing algorithms in the literature can be classified into three categories: (1) energy-efficiency (e.g., [34]), (2) QoS parameters including throughput (e.g., [59]), packet Delivery Ratio (PDR) (e.g., [60]), and outage probability (e.g., [66]), and (3) collision minimization (e.g., [61]). Overall, energy efficiency is the most common objective of cooperative routing algorithms because cooperative communication is a promising approach for energy saving.

2.4.3 Centralization

Cooperative routing decisions are made based on the information of the network. The information of the network can be obtained by either: (1) using a centralized controller in a centralized mode, or (2) having each node be responsible for obtaining network information by itself and making a routing decision in a distributed mode, Fig. 2.3 illustrates these two categories. Therefore, the main difference between the centralized and distributed cooperative routing algorithms is the place where the information is obtained and route decision is made. Having a centralized controller may not be possible in some wireless networks, such as ad hoc networks [67]. Moreover, the centralized routing algorithms are not scalable, particularly in cooperative routing where a complete view of the network including all cooperative links and relay nodes is needed.

In the following three sections, we elaborate on cooperative routing algorithms in the three taxonomic groups, optimality, objective, and centralization, and we discuss the key ideas of cooperative routing algorithms in each group.

2.5 Cooperative Routing Optimality

2.5.1 Optimal Cooperative Routing Schemes

Only algorithms proposed in [63, 68] have focused on optimal cooperative routing. The algorithms in these two papers present frameworks to demonstrate the exact formulation for the optimal relay node and optimal power allocation set, and jointly use of optimal power, relay node allocation, and path selection. The frameworks lead to a Mixed-Integer Linear Programming problem (MILP). In [68], the branch and bound cutting plane algorithm is utilized to solve the MILP problem and obtain the optimal cooperative route. In [63], the MILP problem contains $n+2$ real decision variables (n_r) and $n+2$ binary decision variables (n_b), as well as $4n+9$ inequalities, where n is the maximum number of neighboring relay nodes. The author proved that obtaining the solution, in the worst-case scenario, requires complexity of $O(2^{n_b})$. Therefore, the complexity of the computations required to solve these problems grows exponentially with the number of binary decision variables. Given these points, the initial price for achieving optimal performance is a more complex optimization framework. To ease the implementation of these approaches, powerful techniques, such as multi-parametric programming, are carried out off-line. Multi-programming techniques are utilized to find an explicit solution to the optimization problem. Hence, the major parts of the computation can be performed before the system starts its operation.

2.5.2 Sub-Optimal Cooperative Routing

As mentioned before, due to the required computational complexity of finding optimal cooperative routing, heuristic sub-optimal cooperative routing algorithms are proposed in the literature.

2.5.2.1 Cooperative Along Non-cooperative Path

The key idea in this category is applying cooperative communication techniques to improve performance along the selected non-cooperative path. In other words, the cooperative communication is implemented after non-cooperative path selection. Non-cooperative path, which is an underlying path, is decided based on the traditional single link routing algorithms. Normally, the underlying non-cooperative paths attempt shortest-path methods to achieve the cooperative routing objective(s). After establishing the non-cooperative path, relay node selection is performed using one of the following sub-optimal methods:

- employing the last few nodes along the selected non-cooperative path as the relay nodes, as it is implemented in [42, 43];

- using contention among nodes (i.e., nodes are involved in the competition) to find the relay node that has the best performance (such as longer connection time in [67]) among the neighboring nodes, as it is used in [67, 69];

- utilizing the nodes' location information firstly to find the potential relay set (e.g., nodes located in the coverage intersection area of transmitter and receiver nodes, i.e., node is covered by both transmitter and receiver nodes [59] as shown in Fig. 2.4) or nodes closest to the destination node in [70]), and then assigning a weight to the potential relay nodes. The weight of each node represents the achievable performance when that particular node acts as the relay node. Finally, the nodes which lead to the best performance are selected.

The computational complexity of the sub-optimal cooperative routing algorithms in this category mainly depends on the complexity of the underlying non-cooperative path. For instance, in [42], the complexity of the proposed algorithm is the same as finding the non-cooperative shortest path in the network ($O\left(N^2\right)$, where N is the total number of nodes in the network).

2.5.2.2 Cooperative-Based Path

The optimal cooperative route might be completely different from the underlying non-cooperative shortest path selected without taking cooperative links into consideration.

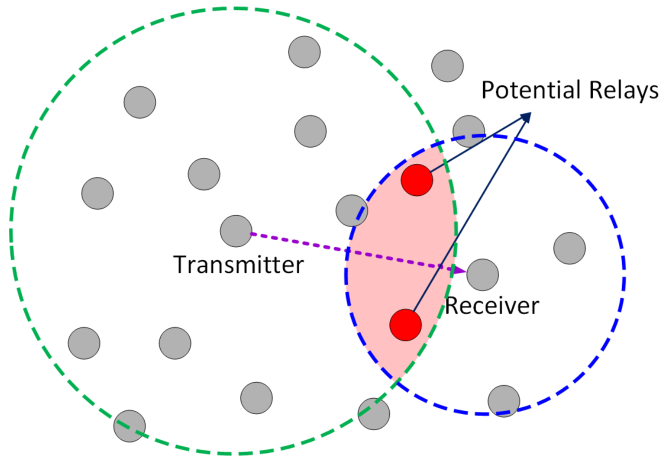


Figure 2.4: The potential relay nodes are located in the intersection area of the coverage circle [59].

Therefore, the merits of cooperative routings are not fully exploited if the cooperation is not taken into consideration while selecting the entire route from the initial source to the final destination. Cooperative-based path algorithms address these issues by including routing algorithms that consider the cooperation schemes during route discovering. Hence, in cooperative-based path algorithms, the relay node selection is performed in the initial steps of the routing. The methods of relay node selection can be described as follows:

- each node that successfully received and decoded the message will join the transmitter node to form a cooperative transmitter set (relay set) [45, 64];

- the location of the nodes is used to obtain the relay node or potential relay set [37,71]. For instance, in [71], the relay node is assumed to be the nearest node to the midpoint of the distance between transmitter and receiver nodes. In [72], the nodes that lie in the intersected transmission area of the transmitter and receiver nodes are potential relay nodes;

- all neighboring nodes are investigated and the node corresponding to the minimum cost function is selected [34];

- the potential relay set or the relay node candidates compete to determine the shortest back-off time (usually, back-off time is inversely proportional to the routing objective; for instance, node that lead to the highest throughput should have shortest back-off time) and when the first back-off time expires, the corresponding relay node is selected [66].

After selecting the relay nodes and potential cooperative links, route selection is performed by applying shortest-path algorithms or dynamic routing protocols [73]. For instance, the Bellman-Ford algorithm is employed in cooperative links in [34], while Dijkstra's algorithm is used in [64].

However, the algorithms in this category are still sub-optimal because of the following reasons: assumptions, such as assigning M levels for the transmission power in [71]; approximations, such as approximating of the exponential function using the first term of the Taylor series to simplify the analytical expressions in [34]; sub-optimal relay node selection, such as assigning the nearest node to the midpoint of the distance between transmitter and receiver nodes in [71] or selecting any nodes that successfully received and decoded the message as the relay node [45]; non-optimal power allocation methods, such as equal power allocation to the transmitter and relay nodes in [37, 73]; not jointly implementing the optimal relay selection, resource allocation, and route selection [65].

The computational complexity of cooperative-based routing algorithms depends both on constructing the cooperative links and selecting cooperative routes. For instance, in [34] with N nodes in the network, the worst case computational complexity of calculating the possible relay node at each transmitter node is N, and the complexity of calculating the cooperation cost at each node is $O(N^2)$; therefore, the complexity of the algorithm is $O(N^3)$.

2.6 Cooperative Routing Objectives

2.6.1 Energy-Efficient Cooperative Routing

Saving energy (or power) is one of the main objectives of routing algorithms in the deployment of various wireless networks, including ad-hoc networks [74,75], sensor networks [76], personal area networks [77], and other wireless networks. Energy efficient cooperative routing algorithms can be classified into two categories. In the first category, the target is to minimize the total energy consumption for the end-to-end transmission. The cooperative routing algorithms presented in [34, 42, 45, 60, 66, 69] are good examples of this category. In most cooperative routing algorithms in this category, such as [34, 42], energy saving is achieved by minimizing the total transmission power of transmitter and relay nodes. Therefore, the problem is formulated as the transmission power minimization. For a given source-destination pair, Ω denotes all possible routes from the source node to the destination node, where each route is defined as a set of hops or intermediate nodes between the source and destination. For a route $\omega \in \Omega$, ω_i denotes the i-th hop of this route. Thus, the problem can be formulated as

$$\underset{\omega \in \Omega}{Min} \sum_{\omega_i \in \omega} P_{\omega_i} \tag{2.1}$$

where P_{ω_i} denotes the transmission power over the i-th hop.

In the second category, the goal of the algorithms is to prolong the network lifetime, such as algorithms in [43, 70, 72, 78–80]. One definition of the network lifetime is the time until the first node dies; this definition is widely used in the literature [43, 72, 79].

The algorithms in the first category focus only on minimizing the total energy consumption from the source node to the destination node; however, consistently using the minimum cost path for routing may lead to an unbalanced energy distribution among nodes. This problem is addressed in the algorithms proposed in the second category. The authors in [43, 70, 72, 78] employ the cooperative routing scheme to balance the energy distribution among nodes in the network, which prolongs the network lifetime. This is achieved by taking into account the residual energy of nodes when selecting nodes for the route (either as the next hop or the relay node). However, implementing the balanced data routing algorithm may be challenging because of heterogeneity among nodes, which is inherited from the physical world as a result of different amounts of nodal traffic, data transmission rates, and bandwidth ranges [81].

All energy-saving algorithms proposed either in the first category or in the second category show high energy saving gains under different network conditions and constraints. However, the power consumption of active radio electronics is not taken into account, except in [37]. This study takes into consideration the radio electronics consumed power that can increase significantly as a result of cooperative transmission by multiple nodes (transmitter and relay nodes) to the next hop receiver node along the cooperative path.

In general, energy saving in cooperative routing algorithms is obtained by employing three mechanisms, namely *Energy-Efficient Cooperative Link*, *Energy-Efficient Relay Node Assignment*, and *Energy-Efficient Path Selection*, or any combination of these techniques.

2.6.1.1 Energy-Efficient Cooperative Link

In this strategy, the algorithms first calculate a cost function for each cooperative link based on the minimum transmission power and then energy-saving links are employed to find the minimum energy routing scheme. The link's cost calculation is performed using various approaches, such as allocating minimum transmission power under certain network constraints (e.g., outage probability constraint). Energy efficient cooperative link selection strategy is used in [34, 42, 43, 45, 47, 66, 69]. Algorithms proposed in [42, 43, 69] are in the *Cooperation Along Non-cooperative Path* category; therefore, minimum transmission power is employed for non-cooperative links. Algorithms proposed in [34,45,47,66] are in the *Cooperative-Based Path* category; therefore, minimum transmission power is employed for either cooperative or non-cooperative links, which leads to less energy consumption.

2.6.1.2 Energy-Efficient Relay Node Assignment

In addition to the energy-efficient cooperative link selection methods, energy-efficient relay node selection is an effective approach to save energy in cooperative routing algorithms. In most of the energy-efficient relay node assignment approaches, a weight is assigned to each relay node candidate. In algorithms presented in [34, 69], the weight represents the amount of power consumption that can be saved if a particular node acts as a cooperative relay node for the specific link. The link checks the weight of all possible relay nodes, and the relay node with the minimum cost function is selected for the corresponding link. In cooperative routing algorithms presented in [70, 72], the rely node candidates are sorted in a descending order based on their remaining lifetime and the algorithm greedily picks the nodes with the longer remaining lifetime and uses them as the relay nodes. Some algorithms, such as those in [42, 47], select the last few nodes in the minimum energy non-cooperative path as the relay nodes. Finally, the algorithm in [37] determines the relay node's location that minimizes the transmission power and a super-node is considered as if it is placed at this optimal location virtually. Each of the transmitting nodes adjusts its phase with respect to the super-node, such that all the nodes appear to be at the same distance from the destination.

2.6.1.3 Energy Efficient Path Selection

In addition to the strategies mentioned above, the minimum energy non-cooperative path (as the underlying path in *Cooperation Along Non-cooperative Path* category) or minimum energy cooperative path (among the cooperative weighted links in *Cooperative-Based Path* category) can be obtained by employing the shortest-path algorithms, such as Dijkstra's algorithm [42, 47], Bellman-Ford algorithm [34, 72], and Suurballe's algorithm [69].

2.6.1.4 Combination of The Aforementioned Techniques

Any combination of the energy-efficient strategies mentioned above leads to saving energy in cooperative routing. In [34], *Energy Efficient Relay Assignment* and *Energy-Efficient Cooperative Link* are combined to save energy utilizing cooperative routing.

2.6.2 QoS-Aware Cooperative Routing

The QoS in proposed cooperative routing algorithms is characterized by the following parameters in the network: (1) throughput (as in [59, 64, 67, 68, 73]), (2) packet delivery ratio (as in [60,80]), and (3) outage probability (as in [34,43,63,65,66,69,82]). In addition to energy efficiency, QoS is also an important criterion to measure the performance of the network. In critical applications, such as security, fire detection, and health monitoring, QoS is a major concern [83, 84]. The goal of QoS in cooperative routing is to find a network path that satisfies given constraints and simultaneously optimizes the utilization of resources. *QoS-Aware Cooperative Routing* algorithms are classified into three categories as follows.

1) Throughput-Aware Cooperative Routing Algorithms maximize the network throughput. The network throughput can be defined as the number of successfully delivered packets at the destination node in time unit [85]. The throughput in a wireless system is limited by a number of factors, such as wireless channel characteristics (e.g., SNR and bandwidth), end-to-end delay, network congestion, and collisions. Throughput optimization cooperative routing algorithms are presented in [59, 60, 64, 67, 68, 73].

In [59], each node across the selected non-cooperative path calculates the throughput gain obtained by each potential relay node. The throughput of each cooperative link is formulated by the channel capacity of the link and Shannon's Theorem [86] is employed to obtain the maximum capacity (i.e., throughput) of the cooperative link. By comparing the throughput gains when different nodes are selected for a cooperative link, the node that leads to the maximum throughput gain is selected as the relay node. This method is employed in [60], where the throughput of *cooperative links* are compared and the cooperative link which leads to the maximum throughput is selected. Moreover, cooperative routing algorithms presented in [64, 67, 73] increase the throughput in wireless networks with multiple active flows by avoiding congestion among the nodes that are receiving packets simultaneously.

2) Packet Delivery Ratio (PDR), which is defined as the percentage of transmitted packets that are successfully delivered to their destination, is another characteristic of

QoS [87]. The proposed cooperative routing algorithms in [60, 80] optimize the network PDR by using a cooperative links-cost-calculation strategy based on the PDR of each link and comparison of the links to select the optimal PDR cooperative routing. In [60], the PDR of each link is simply obtained from the Packet Error Rate (PER) of the link as follows:

$$PDR_{\omega_i} = 1 - PER_{\omega_i}, \tag{2.2}$$

where PER_{ω_i} is the packet error rate of i-th hop. The author employed the approximate expression of the PER for the links over additive white Gaussian noise (AWGN) [60].

3) Outage-Aware Cooperative Routing Algorithms take into consideration the outage probability in cooperative routing. Outage happens when the destination node is unable to detect the received signal from the source node. The end-to-end outage probability of a cooperative routing can be dominated by the maximum outage probability of all transmission links in the route, including direct links and cooperative links [69]. In [61], the end-to-end outage probability of a cooperative link (assuming the hops are selected independently) is defined as the probability that outage takes place in one of the hops of the route, i.e.,

$$Pr_{out}(\omega) = 1 - \prod_{i=1}^{H} \left(1 - Pr_{out}^{C}(\omega_i)\right), \tag{2.3}$$

where i is the hop number, H is the total number of hops in the route, and $Pr_{out}^{C}(\omega_i)$ is the outage probability of the i-th hop (ω_i) in the route. The outage probability of a cooperative link with different cooperative relaying techniques, such as DF and AF, are formulated in [1]. The outage probability constraint can be met using constrained optimization techniques, such as the Lagrange Multipliers [88]. For instance, the Lagrangian method, which is used to allocate resources in [34, 42, 43, 61], is subject to the outage probability constraint.

2.6.3 Minimum Collision Cooperative Routing

The main challenge of cooperative routing with multiple sources and multiple destination nodes (i.e., multiple flows) is the packet collision. The algorithm proposed in [61] mathematically models and minimizes collision probability using cooperative routing. A transmitter node, s, will cause a collision to another node, n, if s is sending while n is simultaenously receiving (from another node, m), provided that the interference from s at n is high enough to cause a collision. Therefore, the collision minimization is formulated as the probability that the entire route causes collision to the network (assuming the hops are selected independently), which is given by

$$Pr\left(Coll._{\omega}^{C}\right) = 1 - \prod_{i=1}^{H}\left(1 - Pr\left(Coll._{s,l}^{C}\left(\omega_i\right)\right)\right), \tag{2.4}$$

where $Pr\left(Coll._{s,l}^{C}\left(\omega_i\right)\right)$ is the collision probability caused by the source node (s) and relay node (l) of i-th hop (ω_i) in the route.

First, the algorithm calculates a cost function for each cooperative link based on the collision probability caused by the cooperative link. Then, the algorithm applies the shortest path Bellman-Ford algorithm to find the path that causes minimum collision probability. A minimum-collision cooperative route is achieved by combining cooperative transmission, power allocation, and route selection. The algorithm selects the route that avoids nodes surrounded by neighbors, which have high probability of reception and are more susceptible to packet collision.

2.7 Centralization

Optimal relay node selection, resource allocation, and route selection in cooperative routing can be implemented only when accurate information of all possible routes is available. Generally, a central controller is utilized to: (1) select the relay node(s), (2) inform each transmitter node of its corresponding relay node(s), (3) use feedback channels from the receiver/relay node(s) to collect instantaneous CSI sending from the transmitter node(s) to the corresponding receiver/relay node(s) (4) perform global optimization for the power allocation for each transmitter/relay node(s), and (5) inform each node of its transmission power level. However, in general, the centralized approach (e.g., scheme proposed in [42]) becomes challenging, as the number of users increases because of the amount of information that needs to be exchanged, as well as the computational complexity required for finding the optimal resource allocation and relay node selection. Distributed cooperative routing is proposed to tackle the centralization problem. In distributed cooperative routing, each transmitter node is responsible for constructing the cooperative route (e.g., scheme proposed in [34]).

2.7.1 Centralized Cooperative Routing

In a centralized cooperative routing protocol, a central node collects information to check for potential cooperative links and relay nodes. This information includes the topology and fading information that helps to make the cooperative routing decision; for instance in [65], the central node collects the cost functions of cooperative links and the channel characteristics while the central controller selects the route based on the collected information.

In routing algorithms where cooperation is applied along the non-cooperative path (*Cooperation Along Non-cooperative Path*, proposed in [42, 43, 47, 64, 69, 70]) the central controller collects the information about the location of the nodes and the cost function of each link and selects the best non-cooperative route. Firstly, nodes in the network consult with the central node to make a non-cooperative routing decision. Next, the controller assigns the relay nodes. In [42, 43, 47], the last few predecessor nodes along the selected non-cooperative path are assigned by the central controller to work as the relay nodes. In cooperative routing algorithms proposed in [69, 70], the controller compares the amount of power consumption that can be saved if each node acts as the relay node and then selects the cooperative relay node.

In *Cooperative-Based Path* algorithms such as [71], the central controller (e.g., the destination (or sink) node in a wireless sensor network) has full knowledge of the location of every node in the network and uses this information to select the cooperative-based path.

2.7.2 Distributed Cooperative Routing

In the previous section, centralized cooperative routing has been discussed. However, in practice, having a central node may not be possible in some wireless network applications (such as ad hoc networks) and routes need to be constructed in a distributed manner. In a distributed cooperative routing protocol, each node is informed about the network status (such as local topology status and cost functions of one-hop connected links) from neighboring nodes. Each node stores the information in its own local database and each node is responsible for relay node selection and next node selection. The algorithms proposed in [34, 37, 45, 59, 63, 65–68, 72, 73] are fully distributed.

Distributed cooperative routing algorithms are scalable because they do not need a complete view of all links and nodes in the network. Moreover, unlike centralized routing algorithms, they do not rely on a central controller to select relay node or make the routing and resource allocation decisions; therefore, they are applicable to ad hoc and wireless sensor networks.

The main challenge in the distributed cooperative routing algorithm implementation is the information availability needed for routing, relay node selection, and resource allocation. Nodes deal with this challenge by sending an updating-message to the neighbours. For instance, in [73], nodes use *Route Request* and *Route Respond* messages to inform the neighbors about the link cost function, interference level, and number of flows. Nodes also listen to a pilot tone to track the number of relays corresponding to the links in their vicinity. In the algorithm proposed in [66], each relay node periodically broadcasts a *Hello* packet to its source-destination pair to measure the link performance. In [72], the $Hello$ packets are periodically broadcast between neighboring nodes to exchange the residual energy and topology information.

2.8 Overview of Existing Cooperative Routing Algorithms

In this section, some of the most significant and well-cited cooperative routing algorithms are discussed.

A. Cooperation Along Minimum Energy Non-Cooperative Path (CAN-L) and Pro-

gressive Cooperative (PC-L) [42] are proposed to minimize the total transmission power subject to the outage probability constraint in a centralized manner. These two heuristic cooperative routing algorithms are sub-optimal and select a non-cooperative shortest path in the first round to obtain the cooperative path in the second round; therefore, they belong to the *Cooperation Along Non-cooperative Path* category. The non-cooperative path in CAN-L and PC-L is obtained using standard shortest path algorithms, such as Dijkstra's algorithm [42], with transmission power as the link cost metric. In CAN-L, after selecting the optimal non-cooperative route, the last "L" nodes along the optimal non-cooperative route (where L is a design parameter, which shows the number of relay nodes) cooperatively send the information to the next node along the optimal non-cooperative route. In a regular grid topology, the minimum-energy non-cooperative path is obtained by a stair-like policy (illustrated in Fig. 2.5). As can be seen in this figure, after applying the CAN-3 algorithm, the last three nodes along the non-cooperative path cooperatively send the packet to the next-hop. For example, nodes 6, 7, and 11 cooperatively send the packet to node 12. In the CAN-L algorithm, the only required processing is to find the optimal non-cooperative route. Hence, the complexity order of this class of algorithms is the same as finding the optimal non-cooperative path in a network with N nodes, which is equal to $(O(N^2))$. The PC-L algorithm combines the last "L" nodes along the best route into a single node. Then, the algorithm finds the shortest path from that combined node to the destination node and sends the information to the next node along that route. This algorithm turns out to have a complexity of $O(N^3)$, since the main loop is repeated N times and each repetition has a complexity order of $O(N^2)$.

B. Minimum Total Energy (MTE-m) and Cooperative Flow Augmentation (FA-m) [43] are sub-optimal cooperative routing algorithms that combine cooperative transmis-

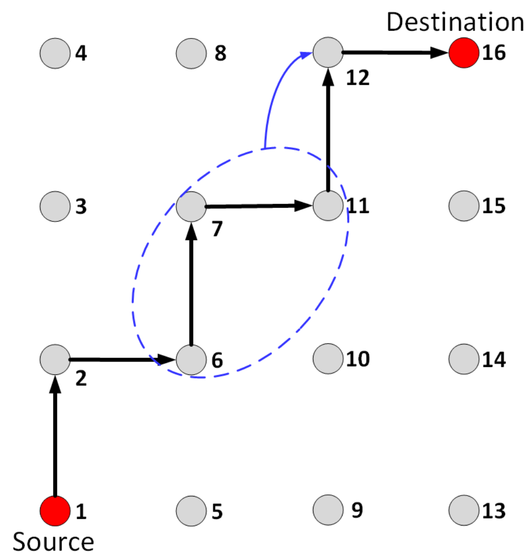


Figure 2.5: Route chosen by the CAN-L algorithm in a grid wireless network [42].

sion and power allocation to prolong the network lifetime in WSNs. In MTE-m and FA-m, cooperation is implemented in the last "m" nodes along the best non-cooperative route (where m is a design parameter, which shows the number of relay nodes). MTE-m and FA-m algorithms are similar to CAN-L in that cooperation is implemented in the last few nodes along the best non-cooperative route. However, in the MTE-m and FA-m algorithms the cost function of the non-cooperative route is proportional to the total energy consumption of nodes along the route. In order to avoid the overuse of nodes along the MTE-m routing algorithm, the heuristic FA-m algorithm takes the remaining energy into consideration in the cost function. The node selection criterion is designed to let nodes with more residual energy help more frequently compared to nodes with less residual energy. The authors in [43] implement both distributed and centralized manner of two algorithms (MTE-m and FA-m). Computational complexity of these algorithms scale as the complexity of finding the best non-cooperative path.

C. Cooperative Along Shortest Non-Cooperative Path (CASNCP) [34] applies cooperative communication to the shortest-path route in a distributed fashion to minimize the total transmission power. The CASNCP algorithm first chooses the conventional shortest-path route by employing the distributed Bellma−Ford shortest path algorithm [89]. Next, for each three consecutive nodes in the route, the algorithm applies either the cooperative transmission mode (where the first node is assigned to be the transmitter node, the second node is assigned as the relay node, and the third node is assigned as the receiver node), or the direct transmission mode from the transmitter to the receiver node. Therefore, the algorithm is a sub-optimal one that belongs to the *Cooperative Along Non-cooperative Path* category. The computational complexity of CASNCP is equal to the complexity of running the Bellman-Ford algorithm, i.e., $O(NM)$ (where N is the number of nodes and M is the number of links in the network).

D. Throughput Optimized Cooperative Routing (TOCR) [59] is proposed to improve the ad hoc network throughput by improving the throughput of each link with the help of cooperative relay nodes. TOCR is based on the Adaptive Forwarding Cluster Routing (AFCR) protocol [90]. In the AFCR protocol, nodes are divided into several 1-hop clusters by a mobile clustering algorithm. In order to establish routes between cluster-heads in adjacent clusters, local routing information is exchanged between neighboring nodes and each node in the network has a neighbor table, namely the Cluster Membership (CM) table. The CM table stores the cluster membership, and a routing table to store routes to each cluster-head. When there are data packets to forward, the node first searches for the destination node in its CM table and, if the destination node is in the table, it sends the data packets to the destination node directly. Otherwise, it searches in the CM table to find the cluster-head to which the destination node belongs. If the cluster head exists, the node checks its routing table, and it sends the data packets to the next hop according to the routing table. If there is no information about the destination node in the tables, it buffers the incoming data packets and waits for building a route to the destination node. As a result, a non-cooperative route is built from each node to the destination node. When the non-cooperative route is built, each node of the selected route executes the following steps to establish the cooperative link to the next hop node along the non-cooperative path. Hence, TOCR is a sub-optimal cooperative routing and belongs to the *Cooperative Along Non-cooperative Path* category. Each node calculates the throughput of the link to its next hop node and the throughput gain of the cooperative link corresponding to each potential cooperative relay. As shown in Fig. 2.4, the potential relay nodes are located in the intersection of the coverage areas of the transmitter and the receiver nodes. The throughput gains obtained by selecting each relay node are compared and the node that leads to the maximum throughput gain is selected as the best relay node of that specific link. The computational complexity of TOCR is mainly related to the AFCR construction and the cooperation scheme slightly increases the complexity.

E. Cross-Layer Cooperative Routing (CLCR) [67] is the only cooperative routing proposed for vehicular networks. Vehicular networks support vehicle-to-vehicle communications and hybrid architectures, which combines roadside units-to-vehicle and vehicle-to-vehicle communication to support vehicular communications. However, since the movements of vehicles is very fast, links between vehicle-to-vehicle or roadside units to vehicle are unreliable and intermittent. CLCR is proposed to overcome the unreliability of the wireless channel in vehicular networks and to maximize the system throughput in a distributed fashion. In the CLCR algorithm, a routing protocol similar to Ad hoc On-Demand Distance Vector (AODV) [91] is used to find a non-cooperative path and then improves the performance using cooperative transmission; therefore, it employs *Co-operation Along Non-cooperative Path* which is a sub-optimal cooperative routing. In the considered scenario shown in Fig. 2.6, every vehicle is under the radio coverage of a road-side unit, and vehicles periodically exchange *Hello* packets with their one hop neighbors to know each others speeds, positions, and directions. Furthermore, roadside units exchange information and synchronize their information using a fixed reliable roadside unit. When the source vehicle has packet to send, it only needs to know the destination vehicle ID. As in AODV, when a source vehicle needs a path to a destination node, the source initiates a route discovery process by generating a route-request packet and then waits for a route-reply. If the destination node receives the route-request packet, it sends a route-reply to the source vehicle along the route travelled by the received route-request packet but in the reverse direction, and therefore, the non-cooperative path is found. Two algorithms are proposed to select the most appropriate relay nodes. In the first algorithm, the holding time of a connection between the transmitter and potential relay nodes, and between the receiver and potential relay node are predicted in order to select the most appropriate relay node. Therefore, the relay node selection is based on the duration during which the potential relay node stays connected to the transmitter and receiver nodes. The relay node should be connected to the receiver and the transmitter nodes as long as possible to achieve the benefit of cooperative transmission and to avoid the overhead caused by frequent relay node reselection. In the second algorithm, the cost of each potential relay node is calculated and the node with the minimum cost (that has the maximum holding connected time and the maximum throughput) is deemed the best choice of the relay node. In this algorithm, the selection of a relay node significantly affects the performance of CLCR.

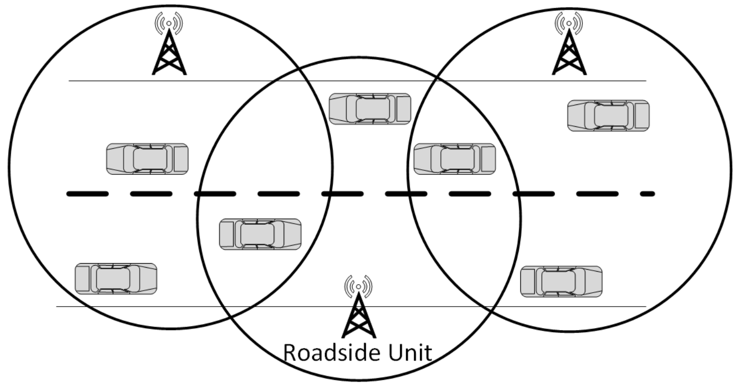


Figure 2.6: Vehicles and roadside units in vehicular networks [67].

F. Cooperative Multipath Routing (CMPR) [69] constructs an energy-efficient node-disjoint cooperative multi-path routing while satisfying the bandwidth constraint on each path. This heuristic cooperative routing algorithm applies cooperation along non-cooperative path; hence, it is a sub-optimal routing. This algorithm consists of two steps: multi-path route construction and cooperative relay node assignment. The first step includes calculating a cost function of each link, based on the routing objective under the direct (or non-cooperative) transmission path. In the second step, k minimum cost node-disjoint paths are constructed from the source to the destination node. The paths are found using the Suurballes algorithm [92]. Suurballe's algorithm is an algorithm that uses iterative process to find two disjoint paths in a network, so that both paths connect the same source-destination pair and have minimum total cost. Each path is a concatenation of direct links. During each iteration, Suurballe's algorithm first applies the Dijkstra's algorithm [89] (using the information obtained by the central controller) to find the shortest path, and then modifies the cost functions of the links in the selected path. The cost function modification preserves the non-negativity, while allowing the Dijkstras algorithm to find the correct path. Given the multiple paths, the CMPR algorithm utilizes a method

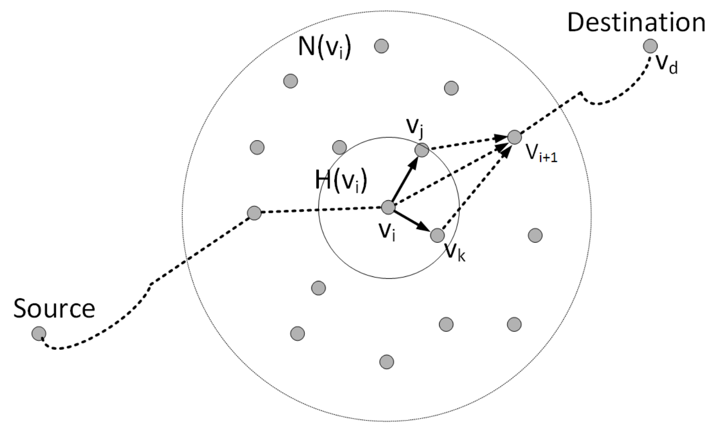


Figure 2.7: Illustration of EBCR to pick the helper set for current node v_i which will send the same packet simultaneously to next hop node v_{i+1}. The large circle represents neighborhood $N(v_i)$ of v_i and the small circle represents one of the potential cooperative helper sets $H(v_i)$ of v_i [70].

based on the dynamic programming for relay node assignment on each path. To select the best relay node of a link, each node in the network will be assigned a weight, which represents the amount of performance achievement if that particular node acts as a cooperative relay node for that specific link in the constructed path. CMPR is applied in wireless multimedia sensor networks for video surveillance. In video surveillance applications using wireless multimedia sensors (e.g., in a battlefield) it is demanded to minimize the power consumption (so as to maximize the lifetime) subject to achieving a sufficient bandwidth (for an acceptable video quality).

G. Energy-Balanced Cooperative Routing (EBCR) [70] performs cooperative communication for each hop along the underlying non-cooperative path to maximize the network lifetime. Hence it belongs to the *Cooperation Along Non-cooperative Path* category. The underlying non-cooperative routing decision is made by any type of non-cooperative routing strategy, such as energy-efficient ad hoc routing protocol or shortest path based routing algorithms. In order to apply cooperative communication to each link, as illustrated in Fig. 2.7, a relay set for each transmitter node along the path is selected using the following steps. Firstly, a potential relay set is defined as any neighbors of the transmitter node that are closer to the transmitter than the receiver node. Given a potential relay set with size k, the remaining lifetimes of the transmitter node and its relay set (under cooperative communication model) are calculated. Then, all of these $k + 1$ nodes are sorted in a descending order by their remaining lifetime. Finally, the algorithm greedily picks those nodes with a longer remaining lifetime and uses them as the relay nodes until the cumulative signal strength at the receiver node is greater than or equal to a detection threshold, i.e, until the received signal strength meets the detection requirement. In this algorithm a central controller is required to collect the potential relay set and pick the best relay nodes to prolong the network lifetime.

H. Minimum Power Cooperative Routing (MPCR) [34] minimizes the transmission power using cooperative routing in a distributed manner. MPCR exploits cooperative communication while constructing a minimum-power route; therefore, it is a cooperative-based routing algorithm. In the MPCR algorithm, first, each node calculates the cost of connection to each of its neighbor either in the cooperative mode (by employing all potential single-relay nodes) or the direct mode. Second, the algorithm applies the distributed shortest path Bellman-Ford algorithm to select the minimum cost route using the calculated costs. To obtain the best relay node in the cooperative mode of the first phase, the algorithm investigates all possible relay nodes in the transmitter node's neighborhood and if the minimum cost (transmission power) corresponds to a specific relay node, that node is selected to cooperate. If there is no available relay node in the neighborhood, a direct

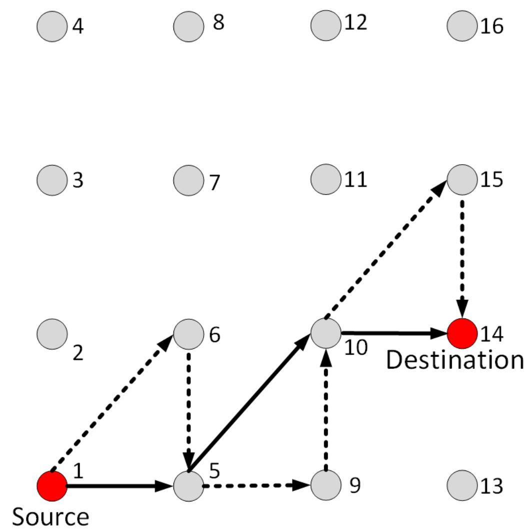


Figure 2.8: Route chosen by the MPCR algorithm in a grid wireless network [34].

transmission mode is considered. Fig. 2.8 shows the route chosen by the MPCR algorithm in a grid regular network. MPCR assumes equal transmission power for both transmitter and relay nodes and uses an approximation to calculate the transmission power; therefore, it is considered a sub-optimal cooperative routing.

I. Minimum Power Selected Decode-and-Forward (MPSDF) [66] is a cooperative routing algorithm to save energy in WSNs. The algorithm starts with routes that have a small number of hops and forms a relationship between the minimum power of cooperative transmission and Bit Error Rate (BER) for each link in the route. MPSDF first selects the best possible relay node and establishes a one-hop cooperative route from the source node to the destination node. To select the best relay node, the relay candidates set a back-off time that is proportional to their BER. When the first back-off time expires, the corresponding relay node, which minimizes the BER of the one-hop route, is selected as the best relay. The relay node broadcasts a *Hello* packet to its source-destination pair to evaluate and monitor the performance of the links (therefore, it is a distributed cooperative routing). Second, if the BER of any link along the selected route is greater than a target BER, MPSDF improves the BER performance by selecting new relay nodes for failed links and recomputes the BER for these newly constructed cooperative transmission links. If the desired performance is achieved, the algorithm adjusts the transmission power to the minimum value. This step is repeated until the BER of all links in the route are equal to or smaller than the target BER. When this is achieved, the cooperative route is finalized. Starting with the minimum number of hops, which may not be necessary the optimal number of hops in the minimum-power route makes the algorithm a sub-optimal routing protocol.

J. Contention-aware Cooperative Routing (CCR) [64] maximizes the overall end-to-end throughput of the whole network, while taking contention relation between multiple links into consideration. CCR introduces a routing cost metric, namely contention-aware cooperative metric and applies an efficient search algorithm, such as Dijkstra or Bellman-Ford, to find the minimum cost path. To avoid contention, which may occur between different flows in the cooperative routing protocols, virtual nodes and virtual links are introduced. Virtual nodes and links support the concept of cooperative diversity and multi-node to node transmission under multiple-flows network scenario. As illustrated in Fig. 2.9, a set of nodes are defined to be a virtual node if all nodes in the set simultaneously receive a packet in the broadcast transmission and cooperatively send a packet to a destination node. A virtual link is a link in which the transmitter or receiver node is a virtual node. To calculate the path cost, a virtual link-based network connection-aware graph, G', is constructed by replacing nodes and links in the original network topology, G, with the virtual nodes and virtual links. The weight of an edge in the virtual link-based

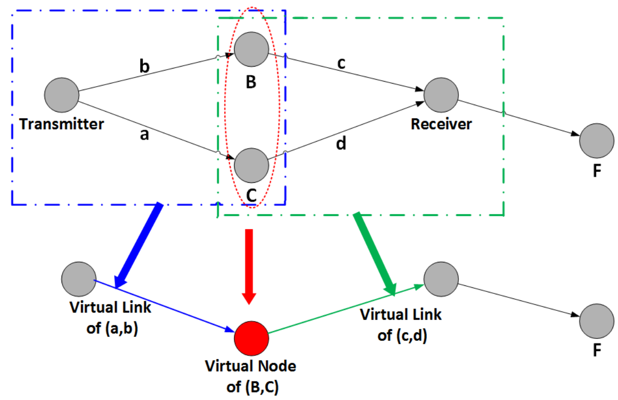


Figure 2.9: Virtual node and virtual link in CCR [64].

graph (G') is the power needed to transmit data along the edge. The information needed to construct the virtual link-based graph is collected by a central controller; therefore CCR is a centralized cooperative routing. Using Dijkstra's algorithm, in G', the shortest path (which minimizes power in the contention-aware graph) can be selected. CCR assumes equal transmission power for the transmitter and relay nodes in cooperative links; this implies that CCR is a sub-optimal cooperative routing protocol.

K. Probabilistic Cooperation (PC) and Equal Power Allocation (EP) [45] are two heuristic routing algorithms which are proposed to minimize the transmission power. In these algorithms, a two-stage cooperative model is used to send a message from a transmitter node, t_k, to a receiver node, r_k, as follows: (1) the transmitter node broadcasts the message to the nodes in its neighborhood with the broadcast transmission power and (2) each node that has successfully received and decoded the message will join the transmitter node to form a cooperative transmission set and will cooperatively transmit the message to the receiver node using the power allocation vector. In the PC algorithm, an approximate of the broadcast transmission power is computed in polynomial time. To estimate the broadcast transmission power (in the first stage), the probability that a node in a transmitting set will participate in the second stage is equal to the probability that the received message is detectable, taking channel fading into account. This results in a probabilistic transmitting set that includes all nodes in the network, each with a certain grade of membership which can be considered as the average probability that t_i participates in the transmitting set over a long period of time. The signal transmitted by t_i is scaled by the membership grade of t_i and yields the received signal at r_k. The PC algorithm is executed in a centralized manner. The EP algorithm is similar to the PC algorithm, except that it is a distributed algorithm that incorporates the equal power allocation of the PC algorithm. After the broadcast phase, the cooperative set is formed and equal power is allocated to nodes in the cooperative transmission set.

L. Cooperative Communication (CC-OPT) [71] achieves minimum power cost with a specific packet error rate between any two nodes. The algorithm is applied in WSNs, where the major concern is achieving minimum power cost with the desired quality of service. CC-OPT is a centralized cooperative routing (because the destination node has knowledge of all nodes in the network) and is implemented in two levels: hop level and network level. First, at the hop level, a power allocation approach is proposed to calculate the per hop power cost either in the direct or cooperative links (whichever consumes lower transmission power). In each cooperative link, a relay node is assumed to be the nearest node to the midpoint of the distance between the transmitter and the receiver node. After eliminating unnecessary combinations, the optimal power level of the transmitter and relay nodes is obtained by evaluating $2M$ combinations of the transmitter and relay node transmission power (M denotes the number of levels for transmission power). Second, at the network level, the minimum power cost is determined by numerically solving a cross-layer optimization problem. The optimal route from the source node to the

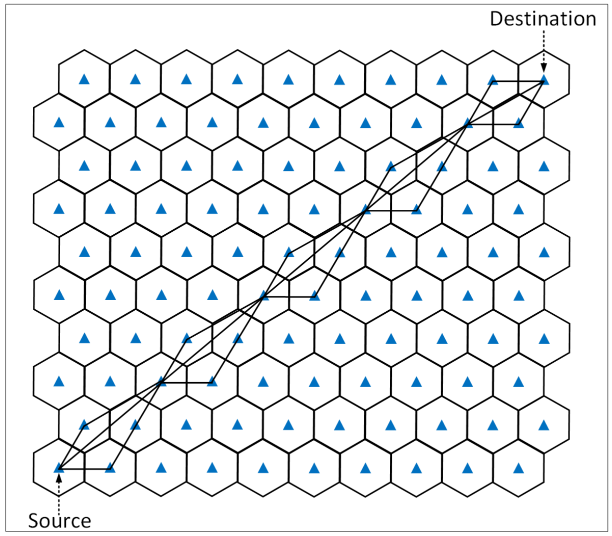


Figure 2.10: Wireless mesh network of base stations [37].

destination node is a combination of multiple direct communication hops and cooperative communication hops. Due to assigning the relay node as the nearest node to the middle point and assuming constant transmission power, CC-OPT is a sub-optimal cooperative routing algorithm.

M. Power Aware Cooperative Routing (PACR) [37] is a distributed cooperative routing that takes the active radio electronic power into account while constructing the route that consumes minimum-power to transmit a message from a source to its destination node. PACR is mainly proposed for cooperative routing in cellular wireless mesh networks. The algorithm is applied to a wireless mesh network consisting of a large number of cellular base stations (BS) and each BS has a single omnidirectional antenna. Fig. 2.10 shows this scenario where a source BS sends data to a destination BS and the algorithm finds a cooperative route between source and the destination with minimum power consumption. In this algorithm, a source node selects its l neighboring nodes, but it does not transfer

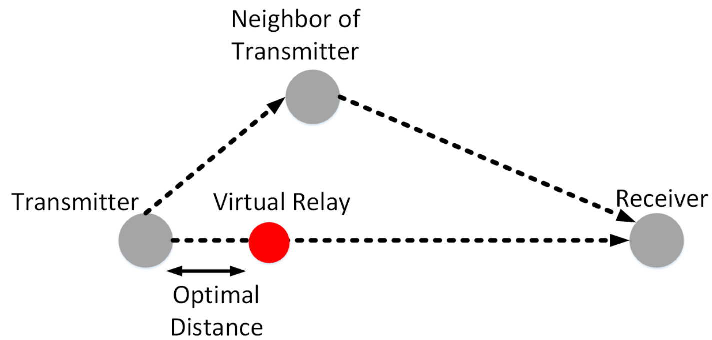


Figure 2.11: Optimal distance in PACR when $l = 1$ [37].

any data to these nodes. Instead, it uses their location information to calculate an optimal transmission distance for cooperative communication. This optimal distance, as shown in Fig. 2.11, depends on: (1) the location of adjacent nodes, (2) the distance between the source and the destination node, (3) the active radio electronics power consumption, and (4) the transmission power consumption. Thus, a virtual node is placed between the source and the destination node, at the optimal location. In other words, a group of cooperative nodes, $l+1$ nodes, are modelled as a single super-node (or a virtual node). It is assumed that each of the transmitting nodes adjusts its phase with respect to the super-node, such that all the nodes appear to be at the same distance from the destination node. The power allocation for each cooperative link (i.e, cooperative group which includes $l+1$ nodes) is obtained using the target SNR at the destination node, subject to the successful decoding, employing the Lagrangian Multipliers method [93]. However, equal power is allocated to each node in a cooperative group; therefore, it is a sub-optimal cooperative routing algorithm.

N. Lifetime Maximization Cooperative Routing with Truncated ARQ (LMCRTA) [72] maximizes the wireless sensor network lifetime with the constraints of link symbol error rate and network throughput in a distributed manner. In order to exchange the residual energy and topology information, the algorithm broadcasts *Hello* packets periodically, with a fixed transmission power, between neighboring nodes. Through measuring the average energy strength of the *Hello* packets, the channel characteristics between each node, i, and its neighboring nodes (e.g., node j) are evaluated. As a result, a two-dimensional adjacency matrix, which includes the channel variance and the residual energy of the neighbors, is formed for each node i. By exchanging the adjacency matrix contained in the $Hello$ packets with any neighbor, j, a transmitter node, i, can abstract a list of the common nodes that lie in the intersected transmission area of node i and j. If no common neighbors exist between i and j, the non-cooperative link cost is used to calculate the optimal power. Otherwise, the cooperative mode is used to compute the link cost. If there is more than one relay node candidate in the overlapping transmission area of node i and j, the node with the minimum path cost is selected. This algorithm can be implemented by using the Bellman-Ford shortest path algorithm in a distributed manner [89]. As can be seen in Fig. 2.12, for a given source-destination pair (S, D), the selected route of the LMCRTA algorithm is a series of non-cooperative and cooperative links. The non-cooperative link is represented by (S, A), whereas the cooperative link is denoted as (A, R, D), where A, R and D represent the transmitter, relay and receiver, respectively. The data transmission and retransmission are run on the built route, which is regulated by the truncated ARQ protocol in the data link layer. The LMCRTA algorithm allocates equal transmission power to the transmitter and relay nodes; therefore, LMCRTA belongs to the sub-optimal cooperative routing category.

O. Proteus [73] is a distributed cooperative routing protocol that includes a solution for two crucial issues to improve throughput in the cooperative routing. These issues are:

(1) the number of cooperative transmitter nodes for each link and (2) the cooperative strategy used by the transmitter nodes. This algorithm is divided into three steps for the route discovery phase. In the first step, a Route Request (RREQ) packet is transmitted by the source node. Similar to the route request packets in conventional routing (e.g., [94]), nodes stamp their IDs on the RREQ packets. In addition to the ID, each node stamps the following information on the RREQ packets: (a) the received signal strength from the previous hop, (b) the neighboring list containing the number of links overheard by each neighboring node, (c) the ambient interference level (determined by the duration of time that the channel is busy), and (d) the number of flows that are already served by the node. The second step involves the route response; once the destination node receives the route request, it transmits the Route Response Packet (RREP) after attaching the information about its neighbor nodes. Intermediate nodes forward the packet as usual; however, when any of their statistics change, they adjust it on the route response packet. In the third step, once the source receives the route response, it uses the statistics available in the packet to obtain the routing throughput. Within a time-out duration, the source node gathers the received information of k paths, where k is a predetermined constant. The source calculates the path throughput metric for a different number of cooperative transmitter nodes (relay nodes) and for different cooperative schemes, and then selects the route with the best metric. In the Proteus algorithm, the fixed equal transmission power is allocated to nodes along cooperative route (either relay or transmitter node); therefore, it is not optimal cooperative routing. Moreover, the algorithm only focuses on the route-discovery step of the routing protocol. Other components such as forwarding are similar to the Dynamic Source Routing protocol (DSR) [95], which is an on-demand routing protocol. However, the source route packet consists of the number of relay nodes

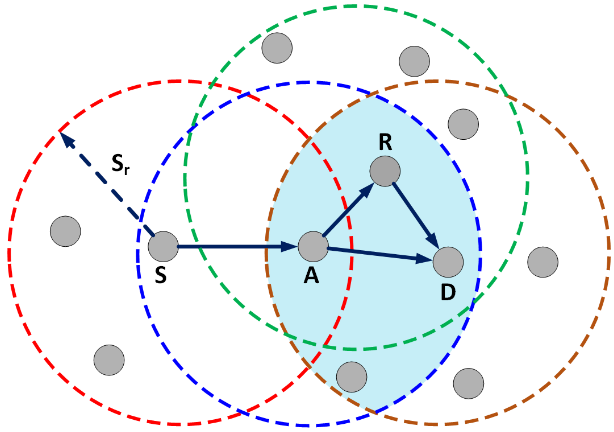


Figure 2.12: Non-cooperative and cooperative links as building blocks for a route from S (source node) to D (destination node). R is selected as a relay node for the cooperative link, and S_r is the communication range. The shadow region is the intersected communication area of A and D [72].

and the schemes to be used, in addition to the IDs of intermediate nodes.

P. Branch-and-Bound Framework Augment with Cutting Plane (BB-CP) [68] aims to maximize the minimum flow rate among all active sessions via an optimal multi-hop cooperative routing. BB-CP formulates the problem of optimal routing in a mixed-integer linear program (MILP) and proposes a solution procedure based on a branch-and-bound framework augmented with cutting planes (BB-CP) [96]. The BB-CP algorithm includes a series of iterative steps, as described below. In the first step, a relaxed mixed integer linear program (MILP) is solved in a polynomial form to achieve an upper bound. However, the relaxed solution is not able to determine whether an available relay node will be used or if a link is active in the solution. The Feasible Solution Construction (FSC) algorithm, which is a local algorithm, is proposed to address this problem. The FSC algorithm leads to a lower bound on the objective value. If the gap between the upper and lower bounds is greater than a predetermined value, ϵ, linear constraints, namely cutting planes, will be added and the relaxed linear programming will be solved again. Cutting planes improve the values of the upper and lower bounds, reducing the feasible region of the relaxed problem. Then, the improved upper bounding solution that is obtained from this relaxed solution is used in the local FSC algorithm to achieve a new feasible (possibly improved) lower bounding solution. A number of cutting planes are added to the relaxed problem until the improvements (of upper and lower bound) are within the certain percentage of threshold, i.e, further improvement in upper and lower bounds becomes marginal. When this certain threshold is met, adding more cutting planes does not improve the bounds and the problem is partitioned into two sub-problems. As the last step of the iteration, the relaxed versions of the two sub-problems are solved and the upper and lower bounds for each sub-problem are obtained using the FSC algorithm. After each iteration, if the gap between the largest upper bound and the largest lower bounds (among all the sub-problems) is greater than ϵ, a similar iterative step is performed on the sub-problem having the largest upper bound. After each iteration, the total number of sub-problems is increased because the chosen sub-problem is partitioned into two sub-problems. BB-CP presents the optimal cooperative routing techniques based on the centralized approach.

Q. Energy Efficient Cooperative Routing in Wireless Sensor Networks [63], which we call *EECRWSN* in this paper, is designed to minimize the total energy consumption in the WSNs. This work proposes a framework for formulation of the optimal relay node selection and power allocation, which leads to a mixed integer linear programming problem. The binary variables are used in this framework to re-express the logical statements as linear relations which contain both linear and binary variables. For instance, binary variable δ_k is used for each neighboring node, k, to show whether the received signal in the neighboring node is greater than prescribed threshold. If the condition is met, i.e., this node will be engaged in cooperative transmission, then $\delta_k = 1$; otherwise, $\delta_k = 0$. The required computational complexity of the algorithm to solve these problems grows exponentially with the number of binary variables; therefore, it may be prohibitive to implement it on the simple hardware utilized in wireless sensor networks. In order to solve this problem, the multi-parametric programming is invoked [97]. Through the use of multi-parametric programming techniques the infinite size problem is decomposed into a number of finite size problems. Multi-parametric programming makes the proposed strategy a low-complexity implementation method. The low-complexity implementation method obtains a solution as a function of the parameters of the network. This solution is calculated off-line, and is saved on the memory chip of every sensing node; therefore, the on-line computation is reduced to the evaluation of the parametric functions. In this work, the optimal routing is obtained and it is shown that for a specific configuration, the proposed framework selects the best set of relaying nodes, as well as the optimal transmission power for broadcasting and cooperative transmission.

2.9 Performance and Challenges of Cooperative Routing

Table 2.1 compares some of the most significant cooperative routing algorithms according to the taxonomy we described in Section 2.4. It is clear from Table 2.1 that most of the proposed algorithms are sub-optimal. Sub-optimal cooperative routing algorithms are simpler to obtain, while their performance is slightly lower than the optimal one (as

Table 2.1: Classification of Cooperative Routing Protocols in the Taxonomy

	Optimality			Centralization		Objective	
Routing Protocol	**Cooperative Along Non-Cooperative Path**	**Cooperative-Based Path**	**Optimal Routing**	**Distributed**	**Centralized**	**Energy-Efficient**	**QoS-Aware**
CAN-L [42]	✓				✓	✓	✓
MTE-m [43]	✓			✓	✓	✓	✓
FA-m [43]	✓			✓	✓	✓	✓
CASNCP [34]	✓			✓		✓	✓
TOCR [59]	✓			✓		✓	
CLCR [67]	✓			✓			✓
DCMPR [69]	✓				✓	✓	✓
EBCR [70]	✓				✓	✓	✓
MPCR [34]		✓		✓		✓	✓
CSP [47]		✓			✓	✓	✓
MPSDF [66]		✓		✓		✓	✓
CCR [64]		✓			✓		✓
EEDCR [65]		✓		✓		✓	
PC [45]		✓			✓	✓	✓
EP [45]		✓		✓		✓	✓
CC-OPT [71]		✓			✓	✓	✓
PACR [37]		✓		✓		✓	✓
LMCRTA [72]		✓		✓		✓	✓
Proteus [73]		✓		✓			✓
BB-CP [68]			✓		✓		✓
EECRWSN [63]			✓	✓		✓	✓

shown in [63]). In sub-optimal cooperative routing algorithms, if the underlying path is a non-cooperative route (i.e., in *Cooperation Along Non-cooperative Path* category), the cooperative routing efficiency is further degraded. Table 2.1 also shows that the majority of cooperative routing algorithms are distributed ones. Additionally, it is also evident that the main objective of cooperative routing is to save energy while guaranteeing a certain QoS. This is understandable because most of the applications of wireless networks are energy constrained; therefore, energy consumption and network lifetime are the main concerns in deployment of several applications of wireless networks, such as mobile ad

Table 2.2: Summary and Comparison of Cooperative Routing Protocols

Routing Protocol	Routing Metric	Complexity	Num. of Relays	Power Allocation	Num. of Flows	Scalability	Protocol Overhead	Application
CAN-L [42]	Required Power	$O\left(N^2\right)$	Multiple ($= L$)	Optimal Power	Single	Limited	Low	Not Specified
MTE-m [43]	Consumed Energy	$O\left(N^2\right)$	Multiple ($= m$)	Optimal Power	Single	Good	Moderate	WSN
FA-m [43]	Lifetime	$O\left(N^2\right)$	Multiple ($= m$)	Optimal Power	Single	Good	Moderate	WSN
CSP [47]	Consumed Energy	$O\left(N^2\right)$	Multiple	Optimal Power	Single	Limited	Low	All WN
CASNCP [34]	Required Power	$O(NM)^1$	Single	Sub-Optimal Power	Single	Good	Moderate	Not Specified
TOCR [59]	Throughput	$O\left(N^2 logN\right)$	Single	Equal Power	Single	Good	Moderate	Ad hoc Network
CLCR [67]	Throughput	$O(2N)$	Single	Optimal Power	Single	Good	High	Vehicular Network
DCMPR [69]	Consumed Energy	$O\left(N^3\right)$	Multiple	Optimal Power	Single	Limited	Low	Multimedia SN
EBCR [70]	Consumed Energy	$O\left(N^3\right)$	Multiple	Optimal Power	Single	Limited	Low	Ad hoc Network
MPCR [34]	Power Consumption	$O\left(N^3\right)$	Single	Sub-Optimal Power	Single	Good	Moderate	Not Specified
MPSDF [66]	Power Consumption	$O\left(N^2\right)$	Multiple	Optimal Power	Single	Good	Moderate	WSN
CCR [64]	Throughput	$O\left(N^2\right)$	Multiple	Sub-Optimal Power	Multiple	Good	Moderate	Mesh Network
EEDCR [65]	Consumed Energy	$O\left(N\Delta(h)2^{\Delta(h)}\right)^2$	Multiple	Optimal Power	Single	Good	Moderate	Ad hoc Network
PC [45]	Power Consumption	$O(N)$	Multiple	Optimal Power	Single	Limited	Moderate	Not Specified
EP [45]	Power Consumption	$O(1)$	Multiple	Sub-Optimal Power	Single	Good	Low	Not Specified
CC-OPT [71]	Power Consumption	$O\left(N^3\right)$	Single	Sub-Optimal Power	Single	Limited	Low	WSN
PACR [37]	Power Consumption	$O(Nl)^3$	Multiple (Single Virtual)	Equal Power	Single	Good	Moderate	Cellular Network
LMCRTA [72]	Lifetime	$O\left(N^2\right)$	Multiple	Equal Power	Single	Good	High	WSN
Proteus [73]	Throughput	$O(F)^4$	Multiple	Equal Power	Multiple	Good	High	Not Specified
BB-CP [68]	Flow Rate	$O\left(2^N\right)$	Multiple	Optimal Power	Single	Limited	Moderate	Not Specified
EECRWSN [63]	Energy Consumption	$O\left(2^N\right)$	Multiple	Optimal Power	Single	Good	Moderate	WSN

[1] M is the number of power levels.
[2] h is the number of hops between source and the destination node and $\Delta(h)$ is the degree of a graph which connects source node to the destination node and exists a path of at most h hops from source to destination node in that graph.
[3] l is the number of neighbors that their location information is used to find the optimal distance in PACR.
[4] F is the number of flows in the network.

hoc networks (in [74, 75]), sensor networks (in [76]), and personal area networks ([77]).

Performance analysis given in most papers show that cooperative routing algorithms outperform the corresponding non-cooperative routing ones even if the cooperative routing algorithm is sub-optimal. For instance, in [42], CAN-L can achieve energy savings of approximately 50% compared to non-cooperative routing. The MTE-m algorithm, in [43], increases the network lifetime by 1 to 3.5 times compared to non-cooperative routing. Power saving of MPCR, in [34], with respect to non-cooperative routing is 65%.

In the simulation results in [34], comparing MPCR and CASNCP shows that, at $N = 100$ (where N is the number of nodes in the network), the power saving of the MPCR is 65.61% when compared to the CASNCP. This result verifies that the algorithms in the *Cooperative-Based Path* category outperform the *Cooperative Along Non-Cooperative Path* algorithms. Moreover, Habibi *et al.* in [63] compared BER of EECRWSN to MPCR with consistent assumptions and similar framework. The results reveal that EECRWSN, which constructs the *Optimal Routing*, significantly outperforms the MPCR algorithm. In addition to this, the network lifetime of MPSDF [66] is compared to MPCR in [66] and the results show that MPSDF slightly outperforms MPCR because MPCR acts as a direct transmission when the link BER is small.

Simulation results obtained in [47] show that the CSP algorithm, saves more energy compared to CAN-L [42], by a margin of 10% with the same settings. This is because the calculated cost function of the link in CSP is based on the minimum transmission power in cooperative links (i.e., *Cooperation-Based Path selection*), while in CAN-L the cost function is the transmission power of non-cooperative links (i.e., *Cooperation Along Non-cooperative Path*). Simulation results in [47] also reveal that as more nodes along the path are allowed to cooperatively transmit the packet to the next hop (i.e., a larger value of L) both CAN and CSP achieve more power-savings compared to the non-cooperative path.

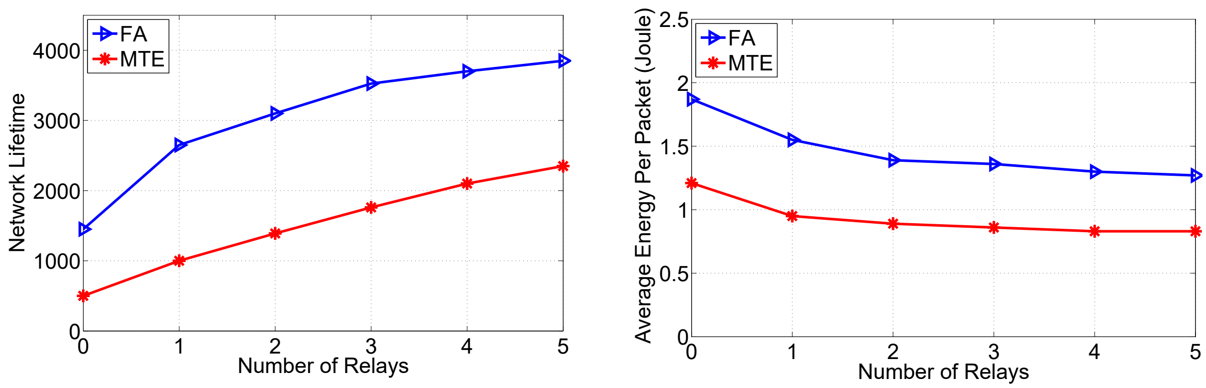
An interesting comparison between distributed cooperative routing and centralized schemes has been introduced in [69]. Comparing CMPR and Distributed CMPR (DCMPR) demonstrates that both algorithms construct the same cooperative route on a given topology. However, DCMPR is slightly more complex than CMPR; the computational complexity of CMPR is $O\left(N^2 \log N\right)$, whereas it is $O\left(N^3\right)$ in DCMPR.

Based on the above discussion, Table 2.2 presents a comparative summary of the parameters and main features of the routing protocols. The features of each protocol include the following:

- Routing Metric: The most commonly used cooperative routing metric is the required transmission power and energy consumption. This is due to the importance of energy efficiency as the routing objective.

- Complexity: It is shown in the literature (such as [42, 69]) that the complexity of optimal cooperative routing algorithms grow exponentially with the number of nodes. As noted before, the sub-optimal cooperative routing algorithms have a lower complexity. The time complexity of the algorithms that are in the category of *Cooperation Along Non-cooperative Path* follows the computational complexity of the underlying non-cooperative path. For instance, TOCR in [59] has the same complexity as the AFCR algorithm, which is its underlying non-cooperative routing algorithm.

- Number of Relay Nodes: Single-relay cooperation is easier to implement and it causes less interference and overhead compared to the multi-relay schemes. However, simulation results show that multi-relay cooperation outperforms single-relay cooperation in energy efficient schemes. For instance, the simulation results of the MTE-m and FA-m algorithms in [43], are shown in Fig. 2.13(a) and (b) for a network consisting of 36 nodes, which are uniformly deployed in a $100 \times 100\ m^2$ area with randomly-selected source and destination nodes. In this network, the packet arrival follows the Poisson distribution, with a packet arrival rate of one packet per second. Fig. 2.13(a) compares the network lifetime (measured in terms of simula-



(a) (b)

Figure 2.13: Routing performance versus the number of relay nodes. (a) Network lifetime (measured in terms of simulation time step) versus number of relay nodes, (b) Average energy per packet versus number of relay nodes [43].

tion time step), which is defined as the time before the first node dies. Fig. 2.13(b) compares the average energy per packet, which is the total energy consumed per delivered packets. As shown in the figure, for the given topology, higher energy saving and longer network lifetime are achieved when a larger number of relay nodes are used in the cooperation.

- Power Allocation: The strategy of assigning fixed "Equal Power" to the transmitter and relay nodes is not optimal; however, the use of the equal power allocation simplifies the implementation. In contrast to "Equal Power", the term "Sub-optimal" power allocation in Table 2.2 is defined as the case that the equal power is allocated to the transmitter and relay nodes of a cooperative link; nevertheless, optimal power is allocated to each cooperative link (i.e., in each link the optimal power is allocated equally to the transmitter and relay nodes). The optimal and sub-optimal power allocation techniques are compared in [45]. Simulation results show that the optimal power allocation used in the PC algorithm outperforms the sub-optimal power allocation in EP. It is shown that the average energy savings range from 8% to 57% for PC compared to EP.

- Number of Flows: The cooperative routing algorithms proposed in [61, 64, 73], and [98] are the only cooperative routing protocols that address the collision problem caused by the interaction between multiple flows in the network. The proposed algorithm [64] avoids collision caused by the hidden and exposed node problem by defining a new concept of virtual nodes and virtual links. Simulation results in Proteus [73] show that cooperative routing leads to a significant reduction in the interference between multiple flows; therefore, the throughput of cooperative routing improved over the non-cooperative path by a factor of 3.

- Scalability: The distributed cooperative routing algorithms, such as CLCR [67], MPCR [34], and MPDDF [66] scale well with the network size. As the number of users increases, the amount of the information that needs to be exchanged increases, and the computational complexity required to find the optimal resource allocation and relay node selection, significantly increases; therefore, the centralized approach becomes challenging. We define the scalability "Limited" in Table 2.2, if the corresponding algorithm is either centralized or computationally complex for the large network size. The scalability of the algorithm is "Good" if it is distributed and the computational complexity does not grow too fast with the number of nodes in the network. For instance, in the PC algorithm [45], the optimal power allocation requires a central controller; therefore, the PC algorithm does not scale well with the network size. In contrast to the PC algorithm, the EP algorithm (also in [45]) is proposed with the equal power allocation; hence, EP is a distributed algorithm and scales well with the network size.

- Protocol Overhead: Dealing with the overhead caused by controlling messages for relay selection, channel estimation, power allocation, and route selection is challenging in cooperative routing algorithms. We define overhead as "High" if the corresponding algorithm has a large number of controlling messages and involves frequent refreshing. Overhead is defined as "Medium" if the algorithm has a large number of control messages and does not require refreshing frequently. Overhead is defined as "Low" if the algorithm has a limited number of controlling messages which rarely get updated. Simulation results in [72] show that the overhead of LMCRTA is higher than that of the MTE-m and FA-m in [43], with the same throughput requirement. Moreover, in CLCR [67], which is a cooperative routing algorithm for vehicular networks, the dynamic features of the network cause overhead by frequent relay node reselection. In other words, in CLCR, the routing overhead is incurred to keep the relay nodes connected or to reselect the best relay nodes in each transmission time.

- Applications: The main application of cooperative routing is in power-limited networks, such as WSNs and ad hoc networks, because energy saving is the main objective of cooperative routing in the literature, such as [66]. Cooperative routing is also applied to vehicular networks in [67] to overcome the unreliability of the wireless channels and to maximize the system throughput.

In the following subsections, we present the most dominant and important factors which challenge effective cooperative routing.

2.9.1 Complexity

Finding the optimal cooperative routing in a large arbitrary wireless network is computationally intractable. Cooperative routing in wireless networks exploits the broadcasting nature of the wireless medium in designing the cooperative routing. The source node broadcasts its information to the relay(s) and the next-hop node in a route. Due to the omni-directional nature of the wireless broadcasting, the number of possible cooperative paths is large. The hardness of finding the optimal cooperative routing can be proved using the concept of broadcasting trees and a cooperative path can be mapped as a broadcasting tree. A broadcasting tree is a spanning tree rooted at one source node to reach all other nodes [99]. In [100], for a given source-destination pair with N nodes in the network, the number of possible broadcasting trees from the source node to the destination node with zero transmitters and zero relaying nodes (i.e., only the source node is transmitting the packet) is given by

$$R\,(0) = \binom{N}{N} = 1, \tag{2.5}$$

The number of possible broadcasting trees with one relay node is given by

$$R\,(1) = \binom{N}{1} \sum_{i=1}^{N-1} \binom{N-1}{i}, \tag{2.6}$$

the above formula means that we first need to pick one node as the relay node and then decide how many nodes are reached directly by the relay node (the remaining nodes are directly reached by the source node). The case of possible broadcasting trees with two relay nodes is more complicated and is given by

$$R\left(2\right)=\binom{N}{2}\sum_{i=1}^{N-2}\left(\binom{N-1}{i}\sum_{j=1}^{N-2}\binom{N-1-i}{j}\right), \tag{2.7}$$

and so on; therefore, the number of possible broadcasting trees with i relay nodes is given by

$$R\left(i\right)= \tag{2.8}$$
$$\binom{N}{i}\sum_{k_1=1}^{N-i}\left(\binom{N-1}{k_1}\sum_{k_2=1}^{N-1}\left(\binom{N-1-k_1}{k_2}\right.\right.$$
$$\left.\left....\sum_{k_j=1}^{N-i}\left(\binom{N-1-\sum_{j=1}^{i-1}k_j}{k_i}\right)\right)...\right).$$

The above formula means that we first need to pick i nodes as the relay nodes with a number of possible of $(\binom{N}{i})$ and then decide how many nodes are reached directly by the relay node (the remaining nodes are directly reached by the source node). Therefore, the total number of possible broadcasting trees in the network is given by

$$T=\sum_{i=0}^{N-1}R\left(i\right). \tag{2.9}$$

For example, for $N=15$ (15 nodes in the network), the number of broadcasting trees is more than 8.7 billion [100]. The equations and discussion above imply that the number of cooperative routes grows very fast with the number of nodes in the network. Therefore, when employing the concept of broadcasting trees, the problem of finding the optimal feasible cooperative route out of all possible routes has proven to be *NP-hard* [101].

In [47], where the optimal cooperative routing is the minimum energy cooperative routing, the authors proved that finding the minimum energy cooperative routing is *NP-hard*. To prove the *NP-hardness* of finding the minimum energy cooperative routing in [47], the combinatorial approach (for picking the relay node(s) in broadcast trees) and Travelling Salesman Extension problem (described in [102] to select the feasible route) are employed. Utilizing the TSE problem, the problem of minimum energy cooperative route from the source node to the destination node, with a specific number of relay nodes, is mapped to a 'minimum-distance tour' between source and destination 'cities' covering all other N cities with specific number of relaying cities. NP-hardness of TSE problem demonstrates that the problem of finding minimum energy cooperative routing is *NP-hard* [100].

In addition to the methods used above, the authors in [103] mapped the problem of finding the minimum energy routing to the knapsack and proved the hardness of selecting the route with minimum energy consumption, when cooperation is involved. Khandani *et al.* in [42] utilized a cooperative graph to prove the hardness of minimum energy cooperative routing. The authors demonstrated that, in a network with N nodes, standard shortest path algorithms have a complexity of $O\left(2^{2N}\right)$.

Furthermore, the problem of determining a maximum throughput cooperative route is mapped to the problem of determining a maximum *independent* set of nodes in the network [73]. Identifying a maximum independent set of nodes with the choice of the relay nodes, which leads to more possibilities and expanded options, is proved to be *NP-hard* in [73].

2.9.2 Multiple Flows

Interactions among multiple neighboring flows may lead to the hidden and exposed terminal problems [104]. Cooperative routing introduces new aspects to the typical hidden and exposed problems in wireless networks. A relay node in a cooperative route not only receives packets from the transmitter node, but also forwards the packets to the destination node. Thus, the transmissions from neighbors of the relay nodes should also be carefully scheduled to avoid collisions caused by the hidden and exposed node problems. Therefore, the gain of a cooperative routing algorithm with multiple flows is different from the one with a single flow. To deal with the collision problem in wireless networks with multiple flows, the concept of virtual nodes is introduced in [64]. Using virtual nodes, a virtual network topology is constructed and cooperative routing is designed in the new topology to avoid collision in the wireless network.

2.10 Conclusion and Future Work

In this paper, we have presented a comprehensive review of the existing cooperative routing protocols. The main challenges associated with optimal route selection and the design requirements of cooperative routing protocols are discussed to provide an insight into the objectives of routing protocols. An accurate classification of the protocols is given and the merits and disadvantages of the protocols are determined.

Despite the large number of research activities and the rapid and significant progress that being made in cooperative routing in recent years, numerous avenues for further research remain. The following research issues are outlined for future investigation:

- Multiple Sources and Multiple Destination nodes: To date, most of the proposed cooperative routing techniques are designed for sending data from a single source node to a single destination node (as in unicasting mode). There are only a few routing algorithms, such as those in [61, 98], that consider networks with multiple sources and multiple destination nodes. In multiple source and multiple destination networks, contention among nodes may lead to the packet collision. Therefore, in a network with multiple source and multiple destination nodes, different network considerations may be required to avoid packet collision. Designing efficient cooperative routing techniques to minimize packet collision probability is an emerging area for exploration.

- Multiple Objectives: While offering a single objective supports one goal, routing algorithms should be flexible to support various application-specific requirements, such as throughput, capacity, coverage, end-to-end delay, real-time delay, and collision. So, designing flexible cooperative routing protocols with multiple cost functions to optimize multiple objectives can be reckoned as an interesting area for future research.

- Multi-constrained QoS guarantee: Cooperative routing algorithms should be flexible enough to support different application-specific QoS requirements, such as outage probability, end-to-end delay, delay jitter, and bandwidth consumption. Thus far, outage probability has been the main QoS requirement considered in cooperative routing algorithms. Although diverse QoS constraints need to be considered, satisfying some QoS metrics in certain wireless networks is in contradiction with achieving other constraints or objectives. For instance, in vehicular ad hoc networks, satisfying QoS is in contradiction with achieving more energy efficiency [66]. Therefore, designing a flexible cooperative routing with adaptive cost functions to provide multi-constrained QoS guarantee is viewed as an interesting area for future investigation.

- Nodes Mobility: Almost in all proposed cooperative routing algorithms, the nodes are assumed to be static. Recently, there has been an increased interest in the applications that support the mobility of users, such as cellular networks and Vehicular Ad Hoc Networks (VANET). An example for this application is the medical-care application, where the mobile wireless network nodes are attached to the patients and need to send continuous data from the patient to the doctor. There is only one cooperative routing protocol that covers mobility (i.e., [67]) and there is much potential for future research in this area. On the other hand, mobility can pose some challenges in cooperative protocol design, such as dynamic relay node assignment methods.

- Security: It has been shown in the literature that the appropriate design of cooperative routing can extend the coverage and improve the performance of the network. However, the security issues raised by increasing the network coverage and allowing nodes to manipulate the signals of other nodes at the signal level (e.g., signal detection by the DF relays and signal combining at each receiving node) are not well-studied. Secure routing is an issue that needs further attention. Moreover, although security was not an objective in the design of recent cooperative routing algorithms, it is important to analyze the performance of these algorithms when security concerns are incorporated.

- Energy Harvesting (EH): Energy is harvested using solar, vibration, and other physical phenomena [105]. EH nodes harvest energy from the environment to carry out their communication tasks. Use of energy harvesting nodes as the relay nodes in cooperative diversity is proved to be a promising and emerging solution in energy-limited wireless networks [106, 107]. However, none of the proposed cooperative routing algorithms are energy harvesting aware.

- Applications: Although there has been extensive work on employing cooperative routing in WSNs, there have been very few works that consider cooperative routing in other network applications, such as delay-sensitive applications and bandwidth-limited applications. Therefore, potential applications of cooperative routing, such as cognitive radio networks, LTE networks, wireless LANs, and cellular networks are an interesting area for future investigation.

- Implementations: Most of the cooperative routing algorithms surveyed in this paper have been evaluated through theoretical analysis and simulation; only one proposed algorithm, namely EERWSN [63], deals with the practical aspects of cooperative routing. The authors in [63] used parametric programming in an off-line manner to reduce the computational requirements for the sensor nodes to very simple operations during network functioning. Further investigation and improvements to the current implementation approaches are identified as an area for future work.

- Optimal Cooperative Route: Due to the computational complexity of the present optimal cooperative routing algorithms, discovering an optimal routing which requires lower complexity still is an interesting open area for research. The optimal cooperative route employs the optimal approaches in the relay node selection, resource allocation, and route selection jointly.

REFERENCES

[1] J. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[2] A. Ibrahim, A. Sadek, W. Su, and K. Liu, "Cooperative communications with relay-selection: when to cooperate and whom to cooperate with?" *IEEE Trans. Wireless Commun.*, vol. 7, no. 7, pp. 2814–2827, July 2008.

[3] ——, "Cooperative communications with partial channel state information: When to cooperate?" in *Proc. IEEE Global Telecommunications Conference, (GLOBECOM)*, vol. 5, Dec. 2005, pp. 3068–3072.

[4] R. Madan, N. Mehta, A. Molisch, and J. Zhang, "Energy-efficient cooperative relaying over fading channels with simple relay selection," *IEEE Trans. Wireless Commun.*, vol. 7, no. 8, pp. 3013–3025, Aug. 2008.

[5] W. Zhuang and M. Ismail, "Cooperation in wireless communication networks," *IEEE Trans. Wireless Commun.*, vol. 19, no. 2, pp. 10–20, Apr. 2012.

[6] A. Nosratinia, T. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[7] A. Akhtar, M. Nakhai, and A. Aghvami, “On the use of cooperative physical layer network coding for energy efficient routing,” *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1498–1509, 2013.

[8] Z. Zhou, S. Zhou, J.-H. Cui, and S. Cui, “Energy-efficient cooperative communication based on power control and selective single-relay in wireless sensor networks,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 8, pp. 3066 –3078, Aug. 2008.

[9] Y.-W. Hong, W.-J. Huang, F.-H. Chiu, and C.-C. Kuo, “Cooperative communications in resource-constrained wireless networks,” *IEEE Signal Process. Mag.*, vol. 24, no. 3, pp. 47–57, May 2007.

[10] A. Chakrabarti, E. Erkip, A. Sabharwal, and B. Aazhang, “Code designs for cooperative communication,” *IEEE Signal Process. Mag.*, vol. 24, no. 5, pp. 16–26, Sep. 2007.

[11] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. Panwar, “CoopMAC: A cooperative MAC for wireless LANs,” *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 340–354, Feb. 2007.

[12] S. Valentin, H. Lichte, D. Warneke, T. Biermann, R. Funke, and H. Karl, “Mobile cooperative WLANs - mac and transceiver design, prototyping, and field measurements,” in *Proc. IEEE 68th Vehicular Technology Conference (VTC)*, Sep. 2008, pp. 1–5.

[13] A. Azgin, Y. Altunbasak, and G. AlRegib, “Cooperative MAC and routing protocols for wireless ad hoc networks,” in *Proc. IEEE Global Telecommunications Conference, (GLOBECOM)*, vol. 5, Dec. 2005, pp. 2853–2859.

[14] H. Shan, W. Zhuang, and Z. Wang, "Distributed cooperative MAC for multihop wireless networks," *IEEE Commun. Mag.*, vol. 47, no. 2, pp. 126–133, Feb. 2009.

[15] M. Khalid, Y. Wang, I. ho Ra, and R. Sankar, "Two-relay-based cooperative MAC protocol for wireless ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 3361–3373, Sep. 2011.

[16] R. Khan and H. Karl, "MAC protocols for cooperative diversity in wireless LANs and wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. PP, no. 99, pp. 1–18, May 2013.

[17] S. Shankar N, C.-T. Chou, and M. Ghosh, "Cooperative communication MAC (CMAC) - a new MAC protocol for next generation wireless LANs," in *Proc. International Conference on Wireless Communications, Networking and Mobile Computing, (WiCOM)*, vol. 1, June 2005, pp. 1–6.

[18] R. Lin and A. Petropulu, "A new wireless network medium access protocol based on cooperation," *IEEE Trans. Signal Process.*, vol. 53, no. 12, pp. 4675–4684, Dec. 2005.

[19] "Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," *IEEE Std 802.11h*, 2003.

[20] Y. Chen, W. Yi, and Y. Yang, "Energy efficient cooperative communication for sensor networks: A cross-layer approach," in *Proc. IEEE Consumer Communications and Networking Conference (CCNC)*, Jan. 2011, pp. 793–797.

[21] L. Le and E. Hossain, “Cross-layer optimization frameworks for multihop wireless networks using cooperative diversity,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 7, pp. 2592–2602, July 2008.

[22] T. Aguilar, S.-J. Syue, V. Gauthier, H. Afifi, and C.-L. Wang, “Coopgeo: A beaconless geographic cross-layer protocol for cooperative wireless ad hoc networks,” *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2554–2565, Aug. 2011.

[23] J. Laneman, G. W. Wornell, and D. Tse, “An efficient protocol for realizing cooperative diversity in wireless networks,” in *Proc. IEEE Intl. Symp. on Information Theory*, June 2001, p. 294.

[24] M. Yu, J. Li, and H. Sadjadpour, “Amplify-forward and decode-forward: the impact of location and capacity contour,” in *in Proc. IEEE Military Communications Conference (MILCOM)*, vol. 3, Oct. 2005, pp. 1609–1615.

[25] S. Atapattu, Y. Jing, H. Jiang, and C. Tellambura, “Relay selection schemes and performance analysis approximations for two-way networks,” *IEEE Trans. Commun.*, vol. 61, no. 3, pp. 987–998, 2013.

[26] D. G. Brennan, “Linear diversity combining techniques,” *Proc. IEEE*, vol. 91, no. 2, pp. 331–356, Feb. 2003.

[27] M. H. Ahmed and S. S. Ikki, *To Cooperate or not to Cooperate That is the Question!* John Wiley & Sons, Ltd, 2011, pp. 21–33.

[28] A. Bletsas, A. Dimitriou, and J. Sahalos, "Interference-limited opportunistic relaying with reactive sensing," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, pp. 14–20, Jan. 2010.

[29] C.-J. Chen, "Multiuser diversity for antenna optimal combining in interference-limited systems," *IEEE Commun. Lett.*, vol. 12, no. 5, pp. 368–370, May 2008.

[30] M. Mohammadi, H. Suraweera, and X. Zhou, "Outage probability of wireless ad hoc networks with cooperative relaying," in *IEEE Global Communications Conference (GLOBECOM)*, Dec. 2012, pp. 4410–4416.

[31] P. Pathak and R. Dutta, "A survey of network design problems and joint design approaches in wireless mesh networks," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 3, pp. 396–428, June 2011.

[32] Y. Zhao, R. Adve, and T. J. Lim, "Improving amplify-and-forward relay networks: optimal power allocation versus selection," *IEEE Trans. Wireless Commun.*, vol. 6, no. 8, pp. 3114–3123, Aug. 2007.

[33] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[34] A. Ibrahim, Z. Han, and K. Liu, "Distributed energy-efficient cooperative routing in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3930–3941, Oct. 2008.

[35] B. Wang, Z. Han, and K. Liu, "Distributed relay selection and power control for multiuser cooperative communication networks using buyer/seller game," in *Proc. IEEE The 26th Conference on Computer Communications (INFOCOM)*, May 2007, pp. 544–552.

[36] X. He, A. Prasad, S. Sethi, and G. Gutierrez, "A survey of stackelberg differential game models in supply and marketing channels," *J. of Syst. Sci. and Syst. Eng.*, vol. 16, no. 4, pp. 385–413, 2007.

[37] A. Akhtar, M. Nakhai, and A. Aghvami, "Power aware cooperative routing in wireless mesh networks," *IEEE Commun. Lett.*, vol. 16, no. 5, pp. 670–673, May 2012.

[38] S. Astaneh and S. Gazor, "Resource allocation and relay selection for collaborative communications," *IEEE Trans. Wireless Commun.*, vol. 8, no. 12, pp. 6126–6133, Dec. 2009.

[39] A. Sadek, W. Su, and K. Liu, "Multinode cooperative communications in wireless networks," *IEEE Trans. Signal Process.*, vol. 55, no. 1, pp. 341–355, Jan. 2007.

[40] H. Al-Tous and I. Barhumi, "Joint power and bandwidth allocation for amplify-and-forward cooperative communications using stackelberg game," *IEEE Trans. Veh. Technol.*, vol. 62, no. 4, pp. 1678–1691, May 2013.

[41] E. Beres and R. Adve, "Optimal relay-subset selection and time-allocation in decode-and-forward cooperative networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 7, pp. 2145–2155, July 2010.

[42] A. Khandani, J. Abounadi, E. Modiano, and L. Zheng, "Cooperative routing in static wireless networks," *IEEE Trans. Commun.*, vol. 55, no. 11, pp. 2185–2192, Nov. 2007.

[43] C. Pandana, W. Siriwongpairat, T. Himsoon, and K. Liu, "Distributed cooperative routing algorithms for maximizing network lifetime," in *Proc. IEEE Wireless Communications and Networking Conference, (WCNC)*, Apr. 2006, pp. 451–456.

[44] F. Mansourkiaie, M. Ahmed, and Y. Gadallah, "Minimizing the probability of collision in wireless sensor networks using cooperative diversity and optimal power allocation," in *Proc. IEEE 9th International Wireless Communications and Mobile Computing Conference (IWCMC)*, July 2013, pp. 120–124.

[45] M. Dehghan, M. Ghaderi, and D. Goeckel, "Minimum-energy cooperative routing in wireless networks with channel variations," *IEEE Trans. Wireless Commun.*, vol. 10, no. 11, pp. 3813–3823, 2011.

[46] H. Goudarzi and M.-R. Pakravan, "Equal power allocation scheme for cooperative diversity," in *Proc. IEEE The 4th International Conference on Internet (ICI)*, Sep. 2008, pp. 1–5.

[47] F. Li, K. Wu, and A. Lippman, "Minimum energy cooperative path routing in all-wireless networks: Np-completeness and heuristic algorithms," *EURASIP J. Wirel. Commun. Netw.*, vol. 10, no. 2, pp. 204–212, June 2008.

[48] S. Draper, L. Liu, A. Molisch, and J. S. Yedidia, "Cooperative transmission for wireless networks using mutual-information accumulation," *IEEE Trans. Inf. Theory*, vol. 57, no. 8, pp. 5151–5162, Aug. 2011.

[49] D. Chen and J. Laneman, "Cooperative diversity for wireless fading channels without channel state information," in *Proc. IEEE The 38rd Asilomar Conf. on Signals, Systems and Computers*, vol. 2, Nov. 2004, pp. 1307–1312.

[50] H. Chen, M. Ahmed, and R. Venkatesan, "Performance analysis of cooperative-diversity wireless systems with adaptive modulation and imperfect channel state information," in *Proc. IEEE 7th Intl. Wireless Communications and Mobile Computing Conference (IWCMC)*, July 2011, pp. 1698–1703.

[51] M. Taghiyar, S. Muhaidat, J. Liang, and M. Dianati, "Relay selection with imperfect CSI in bidirectional cooperative networks," *IEEE Commun. Lett.*, vol. 16, no. 1, pp. 57–59, Jan. 2012.

[52] M. Seyfi, S. Muhaidat, and J. Liang, "Amplify-and-forward selection cooperation over rayleigh fading channels with imperfect CSI," *IEEE Trans. Wireless Commun.*, vol. 11, no. 1, pp. 199–209, Jan. 2012.

[53] G. Atia and A. Molisch, "Cooperative relaying with imperfect channel state information," in *Proc. IEEE Global Telecommunications Conference (GLOBECOM)*, Nov. 2008, pp. 1–6.

[54] C. Chekuri, C. Fragouli, and E. Soljanin, "On average throughput and alphabet size in network coding," *IEEE Trans. Inf. Theory*, vol. 52, no. 6, pp. 2410–2424, June 2006.

[55] D. Nguyen, T. Tran, T. Nguyen, and B. Bose, "Wireless broadcast using network coding," *IEEE Trans. Veh. Technol.*, vol. 58, no. 2, pp. 914–925, Feb 2009.

[56] Y. Wu, P. Chou, and S.-Y. Kung, "Minimum-energy multicast in mobile ad hoc networks using network coding," *IEEE Trans. Commun.*, vol. 53, no. 11, pp. 1906–1918, Nov 2005.

[57] L. Xiao, T. Fuja, J. Kliewer, and D. Costello, "A network coding approach to cooperative diversity," *IEEE Trans. Inf. Theory*, vol. 53, no. 10, pp. 3714–3722, Oct 2007.

[58] A. Argyriou and A. Pandharipande, "Cooperative protocol for analog network coding in distributed wireless networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 10, pp. 3112–3119, October 2010.

[59] L. Wang and K. Liu, "An throughput-optimized cooperative routing protocol in ad hoc network," in *3rd IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*, Oct. 2009, pp. 1255–1258.

[60] X. He and F. Y. Li, "Metric-based cooperative routing in multihop ad hoc networks,," *J. Computer Networks*, vol. 1, pp. 1–12, May 2012.

[61] F. Mansourkiaie and M. H. Ahmed, "Joint cooperative routing and power allocation for collision minimization in wireless sensor networks with multiple," Sep. 2014, accepted to IEEE Wireless Communication Letters.

[62] W. Yu, T. Kwon, and C. Shin, "Adaptive resource allocation in cooperative cellular networks," in *Cooperative Cellular Wireless Networks*, E. Hossain, D. I. Kim, and V. K. Bhargava, Eds. Cambridge University Press, 2011, ch. 9, pp. 233–258.

[63] J. Habibi, A. Ghrayeb, and A. Aghdam, “Energy-efficient cooperative routing in wireless sensor networks: A mixed-integer optimization framework and explicit solution,” *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3424–3437, Aug. 2013.

[64] J. Zhang and Q. Zhang, “Contention-aware cooperative routing in wireless mesh networks,” in *Proc. IEEE International Conference on Communications (ICC)*, June 2009, pp. 1–5.

[65] R. Madan, N. Mehta, A. Molisch, and J. Zhang, “Energy-efficient decentralized cooperative routing in wireless networks,” *IEEE Trans. Autom. Control*, vol. 54, no. 3, pp. 512–527, Mar. 2009.

[66] Z. Sheng, Z. Ding, and K. Leung, “Distributed and power efficient routing in wireless cooperative networks,” in *Proc. IEEE International Conference on Communications (ICC)*, June 2009, pp. 1–5.

[67] W.-H. Chen, A.-C. Pang, A.-C. Pang, and C.-T. F. Chiang, “Cross-layer cooperative routing for vehicular networks,” in *Proc. IEEE International Computer Symposium (ICS)*, Dec. 2010, pp. 67–72.

[68] S. Sharma, Y. Shi, Y. Hou, H. Sherali, S. Kompella, and S. Midkiff, “Joint flow routing and relay node assignment in cooperative multi-hop networks,” *IEEE J. Sel. Areas Commun.*, vol. 30, no. 2, pp. 254–262, Feb. 2012.

[69] H. Xu, L. Huang, C. Qiao, Y. Zhang, and Q. Sun, “Bandwidth-power aware cooperative multipath routing for wireless multimedia sensor networks,” *IEEE Trans. Wireless Commun.*, vol. 11, no. 4, pp. 1532–1543, Apr. 2012.

[70] S. Chen, M. Huang, Y. Li, Y. Zhu, and Y. Wang, "Energy-balanced cooperative routing in multihop wireless ad hoc networks," in *Proc. IEEE International Conference on Communications (ICC)*, June 2012, pp. 307–311.

[71] L. Shi and A. O. Fapojuwo, "Cross-layer optimization with cooperative communication for minimum power cost in packet error rate constrained wireless sensor networks," *Ad Hoc Networks*, vol. 10, no. 7, pp. 1457 – 1468, 2012.

[72] C. Zhai, J. Liu, L. Zheng, H. Xu, and H. Chen, "Maximise lifetime of wireless sensor networks via a distributed cooperative routing algorithm," *Trans. Emerging Telecommun. Technol.*, vol. 23, no. 5, pp. 414–428, 2012.

[73] S. Lakshmanan and R. Sivakumar, "Proteus: Multiflow diversity routing for wireless networks with cooperative transmissions," *IEEE Trans. Mobile Comput.*, vol. 12, no. 6, pp. 1146–1159, 2013.

[74] V. Srinivasan, C. Chiasserini, P. Nuggehalli, and R. Rao, "Optimal rate allocation for energy-efficient multipath routing in wireless ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 3, no. 3, pp. 891–899, May 2004.

[75] W. Liang, "Minimizing energy and maximizing network lifetime multicasting in wireless ad hoc networks," in *Proc. IEEE International Conference on Communications (ICC)*, May 2005, pp. 3375–3379.

[76] C. Karakus, A. Gurbuz, and B. Tavli, "Analysis of energy efficiency of compressive sensing in wireless sensor networks," *IEEE Sensors J.*, vol. 13, no. 5, pp. 1999–2008, May 2013.

[77] D.-M. Han and J.-H. Lim, “Smart home energy management system using ieee 802.15.4 and zigbee,” *IEEE Trans. Consum. Electron.*, vol. 56, no. 3, pp. 1403–1410, Oct. 2010.

[78] J. Zhang, D. Zhang, K. Xie, S. He, H. Qiao, and B. Zeng, *A Cooperative Routing Algorithm for Maximizing Network Lifetime.* Berlin: Springer-Verlag, 2013, vol. 334, pp. 665–675.

[79] J. W. Jung and M. Weitnauer, “On using cooperative routing for lifetime optimization of multi-hop wireless sensor networks: Analysis and guidelines,” *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3413–3423, Aug. 2013.

[80] I. Gravalos, P. Kokkinos, and E. Varvarigos, “Multi-criteria cooperative energy-aware routing in wireless ad-hoc networks,” in *Proc. IEEE 9th International Wireless Communications and Mobile Computing Conference (IWCMC)*, 2013, pp. 387–393.

[81] A. Behzadan, A. Anpalagan, and B. Ma, “Prolonging network lifetime via nodal energy balancing in heterogeneous wireless sensor networks,” in *Proc. IEEE International Conference on Communications (ICC)*, June 2011, pp. 1–5.

[82] L. Ong and M. Motani, “Optimal routing for decode-forward in cooperative wireless networks,” *Communications, IEEE Transactions on*, vol. 58, no. 8, pp. 2345–2355, 2010.

[83] O. Gama, P. Carvalho, J. Afonso, and P. Mendes, “Quality of service support in wireless sensor networks for emergency healthcare services,” in *Proc. IEEE The 30th*

International Conference on Engineering in Medicine and Biology Society (EMBS), Aug. 2008, pp. 1296–1299.

[84] L. Yu, N. Wang, and X. Meng, “Real-time forest fire detection with wireless sensor networks,” in *Proc. IEEE Wireless Communications and Networking Conference, (WCNC)*, vol. 2, Sep. 2005, pp. 1214–1217.

[85] G. Caire and S. Shamai, “On the achievable throughput of a multiantenna gaussian broadcast channel,” *IEEE Trans. Inf. Theory*, vol. 49, no. 7, pp. 1691–1706, July 2003.

[86] A. F. Molisch, “Wireless communications.” Wiley-IEEE Press, 2005.

[87] H. Shariatmadari, A. Mahmood, and R. Jantti, “Channel ranking based on packet delivery ratio estimation in wireless sensor networks,” in *Proc. IEEE Wireless Communications and Networking Conference, (WCNC)*, Apr. 2013, pp. 59–64.

[88] S. Rao, *Engineering Optimization: Theory and Practice.* Wiley, 2009.

[89] D. P. Bertsekas and R. G. Gallager, *Data Networks*, 2nd ed. Prentice Hall, 1992.

[90] L. Wang, T. Liu, and K. Liu, “An adaptive forwarding cluster routing protocol for large scale wireless mobile ad hoc networks,” in *14th Asia-Pacific Conference on Communications (APCC)*, Oct. 2008, pp. 1–5.

[91] C. Perkins, E. Belding-Royer, and S. Das, “Ad hoc on-demand distance vector (AODV) routing,” July 2003.

[92] J. W. Suurballe and R. E. Tarjan, “A quick method for finding shortest pairs of disjoint paths,” *Networks*, vol. 14, no. 2, pp. 325–336, 1984.

[93] B. Peng and A. Kemp, "Energy-efficient geographic routing in the presence of localization errors," *Elsevier Computer Networks*, vol. 55, no. 3, pp. 856 – 872, Feb. 2011.

[94] Z. Haas and M. Pearlman, "The performance of query control schemes for the zone routing protocol," *IEEE/ACM Trans. Netw.*, vol. 9, no. 4, pp. 427–438, Aug. 2001.

[95] D. B. Johnson, D. A. Maltz, and J. Broch, *DSR: The Dynamic Source Routing Protocol for Multi-Hop Wireless Ad Hoc Networks.* Addison-Wesley, 2001, pp. 139–172.

[96] C. M. S. Mokhtar S. Bazaraa, Hanif D. Sherali, *Nonlinear programming: Theory and algorithm.* New York: Wiley, 2006.

[97] P. Dua and M. C. Georgiadis, *Multiparametric Mixed-Integer Linear Programming.* Wiley-VCH Verlag GmbH & Co. KGaA, 2007, pp. 53–71.

[98] B. Han, J. Li, J. Su, and J. Cao, "Self-supported cooperative networking for emergency services in multi-hop wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 2, pp. 450–457, Feb. 2012.

[99] P. Ostovari, A. Khreishah, and J. Wu, "Deadline-aware broadcasting in wireless networks with network coding," in *Proc. IEEE Global Communications Conference (GLOBECOM)*, Dec 2012, pp. 4435–4440.

[100] F. Li and I. Nikolaidis, "On minimum-energy broadcasting in all-wireless networks," in *Proc. IEEE 26th Conference on Local Computer Networks, (LCN)*, Nov. 2001, pp. 193–202.

[101] A. Ahluwalia and E. Modiano, "On the complexity and distributed construction of energy-efficient broadcast trees in wireless ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 4, no. 5, pp. 2136 – 2147, Sept. 2005.

[102] M. R. Garey and D. S. Johnson, *Computers and Intractability; A Guide to the Theory of NP-Completeness.* New York: W. H. Freeman & Co., 1990.

[103] P. Zhou, W. Liu, W. Yuan, W. Cheng, and S. Wang, "An energy-efficient cooperative miso-based routing protocol for wireless sensor networks," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Apr. 2009, pp. 1–6.

[104] K. Nishide, H. Kubo, R. Shinkuma, and T. Takahashi, "Detecting hidden and exposed terminal problems in densely deployed wireless networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 11, pp. 3841–3849, Oct. 2012.

[105] J. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive Comput.*, vol. 4, no. 1, pp. 18–27, Jan 2005.

[106] B. Medepally and N. Mehta, "Voluntary energy harvesting relays and selection in cooperative wireless networks," *Wireless Communications, IEEE Transactions on*, vol. 9, no. 11, pp. 3543–3553, November 2010.

[107] L. Liu, R. Zhang, and K.-C. Chua, "Wireless information transfer with opportunistic energy harvesting," *IEEE Transactions on Wireless Communications*, vol. 12, no. 1, pp. 288–300, January 2013.

Chapter 3

Joint Cooperative Routing and Power Allocation for Collision Minimization in Wireless Sensor Networks

3.1 Abstract

Cooperative diversity has gained much interest due to its ability to mitigate multipath fading without using multiple antennas. There has been considerable research on cooperative transmission discussing how cooperation can improve the performance of the physical layer. During the last few years, researchers have also started to take into consideration cooperative transmission in routing. However, all proposed cooperative routing algorithms in the literature do not take packet collision into account. In this chapter, we propose a

cross-layer cooperative routing algorithm for minimizing the collision probability subject to the end-to-end outage probability constraint in wireless sensor networks. We develop a collision minimization algorithm by combining cooperative transmission, optimal power allocation, and route selection. The proposed cooperative routing algorithm, called Minimum Collision Cooperative Routing (MCCR), selects the route that causes a minimum collision probability to other nodes in the network. Results show that MCCR can significantly reduce the collision probability while keeping the outage probability below the targeted value.

3.2 Introduction

Wireless Sensor Networks (WSNs) are networks of tiny sensor nodes connected with wireless links. These sensor nodes can sense, measure, and gather information from the environment, and then send the sensed data to a sink node. In most applications, WSN nodes are powered by limited non-rechargeable batteries. Therefore, the energy constraint is one of the main challenges in the design of WSNs. In addition, packet collision can be a major source of increasing latency, packet retransmission, and packet loss. When collisions occur in energy constrained wireless networks, packet retransmissions cause excessive energy consumption. In some WSNs, packet collision can cause serious problems. For instance, in WSNs for target detection in security or military applications, packet collision can cause target missing or long delays, which may have severe consequences. Hence, it is desirable to minimize the collision probability in WSNs.

Cooperative diversity has been proposed as an effective technique to improve the robustness of wireless links [1]. Cooperative diversity exploits neighboring nodes in order to relay the packets of transmitting nodes to the intended destination. Combining multiple copies of the same signal at the destination node leads to several advantages, such as better signal quality, reduced transmission power, better coverage, and higher capacity. Although the merits of cooperative transmission in the physical layer have been well-explored in WSNs and other wireless systems (see for example [2, 3]), the effect of cooperative transmissions on the design of upper layers, such as routing protocols, is not yet well-studied.

Routing algorithms which take into consideration the availability of cooperative transmission at the physical layer, are known in the literature as cooperative routing algorithms. Cooperative routing is introduced by Khandani *et al.* in [4]. It is shown that the problem of finding the optimum cooperative route is *NP-hard* [5]. Therefore, heuristic routing algorithms with reduced complexity are proposed by the researchers to find sub-optimal routes [4, 6–11].

The existing algorithm of cooperative routing in the literature can be divided into two categories. The first category of cooperation-based routing algorithms is implemented by first determining the optimal route based on direct transmission on each link and then using cooperative transmission over the links of the selected route. The heuristic routing algorithms proposed in [4, 6–8] are good examples of this category. However, the algorithms in the second category take into consideration the availability of the cooperative transmission on each link during the route selection. The authors in [9–11] proposed cooperative routing schemes based on the second category. The routing schemes in the second category are more complex but more efficient.

One of the heuristic routing algorithms presented in [4] is called cooperative along non-cooperative (CAN-L) shortest path algorithm. The basic idea is to run a non-cooperative shortest path first, and then the last L nodes along the non-cooperative path are allowed to participate in the cooperative transmission. The authors in [9], presented an algorithm named the Minimum Power Cooperative Routing (MPCR). The MPCR algorithm takes into account the availability of cooperative transmission for each link while constructing the route. MPCR finds the minimum-power route (using a combination of cooperative and direct links) that requires the minimum possible transmission power. In the MPCR algorithm, intermediate nodes determine whether cooperative transmission is preferable to direct transmission to minimize power consumption.

In [10] the authors proposed EP-H1 algorithm. The EP-H1 algorithm considers the two-stage cooperation model to find the route that consumes minimum energy. In the first stage the transmitter node broadcasts the message to its neighbors. In the second stage every node that has successfully decoded the message will join the transmitter node to form a cooperative transmitting set. The transmitting set cooperatively transmits the message to a receiver node using equal power. The power allocation vector minimizes the total amount of consumed energy.

The main objective of cooperative routing in all proposed schemes is minimizing the energy consumption. However, packet collision minimization has not been taken into account in the existing cooperative routing algorithms. In this chapter, we aim to design a cross-layer routing scheme for minimizing the collision probability subject to an end-to-end outage probability constraint in WSNs. The proposed scheme is designed by combining cooperative transmission, power allocation, and route selection. To the best of our knowledge, this work is the first to employ the cooperative routing for minimizing collision probability. We compare the proposed algorithm performance with CAN-L [4], MPCR [9], and EP-H1 [10].

In the next section, the system model is presented and the optimization problem is formulated. In Section 3.4, we determine the optimal power allocation to minimize the collision probability subject to the outage probability constraint. Section 3.5 presents the proposed cooperative routing algorithm. Then, in Section 3.6, we discuss the results. Finally, Section 3.7 concludes the Chapter.

3.3 System Model and Problem Formulation

Let h_{ij} and n_{ij} represent the Rayleigh fading channel coefficient and the additive white Gaussian noise of the link between nodes i and j, respectively. We assume that the distance-based attenuation follows the generic exponential path-loss model with an exponent γ.

In direct transmission, where a source node (s) transmits its signal directly to the next destination node (d), the received signal at d is given by

$$y_{sd} = \sqrt{p_s^D K r_{sd}^{-\gamma}}\, h_{sd} u + n_{sd}, \tag{3.1}$$

where p_s^D is the transmission power from the source in the direct transmission mode, K is a constant that depends on the characteristics of the transmitter, receiver and channel, e.g. the frequency and the antenna gain, r_{sd} is the distance between the two nodes (s and d), and u is the transmitted data with a unity power.

The criterion for a good detection is that the received signal-to-noise-ratio (SNR) must be greater than the detection threshold (β). Outage is defined as the status when the receiver is unable to detect data u. Hence, a link is considered to be in outage if the received SNR falls below β; thus, the outage probability, when direct transmission is used, Pr_{out}^{D}, is defined as $Pr(SNR_{sd} < \beta)$. It can be easily shown that the optimal power that minimizes the collision probability subject to the outage probability constraint ($Pr_{out}^{D} \leq Pr_{out}^{*}$) is given by

$$p_s^D = -\frac{\beta N_o r_{sd}^{\gamma}}{Kln(1-Pr_{out}^{*})}, \tag{3.2}$$

where Pr_{out}^{*} is the maximum acceptable outage probability and N_o represents the noise power.

In the cooperative transmission mode, the employed system model is similar to that used by Sadek *et al.* [12]. As shown in Fig. 3.1(a), the cooperative link consists of three nodes: source node (s), destination node (d), and a potential relay node (l). The relaying technique used in this study is the incremental adaptive decode-and-forward relaying. With this technique, the source node sends its signal to the destination using the direct link. If the destination is unable to detect the signal using the direct link, the relay node forwards the signal to the destination (provided that the relay was able to detect the signal). If the relay is unable to detect the signal, it will remain silent. For cooperative transmission, the received signals from the source node (s) at the destination (d) and the relay (l) can be respectively expressed as

$$\begin{aligned} y_{sd} &= \sqrt{p_s^C K r_{sd}^{-\gamma}}\, h_{sd} u + n_{sd}, \\ y_{sl} &= \sqrt{p_s^C K r_{sl}^{-\gamma}}\, h_{sl} u + n_{sl}, \end{aligned} \tag{3.3}$$

where p_s^C is the transmission power from the source in the cooperative transmission. If the relay forwards the signal to the destination, the received signal at the destination from the relay node can be expressed as

$$y_{ld} = \sqrt{p_l^C K r_{ld}^{-\gamma}}\, h_{ld} u + n_{ld}, \tag{3.4}$$

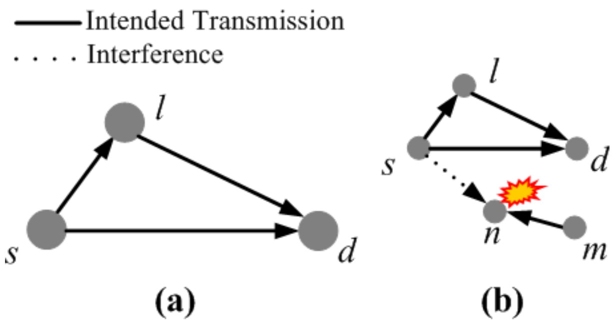


Figure 3.1: (a) System Model, (b) Collision Problem.

where p_l^C is the transmission power of the relay node. If the relay forwards the signal to the destination, the destination will detect the signal using the relay signal only. Although combining schemes such as maximum ratio combining are more efficient, they require storage of the direct signal until the indirect signal is received. Also, combining schemes require more signal processing and perfect knowledge of channel state information. Due to the limited sensor node power and processing capabilities, such combining techniques are not employed in this work.

As illustrated in Fig. 3.1(b), a transmitting node (node s) will cause a collision to another node (node n) if node s is sending while node n is simultaneously receiving (from another node, node m) provided that the interference from node s at node n is high enough to cause collision. As a result, in direct transmission, the probability that node s will cause collision to node n given that node m was unable to sense the transmission of node s, $Pr(Coll._s^D(n))$, can be expressed as

$$Pr(Coll._s^D(n)) = Pr_{rx}(n) \times Pr(I_s(n) > I_{th}^{Coll.}), \tag{3.5}$$

where $Pr_{rx}(n)$ is the probability that node n will be receiving, $I_s(n)$ is the received interference from node s by node n, $I_{th}^{Coll.}$ is the interference threshold above which the interference causes collision and the desired signal is undetectable.

Employing the CSMA-CA mechanism for channel access, nodes that are within the sensing range of a transmitter are inhibited from the transmission. Therefore, the probability that node s will cause a collision to one or more nodes in the network is given by

$$Pr(Coll._s^D) = 1 - \prod_{n \in \mathbb{N}} \left(1 - Pr\left(Coll._s^D(n)\right) Pr\left(NST_s\right)\right), \tag{3.6}$$

where $\mathbb{N}$ is the set of all nodes in the network except node s and d, and $Pr(NST_s)$ is the average probability of not sensing transmission of node s, i.e.,

$$Pr\left(NST_s\right) = \sum_{m \in \mathbb{N}} Pr(I_s(m) < I_{th}^{Sens.}) Pr_{tx}(m), \tag{3.7}$$

where $I_{th}^{Sens.}$ is the carrier sensing threshold above which the channel is deemed busy and $Pr_{tx}(m)$ is the probability that node m is transmitting.

The traffic model assumed to be a Poisson arrival process. Therefore, the probability of being receiving (or transmitting) is given by

$$Pr_{rx}\left(m\right) = Pr_{tx}\left(m\right) = \frac{1}{\left\lfloor \frac{N-2}{2} \right\rfloor} \sum_{j=1}^{\left\lfloor \frac{N-2}{2} \right\rfloor} e^{-\mu_m T_p} \frac{[\mu_m T_p]^j}{(j-1)!}, \tag{3.8}$$

where N is the number of nodes in the network, T_p denotes the packet duration, and μ_m is the average transmission rate (packet/sec.) of node m.

Since incremental relaying is used, the average collision probability caused by the cooperative link to all other nodes in the network is equal to the collision probability caused by the source node, $Pr(Coll._s^D)$, if the direct signal (from the source) is detectable at the destination, or if the relay node is unable to detect the source signal. Otherwise, the collision probability is the union of collision probability caused by the source node, and the collision probability caused by the relay node, $Pr(Coll._l^D)$. Thus, the collision probability caused by the cooperative transmission (from s and l) to all other nodes in the network is given by

$$Pr\left(Coll._{s,l}^{C}\right) = \tag{3.9}$$
$$\begin{cases} Pr\left(Coll._{s}^{D}\right), & (SNR_{sd} > \beta) or (SNR_{sd} < \beta \,\&\, SNR_{sl} < \beta) \\ Pr\left(Coll._{s}^{D} \bigcup Coll._{l}^{D}\right), & (SNR_{sd} < \beta \& SNR_{sl} > \beta), \end{cases}$$

where SNR_{sl} is the SNR of the source-relay link.

Since the fading coefficient follows the Rayleigh distribution, the SNR follows the exponential distribution and by substituting Eq. (3.6) into Eq. (3.9) and after some simplification, $Pr\left(Coll._{s,l}^{C}\right)$ can be expressed as in Eq. (3.10).

$$\begin{aligned} Pr\left(Coll._{s,l}^{C}\right) = &\left(1 - \prod_{n\in\mathbb{N}}\left[1 - Pr_{rx}(n)\, Pr\left(I_s(n) > I_{th}^{Coll.}\right) \sum_{m\in\mathbb{N}} Pr_{tx}(m)\, Pr\left(I_s(m) < I_{th}^{Sens.}\right)\right]\right) \\ &+ \left(1 - \prod_{n\in\mathbb{N}}\left[1 - Pr_{rx}(n)\, Pr\left(I_l(n) > I_{th}^{Coll.}\right) \sum_{m\in\mathbb{N}} Pr_{tx}(m)\, Pr\left(I_l(m) < I_{th}^{Sens.}\right)\right]\right) \\ &\qquad Pr(SNR_{sd} < \beta)\; Pr(SNR_{sl} > \beta) \\ &- \left(1 - \prod_{n\in\mathbb{N}}\left[1 - Pr_{rx}(n)\, Pr\left(I_s(n) > I_{th}^{Coll.}\right) \sum_{m\in\mathbb{N}} Pr_{tx}(m)\, Pr\left(I_s(m) < I_{th}^{Sens.}\right)\right]\right) \\ &\times \left(1 - \prod_{n\in\mathbb{N}}\left[1 - Pr_{rx}(n)\, Pr\left(I_l(n) > I_{th}^{Coll.}\right) \sum_{m\in\mathbb{N}} Pr_{tx}(m)\, Pr\left(I_l(m) < CS_{th}\right)\right]\right) \\ &\qquad Pr(SNR_{sd} < \beta)\; Pr(SNR_{sl} > \beta), \end{aligned} \tag{3.10}$$

In general, a route is a concatenation of cooperative transmission and direct transmission links. Therefore, the collision probability caused by the entire route to all nodes in the network can be expressed as

$$Pr(Coll._{route}) = Pr\left(\bigcup_{h=1}^{H}\left(Coll._{s_h,l_h}^{C} In^{C}(h) + Coll._{s_h}^{D}\overline{In^{C}(h)}\right)\right), \tag{3.11}$$

where h is the hop number, H is the total number of hops in the route, and $In^C(h)$ is the indicator function, which is equal to one if the h-th hop uses cooperative transmission and it is equal to zero if the h-th hop uses direct transmission.

In cooperative transmission with incremental adaptive decode-and-forward, the outage probability is given by

$$Pr_{out}^{C} = Pr(SNR_{sd} < \beta)Pr(SNR_{sl} < \beta) + Pr(SNR_{sd} < \beta)Pr(SNR_{sl} > \beta)Pr(SNR_{ld} < \beta), \tag{3.12}$$

where the first term of the equation refers to the event that the source-to-destination and the source-to-relay links are in outage (i.e., SNR of each link is less than β). The second term refers to the event that the source-to-destination and relay-to-destination links are in outage but the source-to-relay link is not in outage.

Furthermore, the end-to-end outage probability of a certain route is defined as the probability that outage takes place in one of the H hops of the route, i.e.,

$$Pr_{out}(route) = 1 - \prod_{h=1}^{H} \left(1 - Pr_{out}(h)\right), \tag{3.13}$$

where $Pr_{out}(h)$ is the outage probability of the h-th link (either cooperative or direct) in the route.

The goal of the algorithm is to find the route from the source to the sink that minimizes the collision probability caused by the entire route to all nodes in the network, while satisfying the end-to-end outage probability constraint.

3.4 Power Allocation in Cooperative Transmission Links

For a given source-sink nodes, all possible routes are defined as a set of hops between the source and destination. Thus, the problem can be formulated as a constraint optimization problem as follows

$$\begin{aligned} &\underset{p_s,\,p_l}{Min}\; Pr(Coll._{route}),\\ s.t. \quad & Pr_{out}(route) \leq Pr^{*}_{out}. \end{aligned} \tag{3.14}$$

In a cooperative transmission link, the constrained optimization problem can be solved using the Lagrange Multipliers method as follows

$$\begin{aligned} &\tfrac{\partial}{\partial\, p_s}(\, Pr(Coll._{s,l}^{C}) \;+ \lambda\, Pr^{C}_{out}) = 0,\\ &\tfrac{\partial}{\partial\, p_l}(\, Pr(Coll._{s,l}^{C}) \;+ \lambda\, Pr^{C}_{out}) = 0,\\ &Pr^{C}_{out} = Pr^{*}_{out}\;, \;\; \lambda > 0, \end{aligned} \tag{3.15}$$

where λ is the Lagrange Multiplier. Using the exponential distribution of the SNR in Eq. (3.12) and substituting Eqs. (3.10) and (3.12) in Eq. (3.15) and after some manipulations, Eq. (3.15) can be rewritten as Eqs. (3.16), (3.17), and (3.18).

$$\begin{aligned} &\sum_{n\in\mathbb{N}}\left[\frac{I_{th}^{Coll.} r_{sn}^{\gamma}}{K p_s^2}\,\phi\left(p_s,n\right) - \theta\left(p_s,n\right)\right]\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_s,m\right)\right]\\ &\left[1-\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(exp\left(-\tfrac{k2}{p_s}\right)-exp\left(-\tfrac{k1+k2}{p_s}\right)\right)\right]\\ &-\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(\tfrac{k1}{p_s^2}\right)exp\left(-\tfrac{k1+k2}{p_s}\right)+\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right) \end{aligned}$$

$$\left(exp\left(-\tfrac{k2}{p_s}\right)-exp\left(-\tfrac{k1+k2}{p_s}\right)\right)\tfrac{k2}{p_s^2}+\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_s,n\right)\right]\right)$$
$$\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(\tfrac{k1+k2}{p_s^2}exp\left(-\tfrac{k1+k2}{p_s}\right)+\tfrac{k2}{p_s^2}exp\left(-\tfrac{k2}{p_s}\right)\right)$$
$$-\tfrac{\lambda k1}{p_s^2}exp\left(-\tfrac{k1}{p_s}\right)-\tfrac{\lambda k2}{p_s^2}exp\left(-\left(\tfrac{k2}{p_s}+\tfrac{k3}{p_l}\right)\right)-\tfrac{\lambda(k1+k2)}{p_s^2}exp\left(-\tfrac{k1+k2}{p_s}-\tfrac{k3}{p_l}\right)=0, \tag{3.16}$$

$$\sum_{n\in\mathbb{N}}\left\{\frac{I_{th}r_{sn}^{\gamma}}{Kp_l^2}\,\phi\left(p_l,n\right)-\theta\left(p_l,n\right)\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_l,m\right)\right]\right\}$$
$$\times\left[exp\left(-\tfrac{k2}{p_s}\right)-exp\left(-\tfrac{k1+k2}{p_s}\right)\right]\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_s,m\right)\right]$$
$$-\tfrac{\lambda k3}{p_l^2}\left[exp\left(-\tfrac{k2}{p_s}-\tfrac{k3}{p_l}\right)+exp\left(-\tfrac{k1+k2}{p_s}-\tfrac{k3}{p_l}\right)\right]=0, \tag{3.17}$$

$$1-exp\left(-\tfrac{k1}{p_s}\right)-exp\left(-\tfrac{k2}{p_s}-\tfrac{k3}{p_l}\right)-exp(\tfrac{k1+k2}{p_s}+\tfrac{k3}{p_l})=Pr_{out}^{*}, \tag{3.18}$$

where $k1=\frac{N_o\beta r_{sd}^{\gamma}}{K}$, $k2=\frac{N_o\beta r_{sl}^{\gamma}}{K}$, and $k3=\frac{N_o\beta r_{ld}^{\gamma}}{K}$. Moreover, $\phi\left(p,n\right)$ and $\theta\left(p,n\right)$ are defined as follows

$$\phi\left(p,n\right)=Pr_{rx}\left(n\right)exp\left(-\frac{I_{th}^{Coll.}r_{sn}^{\gamma}}{K\,p}\right)$$
$$\times\sum_{m\in\mathbb{N}}Pr_{tx}\left(m\right)\left(1-exp\left(-\frac{I_{th}^{Sens.}r_{sm}^{\gamma}}{K\,p}\right)\right),$$
$$\theta\left(p,n\right)=Pr_{rx}\left(n\right)exp\left(-\frac{I_{th}^{Coll.}r_{sn}^{\gamma}}{K\,p}\right)$$
$$\times\sum_{m\in\mathbb{N}}Pr_{tx}\left(m\right)\frac{I_{th}^{Sens.}r_{sm}^{\gamma}}{K\,p^2}exp\left(-\frac{I_{th}^{Sens.}r_{sm}^{\gamma}}{K\,p}\right).$$

These three expressions (Eqs. 3.16 - 3.18) are solved simultaneously to determine p_s and p_l.

3.5 Proposed Cooperative Routing for Collision Minimization

In this section, we propose an algorithm to minimize the collision probability that a route causes to all nodes in the network through collision-aware route selection. This is achieved by selecting links which cause low collision probability to other nodes in the network. In addition, the algorithm uses cooperative transmission and power allocation jointly to reduce the collision probability, while the outage probability is kept below the targeted value.

As discussed before, finding the optimal cooperative route appears to be *NP-hard* and has a complexity of $O(2^{2N})$. Therefore, we propose the sub-optimal cooperative routing: Minimum Collision Cooperative Routing (MCCR). This algorithm requires a polynomial time complexity to determine the route that causes minimum collision probability in the network. MCCR is implemented using the following steps:

Step 1: Each node in the network calculates the collision probability caused because of transmitting a signal from node i to node j as the minimum of $Pr(Coll.^D)$ (from Eq. 3.6) and $Pr(Coll.^C)$ (from Eq. 3.9). This probability is used as the cost function of link i-j. The calculation is done using the initial transmission power (for the source and relay nodes), which is assumed to be 10 dBm, which is the standard value in IEEE 802.15.4 devices [13]. Since the optimum relay location in the decode-and-forward relaying technique is almost at the middle point between s and d, in cooperative links [14], we select a relay node (k) that is closest to the middle point of each link.

Step 2: The Bellman-Ford algorithm is applied to find the route which has the minimum cost function of the entire route. Therefore, the route which causes the minimum collision probability to all nodes in the network is selected.

Step 3: Optimal power is allocated to all nodes (sources of direct transmission links and sources and relays of cooperative transmission links for all hops of the selected route) in the selected route. The optimal transmission power is obtained either using the Lagrange Multipliers method in Eq. (3.15) (cooperative transmission), or Eq. (3.2) (direct transmission), as discussed in the previous sections.

Step 4: The collision and outage probabilities of the selected route is updated using the allocated optimal transmission power of all sources and relays across the route.

In order to determine the worst-case computational complexity, we first determine the complexity of calculating the cost function of all links, which has a complexity of $O(\frac{N(N-1)}{2})$. Moreover, Bellman-Ford algorithm has a complexity order of $O(N^2)$ in the worst case. Therefore, based on the sequence of statements rule, the worst-case computational complexity is given by

$$O(\frac{N(N-1)}{2}) + O(N^2) = O(N^2). \tag{3.19}$$

Thus, the MCCR has a complexity order of $O(N^2)$ in the worst case.

We developed two additional routing algorithms to investigate the effect of each of the cooperative transmission, route selection, and power allocation separately in minimizing the collision probability (i.e., one technique is used, while the other two are not employed). In the first one, called Cooperative Along Minimum Collision Direct path (CAMCD), cooperation is employed after constructing the route with the minimum caused collision probability using direct links only. Therefore, it does not take into account the possibility of using cooperative links during route selection. However, after route selection it can use cooperative transmission over the links of the selected route. Moreover, the second one, called Minimum Collision Non-cooperative (MCN), considers only direct links during both the route selection and signal transmission. CAMCD and MCN use optimal power allocation, as explained in Section 3.4.

3.6 Results

In order to analyse the performance of the proposed algorithms, we consider a regular grid topology of WSN as shown in Fig. 3.2. We compare the proposed algorithm performance with EP-H1 [10], MPCR [9], and CAN-L [4]. In addition, we investigate the performance of the selected route without optimal power allocation by using equal fixed power during message forwarding for all sources and relays.

In all simulations, we assumed the path-loss exponent (γ) is equal to 4, the noise power (N_o) is equal to -103.8 dBm, and the detection SNR threshold (β) is set to 10 dB. The interference threshold is equal to αN_o, where α is a design parameter. In this chapter we assumed $\alpha = 1$, which means that the interference power threshold is equal to the noise power ($I_{th}^{Coll.} = N_o$). The path-loss attenuation factor (K) is equal to $9.894e^{-3}$, which is determined using the break-point model [15] (at $f_c = 2.4$ GHz and a break-point distance equals 10 m). The carrier sense threshold ($I_{th}^{Sens.}$) assumed to be 10 dB below the detection threshold [13], the end-to-end outage probability constraint (Pr_{out}^{*}) set to 0.1, and T_p assumed to be 0.192 ms [13]. Furthermore, we consider two following cases: 1) nodes have the same traffic intensity; 2) nodes have different traffic intensity. The second case is used to assess the performance of the proposed algorithm when nodes in part of the network are under the higher traffic generation rate than nodes in the rest of the

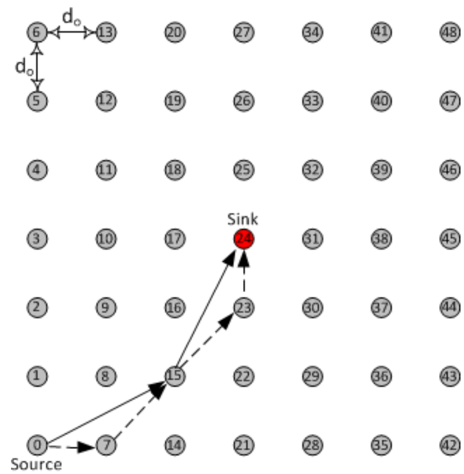


Figure 3.2: A Regular Grid 7x7 Sensor Network Topology

network, which sometimes occurs in event-driven WSNs. In case 2, we assume that for nodes located on the diagonal and above $\mu = 5$ and nodes below diagonal $\mu = 1$. Thus, if (X_i, Y_i) represents the position of node i in Cartesian coordinates, $\mu_i = 5$ if $X_i \leq Y_i$, while $\mu_i = 1$ if $X_i > Y_i$.

Fig. 3.2 illustrates a regular 7x7 grid sensor network topology. Sensor nodes are equidistant from each other and d_0 in this figure denotes minimum distance between a pair of nodes. We also assume that the source node is located at the left bottom and the sink node is located at the center of the network. Fig. 3.2 shows the selected route when MCCR is employed in case 2. It can be seen that for the first hop, node 0 (source node) cooperates with node 7 to transmit a packet to node 15. In the second hop, node 15 sends the data to node 24 (the sink node) through cooperative transmission with node 23 as a potential relay.

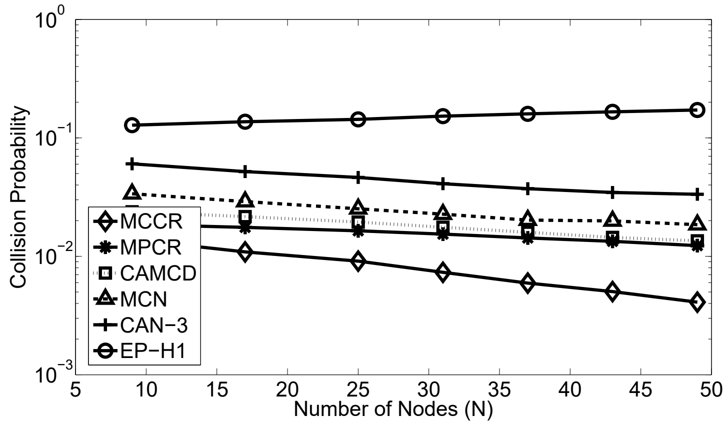


Figure 3.3: Collision probability of the routing algorithms versus number of nodes (N) in case 1.

3.6.1 Evaluation of Routing Algorithms

Fig. 3.3 compares the collision probability caused by the MCCR algorithm and that of the CAMCD, MCN, EP-H1, MPCR and CAN-3 algorithms versus the number of nodes in the network. It is assumed that all nodes have the same transmission rate ($\mu=1$) (case 1). It is evident that the MCCR algorithm outperforms the other schemes and has the lowest collision probability. It can be seen that, at $N = 49$, the collision probability of MCCR is reduced by 85%, 48%, 70%, 40%, and 54% compared with EP-H1, MPCR, CAN-3, CAMCD, and MCN, respectively. This collision probability reduction is expected because MCCR selects the cooperative route that minimizes the collision probability by employing the collision probability as the cost function during the route selection and also by allocating the power (in each hop) to minimize the collision probability caused by the selected links across the route.

Fig. 3.4 depicts the collision probability of the routing schemes for case 2. It can be seen that, at $N = 49$ nodes, the collision probability of MCCR is reduced by 87%, 52%,

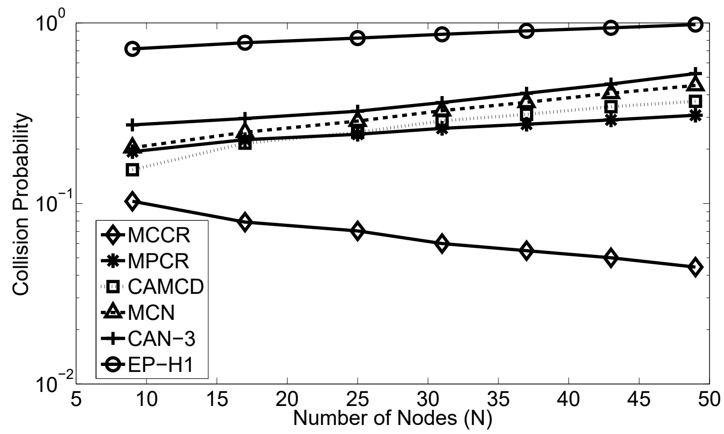


Figure 3.4: Collision probability of the routing algorithms versus number of nodes (N) in case 2.

68%, 58%, and 65% compared with EP-H1, MPCR, CAN-3, CAMCD, and MCN, respectively. This collision probability reduction is because MCCR avoids selecting nodes that can cause high collision probability (either because of the large number of neighbors or because some of these neighbors have high reception(or transmission) probability). Moreover, power allocation and collision minimization-based route selection will also reduce the collision probability caused by the selected route. Comparing the results of case 1 (Fig. 3.3) and those of case 2 (Fig. 3.4) shows that for any specific number of nodes in the network (N) the collision probability in case 2 is greater than case 1. This is because in case 2 some nodes have higher traffic rate (μ) than case 1, which causes higher collision probability.

The required transmission power of the selected routes by different routing algorithms is shown in Fig. 3.5. It can be seen that the EP-H1 requires the minimum total transmission power compared with other schemes. Moreover, it is evident that the MCCR, MPCR, and EP-H1 algorithms which exploit cooperative communication while constructing the

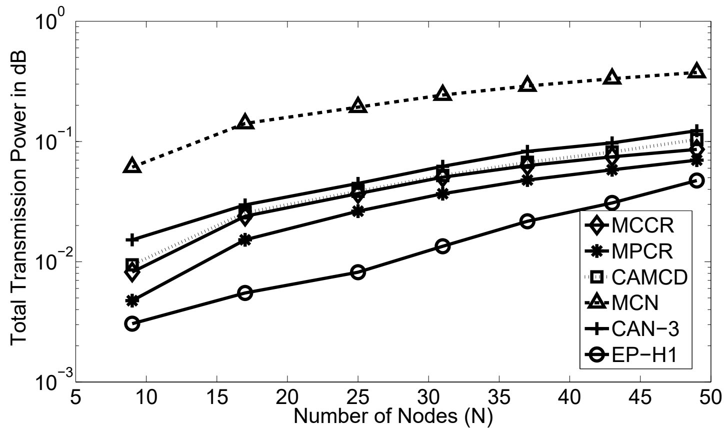


Figure 3.5: Comparing total transmission power of routing algorithms versus number of nodes (N) in case 2.

route (fully cooperative routing) are more energy efficient than the other algorithms. Although EP-H1 performs modestly better than MCCR in the energy consumption aspect, the higher collision probability of EP-H1 leads to a higher packet retransmission rate which can reduce the gap between the total transmission power of the MCCR and EP-H1 algorithm, if the retransmission is taken into account in the transmission power calculation.

3.6.2 Effect of Power Allocation

In order to gain insight into the effect of the optimal power allocation to minimize the caused collision probability with MCCR, we compare the performance of MCCR with optimal power allocation with that of the MCCR with equal power allocation (i.e., $p_s = p_l = 10$ dBm for all nodes in the route).

As shown in Fig. 3.6 in case 2, the contribution of optimal power allocation technique in the collision probability reduction ranges from 39% to 47% for $N = 9$ to 49. On the

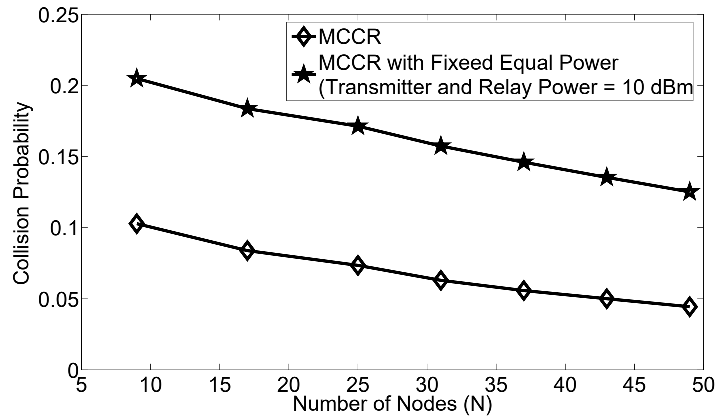


Figure 3.6: Comparing collision probability of the MCCR algorithm with optimal power allocation and MCCR without optimal power allocation in case 2.

other hand, as shown in Fig. 3.7, $Pr_{out}(route)$ with equal power increases with increasing the number of nodes in the network. At a large number of nodes in the network ($N > 28$), $Pr_{out}(route)$ in MCCR with equal power exceeds the target value ($Pr^*_{out} = 0.1$), while MCCR with optimal power achieves the targeted value for all N. Increasing the number of nodes (N) leads to increasing the number of hops. As the number of hops increases with equal transmission power, the outage probability increases. While in MCCR with optimal power, the transmission power is adjusted to keep the outage probability always below the targeted value. Hence, for $N = 28$, the outage probability of MCCR with equal power starts to exceed that of the MCCR with optimal power.

3.7 Conclusion

In this chapter, the problem of collision probability minimization using cooperative routing and power allocation in WSNs is investigated. The power allocation which minimizes the collision probability subject to the outage probability constraint, was mathematically

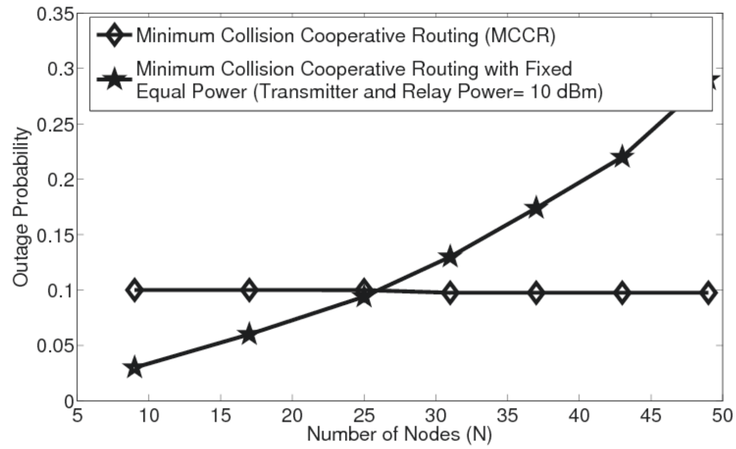


Figure 3.7: Comparing outage probability of the MCCR algorithm with optimal power allocation and MCCR without optimal power allocation in case 2.

determined, using direct and cooperative transmission. Subsequently, a cross-layer routing scheme was proposed; namely, the Minimum Collision Cooperative Routing (MCCR) algorithm, which takes into consideration cooperative transmission during the selection of the optimal route. The MCCR algorithm exploits cooperative transmission, route selection, and optimal power allocation to minimize the collision probability in the network. The performance of MCCR was compared with three cooperative routing algorithms, EP-H1 [10], MPCR [9], and CAN-L [4]. Results show that MCCR reduces the collision probability significantly while keeping the end-to-end outage probability below the targeted value. Moreover, we analysed the effect of each technique (cooperative transmission, route selection, and optimal power allocation) separately. Results show that cooperative transmission is the most effective technique in reducing the collision probability. However, combining cooperative transmission with collision minimization, route selection, and optimal power allocation makes it more efficient in minimizing the collision probability with a small increase in the transmission power compared to other routing schemes.

REFERENCES

[1] J. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[2] Z. Zhou, S. Zhou, J.-H. Cui, and S. Cui, "Energy-efficient cooperative communication based on power control and selective single-relay in wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 8, pp. 3066 –3078, Aug. 2008.

[3] Y.-W. Hong, W.-J. Huang, F.-H. Chiu, and C.-C. Kuo, "Cooperative communications in resource-constrained wireless networks," *IEEE Signal Process. Mag.*, May 2007.

[4] A. E. Khandani, J. Abounadi, E. Modiano, and L. Zheng, "Cooperative routing in static wireless networks," *IEEE Trans. Wireless Commun.*, vol. 55, no. 11, pp. 2185–2192, Nov. 2007.

[5] A. Ahluwalia and E. Modiano, "On the complexity and distributed construction of energy-efficient broadcast trees in wireless ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 4, no. 5, pp. 2136 – 2147, Sep. 2005.

[6] Z. Yang and A. Høst-Madsen, "Routing and power allocation in asynchronous gaussian multiple-relay channels," *EURASIP J. Wirel. Commun. Netw.*, vol. 2006, no. 2, pp. 35–35, Apr. 2006.

[7] J. Zhang and Q. Zhang, "Cooperative routing in multi-source multi-destination multi-hop wireless networks," in *Proc. IEEE The 27th Conference on Computer Communications (INFOCOM'08)*, Apr. 2008, pp. 2369 –2377.

[8] F. Li, K. Wu, and A. Lippman, "Energy-efficient cooperative routing in multi-hop wireless ad hoc networks," in *Proc. IEEE 25th International Performance, Computing, and Communications Conference, (IPCCC'06)*, Apr. 2006, pp. 214–222.

[9] A. Ibrahim, Z. Han, and K. Liu, "Distributed energy-efficient cooperative routing in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3930 –3941, Oct. 2008.

[10] M. Dehghan, M. Ghaderi, and D. Goeckel, "Minimum-energy cooperative routing in wireless networks with channel variations," *IEEE Trans. Wireless Commun.*, vol. 10, no. 11, pp. 3813–3823, Nov. 2011.

[11] C. Zhai, J. Liu, L. Zheng, H. Xu, and H. Chen, "Maximise lifetime of wireless sensor networks via a distributed cooperative routing algorithm," *Transactions on Emerging Telecommunications Technologies*, vol. 23, no. 5, pp. 414 –428, Aug. 2012.

[12] A. K. Sadek, W. Yu, and K. J. R. Liu, "On the energy efficiency of cooperative communications in wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 6, no. 1, pp. 1–21, Jan. 2010.

[13] *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specications for Low-Rate Wireless Personal Area Networks (WPANs)*, IEEE Std. 802.15.4, 2011.

[14] B. Han, J. Li, and J. Su, "Optimal relay node placement for multi-pair cooperative communication in wireless networks," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Apr. 2013, pp. 4724–4729.

[15] A. Molisch, *Wireless Communications*, 2nd ed. Wiley-IEEE Press, 2005.

Chapter 4

Per-Node Traffic Load in Cooperative Wireless Sensor Networks

4.1 Abstract

Cooperative diversity has gained much interest due to its ability to mitigate multipath fading without using multiple antennas. In multi-hop wireless networks, such as wireless sensor networks, per-node traffic load helps to provide important insights into designing efficient network protocols. Cooperative diversity introduces new aspects to the per-node traffic load. In this chapter, we present an analytical model for estimating the per-node traffic load in a cooperative wireless sensor network. We consider a typical scenario, wherein the sensor nodes sense the environment and forwards the events to a sink node using the greedy geographical routing. Our results confirm that traffic load increases as a

function of the node's vicinity to the sink node. Simulation results validate the accuracy of our analytical model.

4.2 Introduction

Cooperative diversity has been proposed as an effective technique to improve the robustness of wireless links [1]. This technique is particularly appropriate for densely populated and randomly deployed networks, such as Wireless Sensor Networks (WSNs). Cooperative diversity exploits neighboring sensor nodes in order to relay the packets from transmitting nodes to the intended destinations. Combining multiple copies of the same signal at the destination leads to several advantages, such as the better signal quality and higher capacity.

In WSNs, upon the detection of an event, packet traffic load in some spots may become intensified, resulting in a high packet collision rate and consequently, packet loss. Moreover, it has been well accepted that the sensor nodes close to the sink node (base station) become heavily involved in packet forwarding and thus, they carry high traffic load. As a result, the sensor nodes close to the sink quickly drain batteries, leading to a possible network disconnection and the functional network lifetime reduction. Similar to other multi-hop networks, in WSNs each node relays the traffic of other nodes in the network. Hence, the traffic load of each node includes the traffic generated by the node, as well as the traffic generated by other nodes, which is relayed by this node. Thus, the per-node traffic load can be defined as the average number of packets transmitted by the sensor node during a time unit [2]. The analytical calculation of the per-node traffic load helps in designing and configuring efficient network protocols. For instance, an analytical model to accurately estimate the traffic load of each node can be used to maximize the network lifetime by balancing the sensor node traffic load [3] or to minimize the packet collision probability [4].

Cooperative diversity introduces new aspects to the typical traffic load of the nodes in WSNs. A relay node in a cooperative link not only receives traffic load from the transmitter node, but also forwards the traffic load to the destination node. To the best of our knowledge, there is no analytical model which can accurately characterize the per-node traffic load in a cooperative wireless network. The available model for estimating the per-node traffic load, presented in [2], does not incorporate cooperative diversity and its implication in the network. This Chapter presents a new and detailed analytical model for calculating the per-node traffic load in cooperative WSNs.

The rest of this chapter is organized as follows. In Section 4.3, we provide an overview of the system model. In Section 4.4, the analysis of the per-node traffic load is presented. Section 4.5 validates the analytical model by comparing the analytical results with those obtained by simulations. Finally, Section 4.6 concludes the Chapter.

4.3 System Model

We focus on event driven applications, wherein the source nodes forward the event (e.g. fire, target detection) to the sink node. A large portion of WSNs deployed today falls into this category (e.g., RIMBAMON [5]). With regards to the routing strategy, we have considered the popular greedy routing forwarding scheme [6]. In greedy routing, a sensor node forwards its packets to a neighbor, which is the closest geographically to the sink node amongst possible neighboring nodes. As a result, greedy routing can approximately find the shortest path in terms of hops between a sensor node and the sink node. Moreover, greedy routing is a scalable routing solution for large WSNs, because it only requires local (i.e., one hop neighborhood) information for making a forwarding decision. However, the proposed model is not limited to the greedy routing and other types of routing algorithms can also be considered in the analysis. Similar to [2], we assume that the sensor nodes are uniformly randomly deployed in a circular disc, while the sink node is located at the center. Upon detecting an event, the source nodes generate a data packet, containing the relevant sensed data, and routes the packet toward the sink node. The packet generation follows the Poisson model with a rate of λ packets per second.

The wireless channel is assumed to suffer from Rayleigh fading. Variables $|h_{ij}|$ and n_{ij} represent the Rayleigh fading channel coefficient and the additive white Gaussian noise of the link between nodes i and j, respectively. We also assume that the distance-based attenuation follows the generic exponential path-loss model with an exponent γ [7,8].

For the cooperative system model, similar to [7], we use incremental relaying with adaptive decode-and-forward relaying. As such, the source node sends its signal to the destination using the direct link. If the destination is not able to detect the signal using the direct signal, the destination sends a negative acknowledgement (NACK) signal to the relay. Consequently, the relay node forwards the signal to the destination (provided that the relay was able to detect the signal). Since the optimum relay location in the decode-and-forward relaying technique is at the middle point between the transmitter and the receiver nodes of a cooperative link [9], we select the closest node to the middle point of each link as the relay node.

Although diversity combining schemes such as maximum ratio combining, are more efficient than selection combining, they require storage of the direct signal until the indirect signal is received. Moreover, more signal processing and perfect knowledge of the channel state information are required for combining schemes. Due to the limited resources at sensor nodes, such combining techniques are not employed.

In direct transmission, where a source node (s) transmits its signal directly to the destination node (d), the received signal at d is given by $y_{sd} = \sqrt{p_s^D K r_{sd}^{-\gamma}}\ h_{sd}u + n_{sd}$, where p_s^D is the transmission power from the source in the direct transmission mode, K is a constant that depends on the characteristics of the transmitter, the receiver, and channel (e.g., the frequency and the antenna gain), r_{sd} is the distance between the two nodes (s and d), and u is the transmitted data with a unity power.

In the cooperative transmission mode, the employed system model is similar to that used by Sadek *et al.* [7]. The cooperative link consists of three nodes: a source node, s, a destination node, d, and a potential relay node, l. Recall that the relaying technique used in this study is the incremental adaptive decode-and-forward relaying. With this technique, node s sends its signal to node d using a direct link. If d is unable to detect the signal using the direct link, node l forwards the signal to d (provided that l was able to detect the signal). If l is unable to detect the signal, it will remain silent. For cooperative transmission, the received signals from the source node (s) at the destination (d) and the relay (l) can be respectively expressed as

$$\begin{aligned} y_{sd} &= \sqrt{p_s^C K r_{sd}^{-\gamma}}\ h_{sd}u + n_{sd}, \\ y_{sl} &= \sqrt{p_s^C K r_{sl}^{-\gamma}}\ h_{sl}u + n_{sl}, \end{aligned} \tag{4.1}$$

where p_s^C is the transmission power from the source in the cooperative scenario. If the relay forwards the signal to the destination, the received signal at the destination from the relay node can be expressed as

$$y_{ld} = \sqrt{p_l^C K r_{ld}^{-\gamma}}\, h_{ld} u + n_{ld}, \tag{4.2}$$

where p_l^C is the transmission power of the relay node. If the relay forwards the signal to the destination, the destination will detect the signal using the relayed signal only.

4.4 Analysis of Per-Node Traffic Load in a Cooperative Link

The packet traffic load of node n includes the packets originated by node n as well as the transmitted traffic load of the neighbouring nodes that either employ node n as the next node in the route or as the relay node. Therefore, the average traffic load of node n is given by

$$\Lambda_t(n) = \Lambda_0(n) + \sum_{i \in \mathbb{N}}^{i \neq n} \Lambda_t(i) \left(S_{i,n} + \sum_{j \in \mathbb{N}}^{j \neq n,i} S_{i,j} S_{i,j}^n \right), \tag{4.3}$$

where $\Lambda_0(n)$ is the packet traffic load originated by node n, $\mathbb{N}$ denotes set of nodes in the network, $S_{i,n}$ and $S_{i,j}^n$ are the forwarding probabilities. $S_{i,n}$ is the probability that node i uses node n as the next node in the route, $S_{i,j}^n$ is the probability that node i uses node n as the relay node, while node j is the next node in the route. Thus, the traffic load of nodes in the network, denoted by vector $\boldsymbol{\Lambda_t}$, can be expressed as the traffic originated by the nodes, denoted by vector $\boldsymbol{\Lambda_0}$, plus the load coefficient between the nodes in the network, denoted by matrix $\boldsymbol{C}$, multiplied by the respective traffic load as follows

$$\boldsymbol{\Lambda_t} = \boldsymbol{\Lambda_0} + \boldsymbol{C}\boldsymbol{\Lambda_t}, \tag{4.4}$$

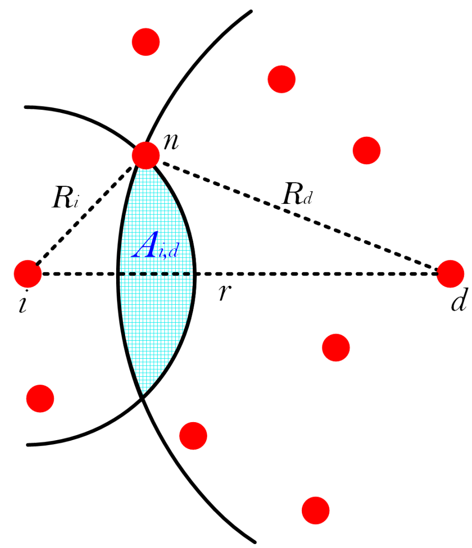


Figure 4.1: State transition when node j works as the next hop.

where the load coefficient between node i and node n, the element of $\boldsymbol{C}$, is defined as

$$C_{i,n} = \begin{cases} S_{i,n} + \sum\limits_{j \in \mathbb{N}}^{j \neq i,n} S_{i,j} S_{i,j}^{n} & i \neq n \\ 0 & i = n \end{cases} \tag{4.5}$$

4.4.1 Determining the Forwarding Probability to the Next Node in the Route (Next Hop)

To determine the forwarding probability, $S_{i,n}$, let us assume that a packet is currently at node i as it makes its way toward the sink. Employing the greedy routing, sensor node n is used as the next hop if all these three conditions are met: (1) the signal received form node i is not detectable by the sink node, (2) the signal received from node i is detectable by node n, and (3) there is not any other node closer to the sink, d, (i.e, no node within $A_{i,d}$ in Fig. 4.1) available to be used as the next hop. Since these three conditions are independent, the forwarding probability that node i uses node n as the next hop is given by

$$S_{i,n} = P_1 P_2 P_3, \tag{4.6}$$

where P_1 is the probability of no transmission link between node i and d even with the the help of relay node, P_2 is the probability that the signal from node i is detectable at node n, and P_3 is the probability of no nodes within $A_{i,d}$. Recall that we have assumed that the node distribution follows a random uniform distribution process with density of ρ. Thus, the number of nodes in region $A_{i,d}$ has a uniform distribution with a mean of $\rho A_{i,d}$. Therefore, P_1, P_2, and P_3 are calculated as follows

$$\begin{gathered} P_1 = Pr\left(SNR_{id} < \beta\right) Pr\left(SNR_{il} < \beta\right) + \\ Pr\left(SNR_{id} < \beta\right) Pr\left(SNR_{il} > \beta\right) Pr\left(SNR_{ld} < \beta\right), \end{gathered} \tag{4.7}$$

$$\begin{gathered} P_2 = Pr\left(SNR_{in} > \beta\right) + Pr\left(SNR_{in} < \beta\right) \\ Pr\left(SNR_{il'} > \beta\right) Pr\left(SNR_{l'n} < \beta\right), \end{gathered} \tag{4.8}$$

$$P_3 = e^{-\rho A_{i,d}}, \tag{4.9}$$

where l and l' are the potential relay nodes between nodes i to n and i to d, respectively and $A_{i,d}$ is also given by [2]

$$\begin{gathered} A_{i,d} = R_d^2 Cos^{-1}\left(\frac{r^2+R_d^2-R_i^2}{2dR_d}\right) + R_i^2\, Cos^{-1}\left(\frac{r^2+R_i^2-R_d^2}{2dR_i}\right) - \\ \frac{1}{2}\sqrt{\left(-r+R_d+R_i\right)\left(r+R_d-R_i\right)\left(r-R_d+R_i\right)\left(r+R_d+R_i\right)}. \end{gathered} \tag{4.10}$$

In order to illustrate the probability of forwarding to the next node of the route (i.e., $S_{i,n}$), an example is provided. Let us assume that the path-loss exponent (γ) is equal to 4, the noise power (N_o) is equal to -103.8 dBm, and the detection SNR threshold (β)

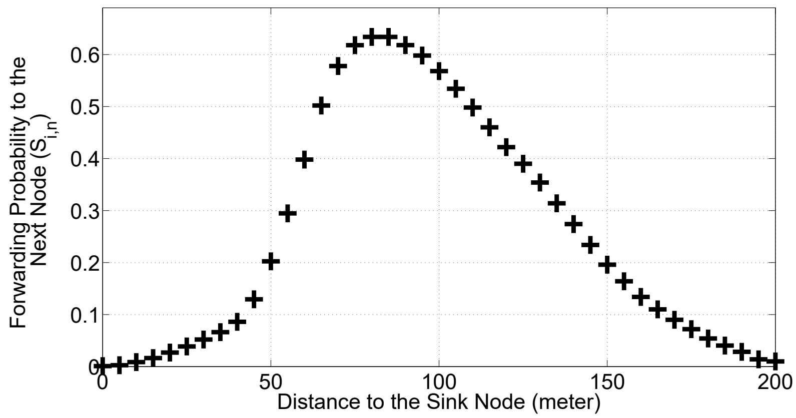


Figure 4.2: Forwarding probability to the next hop from the node located at $r = 200$ meter versus the distance of the next node to the sink R_d.

is set to 10 dB. We also assume that the path-loss attenuation factor (K) is equal to $9.894e^{-3}$, which is determined using the break-point model [10] (at $f_c = 2.4$ GHz and a break-point distance equals 10 m). We assume the equal and fixed transmission power of the source and the relay node is set to 0 dBm, which is the standard value in IEEE 802.15.4 devices [11]. The event is sensed by node i in Fig. 4.1, located at distance 200 meter from the sink node, thus, $r = 200m$. The average probability of forwarding to node n as the next hop versus the distance of node n from the sink node is illustrated in Fig. 4.2. As can be seen, the peak of the distribution is around $R_d = 82$ and the traffic is routed over a two-hop path with an intermediate node from source to the sink node. The forwarding probability is low for the nodes nearby the sink and source nodes. The forwarding probability is low for nodes near the sink because there is a little chance for detecting the signal from the source near the sink node, even with the help of relay node (i.e., P_2 is low). Moreover, because of employing the greedy routing algorithm, the forwarding probability is low for the nodes close to the source node (i.e, P_3 is low). Thus,

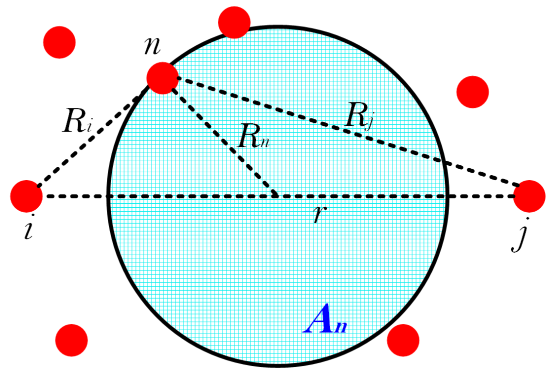


Figure 4.3: Forwarding transition when node n works as the relay node.

nodes near the sink and source nodes have little chance to be the next node in the route to carry the traffic load.

4.4.2 Evaluating the Forwarding Probability to the Relay

Employing the incremental relaying technique for the illustrated cooperative link in Fig. 4.3, node n is used as a relay node if all these three conditions are met: (1) the signal received from node i is not detectable by node j, as the next node, (2) signal received from the relay node, n, is detectable by node j, and (3) there is no node closer to the middle point of the link between i and j. Therefore, the forwarding probability that node i uses node n as the relay node is given by

$$S_{i,j}^{n} = P_1' P_2' P_3', \tag{4.11}$$

where P_1' is the probability of no transmission link between node i and node j, P_2' is the probability that node n can detect the signal received from node i, and P_3' is the probability of no nodes within A_n in Fig 4.3. Therefore, P_1', P_2', and P_3' are calculated as

$$P_1' = Pr\left(SNR_{ij} < \beta\right), \tag{4.12}$$

$$P_2^{'} = Pr\left(SNR_{in} > \beta\right), \tag{4.13}$$

$$P_3^{'} = e^{-\rho A_n}, \tag{4.14}$$

where A_n is the circle region of radius R_n, the distance between node n and the middle point of the link between node i and j. Inserting Eqs. (4.7)-(4.9) into Eq. (4.6) and Eqs. (4.12)-(4.14) into Eq. (4.11), the forwarding probabilities are obtained. By substituting Eqs. (4.6) and (4.11) in Eq. (4.5), the per-node traffic coefficient, $C_{i,n}$, is obtained in Eq. (4.15). Then, $C_{i,n}$ is used in Eq. (4.4) to obtain the average per node traffic load employing the Gaussian elimination method.

$$\begin{aligned} C_{i,n} = & \qquad\qquad (4.15)\\ & e^{-\rho A_{i,d}}\left\{Pr\left(SNR_{id} < \beta\right)Pr\left(SNR_{il} < \beta\right) + Pr\left(SNR_{id} < \beta\right)Pr\left(SNR_{il} > \beta\right)Pr\left(SNR_{ld} < \beta\right)\right\} + \\ & \sum_{j\in\mathbb{N}}^{j\neq i,n}\Bigg(e^{-\rho A_{i,j}}\left\{Pr\left(SNR_{ij} < \beta\right)Pr\left(SNR_{il} < \beta\right) + Pr\left(SNR_{in} < \beta\right)Pr\left(SNR_{il} > \beta\right)Pr\left(SNR_{ln} < \beta\right)\right\} \\ & e^{-\rho\pi R_n^2}Pr\left(SNR_{ij} < \beta\right)Pr\left(SNR_{in} > \beta\right)Pr\left(SNR_{nj} > \beta\right)\Bigg) \end{aligned}$$

In order to illustrate the probability of forwarding to the relay node (i.e., $S_{i,j}^{n}$), the example in the previous subsection with the same assumption is used. In addition, we assume that the next hop is located at $R_d = 82$, where the nodes have the maximum chance of being used as the next hop (as obtained in the previous subsection). The probability of forwarding to node n as the relay node versus the distance of node n from the sink node illustrated in Fig. 4.4. As expected, there are two peaks of the distribution which are around the middle point of the transmitter and receiver nodes of each hop (i.e., $P_3^{'}$ is high at those points). Moreover, the distance between the next hop and the sink node is less than the distance between destination and the next hop (i.e., $P_1^{'}$ is lower for the link between next hop and sink node than the link between source and the next hop).

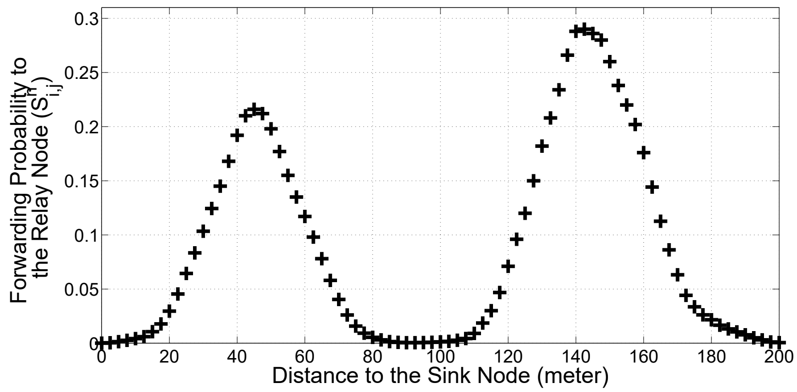


Figure 4.4: Forwarding probability to the relay node from the node located at $r = 200$ meter versus the distance of the next node to the sink R_d

Therefore, the probability of having the relay node for the link between next hop and sink is less than the probability of having the relay node for the link between source node and the next hop. As a result, the peak distribution value for the nodes between next hop and the sink is smaller than that for the nodes between the source and the next hop.

4.5 Simulation Results

In this section, we present results from the simulation and the analytical model given above. The goal of our evaluations is to validate the results of our analytical model. We developed a C++ simulator, which conforms to the assumptions listed in Section 4.3. In order to analyse the per-node traffic load of the system, we considered a uniform random topology of WSNs nodes and we focused on a circular region of area πR^2 (R being the radius). We considered a circular region assuming 300 sensor nodes deployed with a node density of $\rho = 0.0019$ under various number of flows in the network: $F = 5$, 10, and 20 within the area. Upon detecting an event, each source node generates 4 packets per

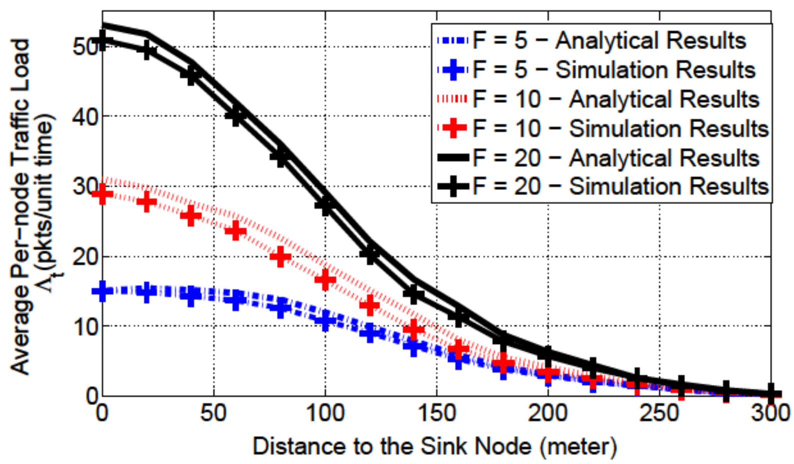


Figure 4.5: Average per-node traffic load as a function of distance to the sink under various number of flows, F= 5, 10, and 20 flows, in the network.

second which follows Poisson arrival distribution; hence, $\Lambda_0 = 4$.

Fig. 4.5 illustrates the results assuming that 5, 10, or 20 source nodes detect the events in the network and forward the packets to the sink node located at the center. Fig. 4.5 shows the per-node traffic load versus the distance of the node to the sink node. The traffic load of a node in the network highly depends on the forwarding probability, either as the relay node or as the next hop. As we intuitively expected, the nodes near the sink node carry more network traffic load than the other nodes in the network. It is also evident that, increasing the number of source nodes leads to higher per-node traffic load. Moreover, the close match between the simulation results and the analytical results confirms the accuracy and correctness of the proposed analytical model.

4.6 Conclusion

In this Chapter, we proposed an accurate mathematical model to analyze the per-node traffic load in a cooperative link. The per-node traffic load is obtained from the probability of forwarding either as the relay or as the next hop while the packet makes its way toward the sink. The accuracy of the analytical model is verified as there is a good match between the analytical results and the simulation results. The simulation results reveal that the nodes that are closer to the sink node typically have higher traffic loads. The proposed traffic model can be extended toward several directions, such as conducting energy efficient cooperative sensor network, or collision minimization protocols in cooperative wireless networks. Moreover, analysis of the per-node traffic load employing other types of routing protocols is an interesting issue for future investigation.

REFERENCES

[1] J. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[2] Q. Chen, S. Kanhere, and M. Hassan, "Analysis of per-node traffic load in multi-hop wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 958–967, Feb 2009.

[3] F. Bouabdallah, N. Bouabdallah, and R. Boutaba, "Load-balanced routing scheme for energy-efficient wireless sensor networks," in *IEEE GLOBECOM0'8*, Nov. 2008, pp. 1–6.

[4] F. Mansourkiaie and M. H. Ahmed, "Joint cooperative routing and power allocation for collision minimization in wireless sensor networks with multiple," *IEEE Commun. Lett.*, vol. PP, no. 99, pp. 1–1, Sep. 2014.

[5] A. Awang and M. Suhaimi, "Rimbamon: A forest monitoring system using wireless sensor networks," in *Proc. ICIAS*, Nov 2007, pp. 1101–1106.

[6] B. Karp and H. T. Kung, "GPSR: Greedy perimeter stateless routing for wireless networks," in *Proc. of the 6th Annual International Conference on Mobile Computing and Networking*. New York, NY, USA: ACM, Aug. 2000, pp. 243–254.

[7] A. K. Sadek, W. Yu, and K. J. R. Liu, "On the energy efficiency of cooperative communications in wireless sensor networks," *ACM Trans. Sen. Netw.*, vol. 6, no. 1, pp. 5:1–5:21, Jan. 2010.

[8] A. Ibrahim, Z. Han, and K. Liu, "Distributed energy-efficient cooperative routing in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3930–3941, Oct. 2008.

[9] B. Han, J. Li, and J. Su, "Optimal relay node placement for multi-pair cooperative communication in wireless networks," in *Proc. IEEE WCNC*, Apr. 2013, pp. 4724–4729.

[10] A. Molisch, *Wireless Communications*, 2nd ed. Wiley-IEEE Press, 2005.

[11] *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specications for Low-Rate Wireless Personal Area Networks (WPANs)*, IEEE Std. 802.15.4, 2011.

Chapter 5

Joint Cooperative Routing and Power Allocation for Collision Minimization in Wireless Sensor Networks with Multiple Flows

5.1 Abstract

In this Chapter, a cross-layer cooperative routing algorithm is proposed for minimizing the collision probability subject to an end-to-end outage probability constraint. We develop a collision minimization algorithm by combining cooperative transmission, optimal power allocation, and route selection. The proposed cooperative routing algorithm, called Minimum Collision Cooperative Routing (MCCR), selects the route that causes minimum collision probability to other nodes in the network. Results show that MCCR can

significantly reduce the collision probability compared with existing cooperative routing schemes.

5.2 Introduction

Recently, cooperative diversity has been proposed as an effective technique to improve the robustness of wireless links [1]. Cooperative diversity exploits neighboring nodes in order to relay the packets from transmitting nodes to the intended destinations. Combining multiple copies of the same packet at the destination leads to several advantages, such as better signal quality and higher capacity.

Routing algorithms that take into consideration the availability of cooperative transmission at the physical layer are known in the literature as cooperative routing algorithms. Cooperative routing was introduced by Khandani *et al.* [2] and the authors also showed that the problem of finding the optimum cooperative route is *NP-hard*. Therefore, heuristic routing algorithms with reduced complexity are proposed by researchers to find sub-optimal routes, e.g., [2, 3].

Existing cooperative routing algorithms in the literature can be divided into two categories: (1) routing algorithms which are implemented by first selecting the optimal route based on direct transmission in each link and then using cooperative transmission over the links of the selected route (e.g., [2]), and (2) routing algorithms which take into account the availability of the cooperative transmission on each link during route selection (e.g., [3]). Routing schemes in the second category are more complex but more efficient. One of the heuristic cooperative routing algorithms presented in [2] is called the Cooperative Along Non-cooperative (CAN-L) shortest path algorithm with the objective of minimizing total transmitted power. The basic idea is to run a non-cooperative shortest path first, and then to use cooperative transmission by the last L nodes along the non-cooperative path. Authors in [3] presented an algorithm called Minimum Power Cooperative Routing (MPCR). The MPCR algorithm makes routing decisions by assuming the cooperative transmission is also available for each link. MPCR finds the route that minimizes the total transmission power.

Interactions among multiple neighboring flows may lead to the hidden and exposed node problems, which causes packet collision [4]. In general, cooperative routing can improve the performance due to the more robust links and less power consumption. However, cooperative routing causes extra packet transmission by the relays. Therefore, the gain of a cooperative routing algorithm with multiple flows is different from the one with a single flow, especially in terms of the packet collision probability. There are only a few papers, such as [5, 6], that considered multiple flows in cooperative routing. In [5] collision is avoided using a contention graph approach, where a set of transmitting nodes coordinate their transmissions to a set of receiving nodes. The algorithm approaches the non-cooperative protocol when network congestion emerges. Moreover, in [6] the congestion problem is solved in the MAC layer. The main objective of cooperative routing in all proposed schemes is to minimize the energy consumption. However, packet collision minimization, using cooperative routing, has not been addressed in the existing schemes. Moreover, as it will be shown in the results, cooperative routing protocols, that aim to minimize the transmitted power (e.g., MPCR and CAN-L), do not necessarily lead to collision probability minimization. In energy constraint networks, such as Wireless Sensor Networks (WSNs), packet collision can cause serious problems. For instance, for target detection in security or military applications of WSNs, packet collision can lead to missing the target or to long delays, which may have severe consequences. Hence, it is desirable to minimize the collision probability in WSNs. In this chapter, we aim to design a cross-layer cooperative routing scheme for minimizing the collision probability subject to an end-to-end outage probability constraint. The cross-layer scheme is designed by combining cooperative transmission, power allocation, and route selection when there are multiple flows in the network. To the best of authors' knowledge, this work is the first to employ the cooperative routing for minimizing collision probability in the presence of multiple flows. We compare the proposed algorithm performance with existing cooperative routing schemes that minimize the transmission power, such as CAN-L [2] and MPCR [3].

5.3 System Model and Problem Formulation

Let h_{ij} and n_{ij} represent the Rayleigh fading channel coefficient and the additive white Gaussian noise of the link between nodes i and j, respectively. We assume that the distance-based attenuation follows the generic exponential path-loss model with an exponent γ [3].

In direct transmission, where a source (s) transmits its signal directly to the next destination (d), the received signal at d is given by $y_{sd} = \sqrt{p_s^D K r_{sd}^{-\gamma}} h_{sd} u + n_{sd}$, where p_s^D is the transmission power from the source in the direct transmission mode, K is a constant that depends on the characteristics of the transmitter, the receiver, and channel (e.g., the frequency and the antenna gain), r_{sd} is the distance between the two nodes (s and d), and u is the transmitted data with a unity power.

The criterion for good detection is that the received signal-to-noise-ratio (SNR) must be greater than the detection threshold (β). Outage is defined as the status when the receiver is unable to detect data u. Hence, a link is considered to be in outage if the received SNR falls below β. Thus, the outage probability, when direct transmission is only used, Pr_{out}^{D}, is defined as $Pr(SNR_{sd} < \beta)$. It can be easily shown that the power that minimizes the collision probability subject to the outage probability constraint ($Pr_{out}^{D} \leq Pr_{out}^{*}$) is given by

$$p_s^D = -\frac{\beta N_o r_{sd}^{\gamma}}{K \ln(1 - Pr_{out}^{*})}, \tag{5.1}$$

where Pr_{out}^{*} is the maximum acceptable outage probability and N_o represents the noise power.

In cooperative transmission, the employed system model is similar to that used in [3]. A cooperative link consists of three nodes: source (s), destination (d), and a potential relay node (l). The relaying technique used in this study is the incremental adaptive decode-and-forward. With this technique, the source sends its signal to destination using the direct link. If the destination is unable to detect the signal using the direct link, the relay forwards the signal to the destination (provided that the relay was able to detect the signal). If the relay is unable to detect the signal, it will remain silent and the destination will rely on the direct signal only. For cooperative transmission, the received signals from s at d and l can be respectively expressed as $y_{sd} = \sqrt{p_s^C K r_{sd}^{-\gamma}} h_{sd} u + n_{sd}$, $y_{sl} = \sqrt{p_s^C K r_{sl}^{-\gamma}} h_{sl} u + n_{sl}$, where p_s^C is the transmission power from the source in the cooperative transmission. If the relay forwards the signal to the destination, the received signal at the destination from the relay node can be expressed as $y_{ld} = \sqrt{p_l^C K r_{ld}^{-\gamma}} h_{ld} u + n_{ld}$, where p_l^C is the transmission power of the relay node. In this case, the destination detects the signal using the relay signal only. Although combining schemes such as Maximum Ratio Combining are more efficient, they require storage of the direct signal until the indirect signal is received. Also, combining schemes require more signal processing and perfect knowledge of the channel state information. Due to the limited power and processing capabilities in WSNs, such combining techniques are not employed in this work.

A source node, s, will cause a collision to another node, n, if s is sending while n is simultaneously receiving (from another node, m), provided that the interference from s at n is high enough to cause a collision. As a result, in direct transmission, the probability that s will cause collision at n, given that m was unable to sense the transmission of s, $Pr(Coll._s^D(n))$, can be expressed as

$$Pr\left(Coll._s^D\left(n\right)\right) = Pr_{rx}(n)Pr(I_s(n) > I_{th}^{Coll.}), \tag{5.2}$$

where $Pr(I_s(n) > I_{th}^{Coll.})$ is the probability that the received interference from s by n, $I_s(n)$, is greater than the interference threshold, $I_{th}^{Coll.}$, above which the interference causes a collision and the desired signal is undetectable and $Pr_{rx}(n)$ is the probability that n will be receiving given by

$$Pr_{rx}(n) = \sum_{i \in \mathbb{N}}^{i \neq n} Pr_{tx}\left(i\right) E_{i,n} + \sum_{j \in \mathbb{N}}^{j \neq n} \sum_{u \in \mathbb{N}}^{u \neq n, u \neq j} Pr_{tx}\left(j\right) F_{j,u}^{n}, \tag{5.3}$$

where $E_{i,n}$ is a binary variable to specify whether the link between i to n is in the routing solution, $F_{j,u}^{n}$ is another binary variable to specify whether n is used as a relay node for the link between j to u in the routing solution, and $Pr_{tx}(n)$ is the probability that n is transmitting, hence, $Pr_{tx}(n) = \Lambda_t\left(n\right) T_p$, where T_p is the packet time duration and $\Lambda_t\left(n\right)$ is defined as the total packet transmission rate of node n. Therefore, $\Lambda_t\left(n\right)$ is the sum of the packet generation rate of node itself, $\Lambda_0(n)$, and the transmission rate of packets that node n forwards either as a next hop or a relay node, thus,

$$\Lambda_t(n) = \Lambda_0(n) + \sum_{m\in\mathbb{N}}^{m\neq n} \Lambda_t(m)\Big\{E_{m,n}\big(Pr\left(SNR_{m,n} > \beta\right) +$$
$$Pr\left(SNR_{mn} < \beta\right) \sum_{l\in\mathbb{N}}^{l\neq n, l\neq m} Pr\left(SNR_{ml} > \beta\right) Pr\left(SNR_{ln} < \beta\right)\big)$$
$$+ \sum_{k\in\mathbb{N}}^{k\neq n, k\neq m} F^n_{m,k} Pr\left(SNR_{mk} < \beta\right)\left(SNR_{mn} > \beta\right)\Big\}, \quad (5.4)$$

where SNR_{mn} is the SNR of the m to n link.

Employing Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism for channel access, nodes that are within the sensing range of a transmitter are inhibited from transmitting. Therefore, the probability that s will cause a collision to one or more nodes in the network is given by

$$Pr(Coll._s^D) = \Big(1 - \prod_{n\,\in\,\mathbb{N}} \left(1 - Pr\left(Coll._s^D\left(n\right)\right)\right)\Big) Pr\left(NST_s\right), \quad (5.5)$$

where $\mathbb{N}$ is the set of all nodes in the network except s and d, and $Pr(NST_s)$ is the average probability of not sensing transmission of s by a node that has traffic to send to n, thus,

$$Pr\left(NST_s\right) = \sum_{m\in\mathbb{N}} Pr(I_s(m) < I_{th}^{Sens.})\big(Pr_{tx}(m)E_{m,n} + \quad (5.6)$$
$$\sum_{k\in\mathbb{N}}^{k\neq m,n} Pr_{tx}(k) F^k_{m,n} Pr\left(SNR_{mn} < \beta\right) Pr\left(SNR_{kn} > \beta\right)\big),$$

where $I_{th}^{Sens.}$ is the carrier sensing threshold above which the channel is deemed busy.

Since incremental relaying is used, the average collision probability caused by the cooperative link to all other nodes in the network is equal to the collision probability caused by the source, $Pr(Coll._s^D)$, if the direct signal (from the source) is detectable at the destination or if the relay node is unable to detect the source signal. Otherwise, collision happens by either the source or the relay; hence, the collision probability is the probability of the union of two events: 1) collision caused by the source, 2) collision caused by the relay. Thus, the collision probability caused by the cooperative transmission (from s and l) to all other nodes in the network is given by

$$Pr\left(Coll._{s,l}^{C}\right) = Pr(Coll._{s}^{D})\Big[Pr\left(SNR_{sd} > \beta\right) + Pr\left(SNR_{sd} < \beta\right)Pr\left(SNR_{sl} > \beta\right)\Big] + \Big[1 - \left(1 - Pr(Coll._{s}^{D})\right)\left(1 - Pr(Coll._{l}^{D})\right)\Big]Pr(SNR_{sd} < \beta)Pr(SNR_{sl} > \beta). \quad (5.7)$$

Therefore, the probability that the entire route causes collision can be expressed as

$$Pr(Coll._{route}) = 1 - \prod_{h=1}^{H}\left(1 - Pr\left(Coll._{s_h,l_h}^{C}(h)\right)\right), \quad (5.8)$$

where h is the hop number and H is the total number of hops in the route.

In cooperative transmission link with incremental adaptive decode-and-forward relaying, outage probability is given by

$$Pr_{out}^{C} = Pr(SNR_{sd} < \beta)Pr(SNR_{sl} < \beta) + Pr(SNR_{sd} < \beta)Pr(SNR_{sl} > \beta)Pr(SNR_{ld} < \beta). \quad (5.9)$$

Furthermore, the end-to-end outage probability of a certain route is defined as the probability that outage takes place in one of the H hops of the route, i.e.

$$Pr_{out}(route) = 1 - \prod_{h=1}^{H}\left(1 - Pr_{out}^{C}(h)\right), \quad (5.10)$$

where $Pr_{out}^{C}(h)$ is the outage probability of the h-th link in the route.

The goal of the algorithm is to find the route from each source to the sink that minimizes the collision probability caused by each route to other nodes in the network, while satisfying the end-to-end outage probability constraint.

5.4 Power Allocation in Cooperative Transmission Links

For a given source-sink pair, all possible routes are defined as a set of hops between the source and destination. Thus, the problem can be formulated as a constraint optimization problem as follows

$$\begin{aligned} &\min_{p_s, p_l} Pr(Coll._{route}), \\ s.t. \quad & Pr_{out}(route) \leq Pr^*_{out}. \end{aligned} \tag{5.11}$$

In a cooperative transmission link, the constrained optimization problem can be solved using the Lagrange Multipliers method [7]. With the exponential distribution of the SNR, and after differentiation with respect to p_s, p_l, and Lagrange Multiplier (λ), Eqs. (5.12) - (5.14) can be obtained from Eq. (5.11)

$$\begin{aligned} &\sum_{n\in\mathbb{N}} \left[\frac{I_{th}^{Coll.} r_{sn}^{\gamma}}{Kp_s^2}\,\phi(p_s,n) - \theta(p_s,n)\right] \prod_{m\in\mathbb{N}} [1-\phi(p_s,m)] \left[1 - \left(1 - \prod_{n\in\mathbb{N}} [1-\phi(p_l,n)]\right)\right. \\ &\left.\left(exp\left(-\tfrac{k2}{p_s}\right) - exp\left(-\tfrac{k1+k2}{p_s}\right)\right)\right] - \\ &\left(1 - \prod_{n\in\mathbb{N}} [1-\phi(p_l,n)]\right)\left(\tfrac{k1}{p_s^2}\right) exp\left(-\tfrac{k1+k2}{p_s}\right) + \left(1 - \prod_{n\in\mathbb{N}} [1-\phi(p_l,n)]\right) \\ &\left(exp\left(-\tfrac{k2}{p_s}\right) - exp\left(-\tfrac{k1+k2}{p_s}\right)\right)\tfrac{k2}{p_s^2} + \left(1 - \prod_{n\in\mathbb{N}} [1-\phi(p_s,n)]\right) \\ &\left(1 - \prod_{n\in\mathbb{N}} [1-\phi(p_l,n)]\right)\left(\tfrac{k1+k2}{p_s^2} exp\left(-\tfrac{k1+k2}{p_s}\right) + \tfrac{k2}{p_s^2} exp\left(-\tfrac{k2}{p_s}\right)\right) - \\ &\tfrac{\lambda k1}{p_s^2} exp\left(-\tfrac{k1}{p_s}\right) - \tfrac{\lambda k2}{p_s^2} exp\left(-\left(\tfrac{k2}{p_s} + \tfrac{k3}{p_l}\right)\right) - \tfrac{\lambda(k1+k2)}{p_s^2} exp\left(-\tfrac{k1+k2}{p_s} - \tfrac{k3}{p_l}\right) = 0, \end{aligned} \tag{5.12}$$

$$\sum_{n\in\mathbb{N}}\left\{\frac{I_{th}r_{sn}^{\gamma}}{Kp_l^2}\,\phi\left(p_l,n\right)-\theta\left(p_l,n\right)\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_l,m\right)\right]\right\}\times\left[exp\left(-\frac{k2}{p_s}\right)-exp\left(-\frac{k1+k2}{p_s}\right)\right]$$
$$\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_s,m\right)\right]-\frac{\lambda k3}{p_l^2}\left[exp\left(-\frac{k2}{p_s}-\frac{k3}{p_l}\right)+exp\left(-\frac{k1+k2}{p_s}-\frac{k3}{p_l}\right)\right]=0, \tag{5.13}$$

$$1-exp\left(\frac{-k1}{p_s}\right)-exp\left(-\frac{k2}{p_s}-\frac{k3}{p_l}\right)-exp\left(\frac{k1+k2}{p_s}+\frac{k3}{p_l}\right)=Pr_{out}^{*}, \tag{5.14}$$

where $k1=\frac{N_o\beta r_{sd}^{\gamma}}{K}$, $k2=\frac{N_o\beta r_{sl}^{\gamma}}{K}$, and $k3=\frac{N_o\beta r_{ld}^{\gamma}}{K}$. Moreover, $\phi\left(p,n\right)$ and $\theta\left(p,n\right)$ are defined as follows

$$\phi\left(p,n\right)=Pr_{rx}\left(n\right)exp\left(-\frac{I_{th}^{Coll.}r_{sn}^{\gamma}}{K\,p}\right)Pr\left(NST_s\right),$$

$$\theta\left(p,n\right)=Pr_{rx}\left(n\right)exp\left(-\frac{I_{th}^{Coll.}r_{sn}^{\gamma}}{K\,p}\right)\sum_{m\in\mathbb{N}}\frac{I_{th}^{Sens.}\,r_{sm}^{\gamma}}{K\,p^2}Pr\left(NST_s\right).$$

These three expressions (Eqs. (5.12) - (5.14)) are solved simultaneously to determine p_s and p_l.

5.5 Proposed Cooperative Routing for Collision Minimization

In this section, we propose a collision-aware routing algorithm, which minimizes the probability that a route causes collision to other nodes in the network. This is achieved by selecting links which cause low collision probability to other nodes in the network. In addition, the algorithm uses cooperative transmission and power allocation jointly to reduce the collision probability, while the outage probability is kept below the targeted value.

As discussed before, finding the optimal cooperative route appears to be *NP-hard*. Therefore, we propose a sub-optimal cooperative routing: Minimum Collision Cooperative

Routing (MCCR), which has a polynomial time complexity to determine the route that causes minimum collision probability in the network. MCCR is implemented using the following steps:

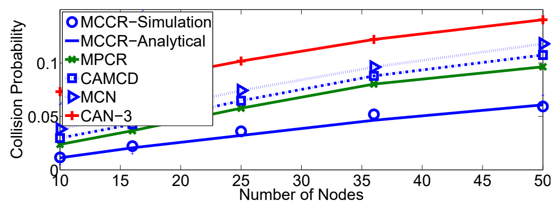
Step 1: Each node in the network calculates the collision probability caused because of transmitting a signal from node i to node j using $Pr(Coll.^C)$ (from Eq. (6.12)). This probability is used as the cost function of link i-j. The calculation is done using the initial transmission power (for the source and relay), which is assumed to be 10 dBm, that is the standard value in IEEE 802.15.4 devices [8]. Since the optimum relay location in decode-and-forward relaying technique is at the middle point between i and j of a cooperative link [9], we select a relay node (k) which is the closest to the middle point of each link.

Step 2: The Bellman-Ford algorithm is applied to find the route which has the minimum cost function of the entire route. Therefore, the route which causes the minimum collision probability to all nodes in the network is selected.

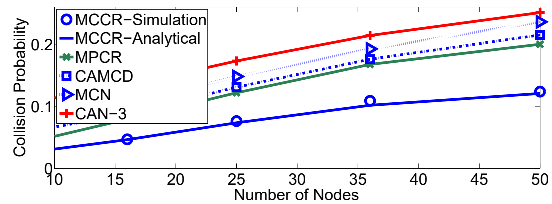
Step 3: Optimal power is allocated to all nodes (sources and relays of h-th transmission links, s_h, l_h) among the hops of the selected route. The optimal transmission power is obtained using the Lagrange Multipliers method in Eq. (5.11), as discussed in the previous sections.

Step 4: The collision and outage probabilities of the selected route are updated using the allocated optimal transmission power of all sources and relays across the route. From the discussion above, in the worst case, the MCCR requires two nested loops and each has a maximum length of $(N-1)$, where N is the total number of nodes in the network; therefore, it has a complexity order of $O(N^2)$.

We developed two additional routing algorithms to investigate the effect of each of the cooperative transmission and route selection separately in minimizing the collision



(a)



(b)

Figure 5.1: Collision Probability versus the number of relay nodes. (a) Number of flows in the network = 3 , (b) Number of flows in the network = 4.

probability (i.e., one technique is used, while the other is not employed). In the first algorithm, called Cooperative Along Minimum Collision Direct path (CAMCD), cooperation is employed after constructing the route which causes minimum collision probability using direct links only. Therefore, it does not take into account the possibility of using cooperative links during route selection. However, after route selection, it can use cooperative transmission over the links of the selected route. The second algorithm, called Minimum Collision Non-cooperative (MCN), considers only direct links during both the route selection and signal transmission. CAMCD and MCN use optimal power allocation, as explained in Section III.

5.6 Results

In order to analyze the performance of MCCR, we consider a random topology consisting of 10 to 50 sensor nodes (i.e., N varies from 10 to 50) and 3 or 4 flows (with randomly selected sources) within an area of 250×250. The simulation scenario is similar to the one used in [5]. We compare the proposed algorithm performance with MPCR [3] and CAN-L [2]. We assume the path-loss exponent (γ) equals 4, the noise power (N_o) equals

-103.8 dBm, and the detection SNR threshold (β) equals 10 dB. The interference threshold equals αN_o, where α is a design parameter. In this chapter we assume $\alpha = 1$, which means the collision interference threshold is equal to the noise power ($I_{th}^{Coll.} = N_o$). We also assume the sensing threshold equals the noise power, i.e., $I_{th}^{Sens.} = N_o$ [8]. The packet generation rate (Λ_0) at each source node follows Poisson traffic model with a rate of 4 pkt/s. The end-to-end outage probability constraint (Pr_{out}^{*}) is set to 0.1.

To deal with the practical aspects of the presented framework, the technique can be implemented in an off-line manner during the initialization phase. Fig. 5.1(a) and (b) compare the collision probability caused by the MCCR algorithm and that of the CAMCD, MCN, MPCR, and CAN-3 algorithms in a network having 3 and 4 flows, respectively. The analytical performance is obtained using the optimal power of source and relay nodes which is determined by solving Eqs. (5.12) - (5.14) and substituting in Eq. (6.14). We also developed a C++ time-driven simulation to validate the analytical results. Results show a very good agreement between the analytical results and simulation results. From Fig. 5.1, it is also evident that MCCR outperforms the other schemes and has the lowest collision probability. It can be seen that, at $N = 50$ and 4 flows in the network, the collision probability of MCCR is reduced by 43%, 68%, 47%, and 61% compared with MPCR, CAN-3, CAMCD, and MCN, respectively. This collision probability reduction is expected because MCCR selects the cooperative route that minimizes the collision probability by employing the collision probability as the cost function during the route selection and also by allocating the power (in each hop) to minimize the collision probability caused by selected links across the route.

The required transmission power of the selected routes by different routing algorithms, in network with 4 flows, is shown in Fig. 5.2. Larger number of nodes increases the dis-

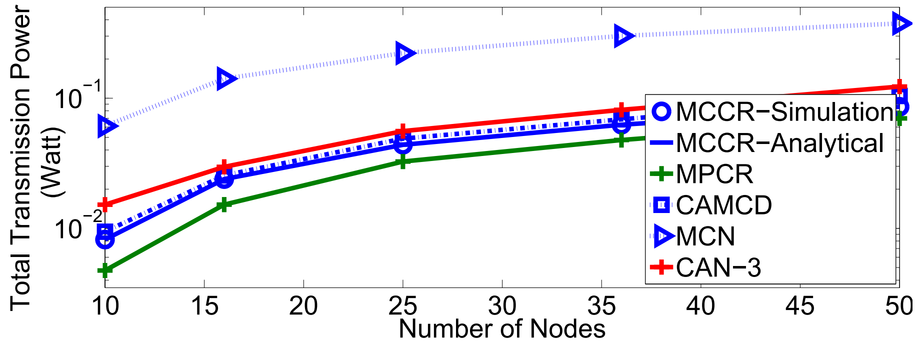


Figure 5.2: Total transmission power versus number of nodes.

tance between source-sink nodes; therefore, the total transmission power increases. It can be seen that the MCCR and MPCR algorithms, which exploit cooperative communication while constructing the route (fully cooperative routing), are more energy efficient than the others. Moreover, the objective in MPCR is to minimize transmission power; therefore, it is more energy efficient than MCCR. From Fig. 5.1 and 5.2, it is evident that minimizing the transmission power does not necessarily minimize the collision probability in the cooperative routing.

5.7 Conclusion

In this chapter, a cross-layer routing scheme, namely, the Minimum Collision Cooperative Routing (MCCR) algorithm was proposed. MCCR exploits cooperative transmission, route selection, and optimal power allocation to minimize the collision probability in the network. The performance of MCCR was compared with two cooperative routing algorithms, MPCR [3] and CAN-L [2]. Results show MCCR reduces the collision probability significantly and prove that collision-aware cooperative routing is essential for collision probability minimization.

REFERENCES

[1] J. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[2] A. E. Khandani, J. Abounadi, E. Modiano, and L. Zheng, "Cooperative routing in static wireless networks," *IEEE Trans. Wireless Commun.*, vol. 55, no. 11, pp. 2185–2192, Nov. 2007.

[3] A. Ibrahim, Z. Han, and K. Liu, "Distributed energy-efficient cooperative routing in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3930 –3941, Oct. 2008.

[4] L. Wang, K. Wu, and M. Hamdi, "Combating hidden and exposed terminal problems in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 11, pp. 4204–4213, Nov. 2012.

[5] J. Zhang and Q. Zhang, "Cooperative routing in multi-source multi-destination multi-hop wireless networks," in *Proc. IEEE INFOCOM*, Apr. 2008, pp. 306–310.

[6] B. Han, J. Li, J. Su, and J. Cao, “Self-supported cooperative networking for emergency services in multi-hop wireless networks,” *IEEE J. Sel. Areas Commun.*, vol. 30, no. 2, pp. 450–457, Feb. 2012.

[7] S. Rao, *Engineering Optimization: Theory and Practice.* Wiley, 2009.

[8] *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specications for Low-Rate Wireless Personal Area Networks (WPANs)*, IEEE Std. 802.15.4, 2011.

[9] B. Han, J. Li, and J. Su, “Optimal relay node placement for multi-pair cooperative communication in wireless networks,” in *Proc. IEEE WCNC*, Apr. 2013, pp. 4724–4729.

Chapter 6

Optimal and Near-Optimal Cooperative Routing and Power Allocation for Collision Minimization in Wireless Sensor Networks

6.1 Abstract

Cooperative communication has gained much interest due to its ability to exploit the broadcast nature of the wireless medium to mitigate multipath fading. There has been considerable research on how cooperative transmission can improve the performance of the network physical layer. Recently, researchers have started to take into consideration cooperative transmission in routing and there has been a growing interest in developing cooperative routing protocols. Most of the existing cooperative routing algorithms are

designed to reduce the energy consumption; however, packet collision minimization using cooperative routing has not been addressed yet. This chapter presents an optimization framework to minimize collision probability using cooperative routing in wireless sensor networks. We develop a mathematical model and formulate the problem as a large-scale Mixed Integer Non-Linear Programming problem. We also propose a solution based on the branch and bound algorithm augmented with reducing the search space. The proposed strategy builds up the optimal routes from each source to the sink node by providing the best set of hops in each route, the best set of relays, and the optimal power allocation for the cooperative transmission links. To reduce the computational complexity, we propose a near-optimal cooperative routing algorithm in which we solve the problem by decoupling the power allocation problem and the route selection problem. Therefore, the problem is formulated by an Integer Non-Linear Programming, which is solved using branch and bound space reduced method. The simulation results reveal the presented algorithms can significantly reduce the collision probability compared with existing schemes.

6.2 Introduction

Cooperative communication has emerged as a promising approach for mitigating wireless channel fading and improving the reliability of wireless networks by allowing nodes to collaborate with each other. Nodes in cooperative communication help each other with information transmission by exploiting the broadcasting nature of wireless communication [1]. In a cooperative transmission scheme, neighboring nodes are exploited as relay nodes, in which they cooperate with the transmitter-receiver pair to deliver multiple copies of a packet to the receiver node through independent fading channels. The idea behind

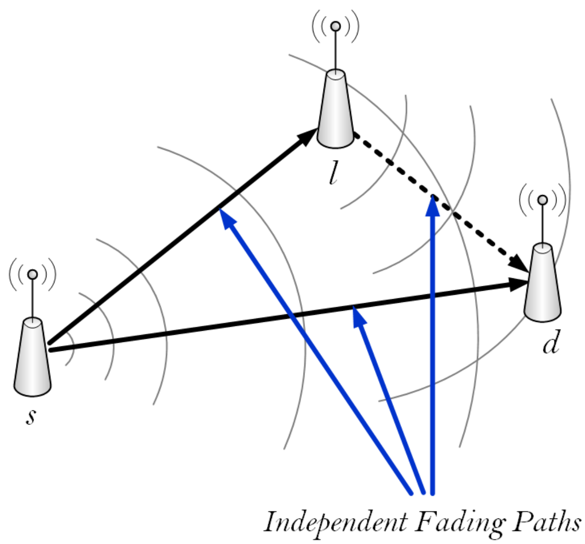


Figure 6.1: Collision Problem.

cooperative transmission is shown in Fig. 6.1. This figure illustrates a simple cooperative transmission scheme where two nodes (one source node and one relay node) communicate with the same destination node. Each node has one antenna and does not individually have spatial diversity. However, it may be possible for one node to overhear the signal of other nodes and forward them to the destination node. Because the fading paths from the two nodes are statistically independent, this generates spatial diversity. Combining multiple copies of the same signal at the destination node leads to several advantages, including a better signal quality, reduced transmission power, better coverage, and higher capacity [2–4].

Routing algorithms that take into consideration the advantages of cooperative transmission are known as cooperative routing. Therefore, cooperative routing is a cross-layer design approach that combines the network layer and the physical layer to transmit packets through cooperative links. This cross-layer design approach effectively enhances the performance of the routing protocols in wireless networks.

Cooperative routing was introduced by Khandani *et al.* [5] and the authors also showed that the problem of finding the optimum cooperative route is *NP-Hard*. In the past few years, significant progress has been made on the design and development of cooperative routing protocols. In [6], we presented a comprehensive survey of existing cooperative routing techniques together with the highlights of the performance of each strategy. While many efficient sub-optimal cooperative routing algorithms are proposed in the literature, only a few studies have focused on optimal cooperative routing. Sub-optimal cooperative routing algorithms can be divided into two categories. The first category of cooperation-based routing algorithms, namely Cooperative Along Shortest-Path (such as the proposed algorithms in [5, 7]) is implemented by finding the shortest-path route first, and then building the cooperative route based on the shortest path. The main idea of algorithms in this category is to use cooperative transmission to improve performance along the selected non-cooperative route. However, the optimal cooperative route might be completely different from the non-cooperative shortest path. Therefore, the merits of cooperative routing are not fully exploited if cooperation is not taken into account while selecting the route. One of the heuristic cooperative routing algorithms presented in [5] is called the Cooperative Along Non-cooperative (CAN-L) algorithm with the objective of minimizing total transmitted power. The basic idea is to run a non-cooperative shortest path first, and then to use cooperative transmission by the last L nodes along the non-cooperative path. The algorithms in the second category, Cooperative Based Path (e.g., the proposed algorithms in [8, 9]), address the above problem by exploiting cooperative routing during the route selection process. However, the algorithms in this category are not optimal due to the following reasons: (1) they employ sub-optimal approaches in the relay node selection [9], power allocation [8], or route selection [10] and (2) they utilize optimal relay node selection, resource allocation, and route selection but not jointly (as will be discussed in detail in Section 6.5), such as the algorithm in [2]. Authors in [8] presented an algorithm called Minimum Power Cooperative Routing (MPCR). The algorithm finds the route that minimizes the total transmission power. MPCR makes routing decisions by assuming the cooperative transmission is also available for each link. In [9] the authors proposed the EP-H1 algorithm. The EP-H1 algorithm considers the two-stage cooperation model to find the route that consumes minimum energy. In the fist stage the transmitter node broadcasts the message to its neighbors. In the second stage every node that has successfully decoded the message will join the transmitter node to form a cooperative transmitting set. The transmitting set cooperatively transmits the message to a receiver node using equal power. The power allocation vector minimizes the total amount of consumed energy.

The main objective of cooperative routing in all proposed schemes, either the optimal or sub-optimal cooperative routing algorithms, is to save energy while guaranteeing a certain QoS. However, packet collision minimization has not been taken into account in existing cooperative routing algorithms.

Interactions among multiple neighboring flows may lead to the hidden and exposed node problems which cause packet collision. In general, cooperative routing can improve the performance due to the more robust links and less power consumption. However, cooperative routing causes extra packet transmission by the relays. Therefore, the gain of a cooperative routing algorithm with multiple flows is different from the one with a single flow, especially in terms of the packet collision probability. There are only a few papers, such as [11–13], that considered multiple flows in cooperative routing. In [11] collision is brought into attention by defining a contention graph, where a set of transmitting nodes coordinates their transmissions to a set of receiving nodes. The algorithm approaches the non-cooperative protocol when network congestion emerges. Moreover, the congestion problem of cooperative routing in [12] is solved in the MAC layer. In [13], we proposed Minimum Collision Cooperative Routing (MCCR) algorithm by combining cooperative transmission, optimal power allocation, and route selection. However, the proposed algorithm is a sub-optimal routing due to the following reasons; (1) the optimal power allocation technique is decoupled from the optimal route selection and (2) a sub-optimal approach is employed in the relay node selection and relay nodes are selected as the node closest to the middle point of the transmitter and receiver nodes of each link.

In WSNs, upon the detection of an event, packet traffic load in some spots may get intensified, resulting in a high packet collision rate and consequently, packet loss. To solve this problem, we develop a mathematical characterization for the collision probability in cooperative routing. The presented framework demonstrates the exact formulation for the optimal relay node and optimal power allocation set, and the joint use of optimal power, relay node allocation, and path selection. The final problem formulation is in the form of Mixed Integer Non-linear Programming (MINLP). We propose a solution procedure based on the branch and bound method augmented with the effective space reduction method. The computational complexity of the algorithm for solving these problems grows exponentially with the number of binary variables. Due to the high complexity of the problem, one cannot obtain optimal solutions within reasonable time for the large network topologies. Therefore, one needs to resort to the heuristic approach. We present a heuristic near-optimal algorithm for the formulated problem by decoupling the optimal transmission power allocation from the route selection; we solve the INLP in the first phase and apply optimum power in the second phase.

To the best of our knowledge, there is no framework which can accurately characterize the collision probability in the cooperative network and minimize the collision problem employing cooperative routing. Overall, the main contribution of this chapter includes the following:

1. The collision problem in WSNs is formally defined and formulated. The traffic load per node in cooperative transmission is also explored.

2. An MINLP model, employing the cooperative routing, is presented to minimize the collision problem subject to the outage probability constraint.

3. The MINLP solution serves as a benchmark for evaluating the quality of the solutions obtained by any sub-optimal algorithm for this problem.

4. The obtained solution applies a joint optimization approach for power allocation, relay node assignment, and path selection which are the main optimization issues in cooperative routing.

5. Moreover, near-optimal algorithms are proposed by separating one of the optimization variable decisions, i.e., optimal transmission power, from the other optimization variables.

6. Our proposed algorithms find good solutions which ensure minimizing collision probability compared to the existing cooperative routing algorithms.

The remainder of this chapter is organized as follows. In Section 6.3, we illustrate the system model and formulate our optimization task. In Section 6.4, we develop a mathematical model and we formulate the problem to minimize collision probability by optimizing the relay node assignment, power allocation and path selection jointly. In Section 6.5, we propose the optimal solution to the problem. In Section 6.6, a near-optimal cooperative routing algorithm is presented. Simulation results and performance evaluations are given in Section 6.7. Finally, we conclude the chapter in Section 6.8.

6.3 System Model

We consider a WSN, where source nodes communicate with the destination nodes (or sink nodes) via cooperative routing. Let h_{ij} and n_{ij} represent the Rayleigh fading channel coefficient and the additive white Gaussian noise of the link between nodes i and j, respectively. We assume that the distance-based attenuation follows the generic exponential path-loss model with an exponent γ [8].

In direct transmission, where a source (s) transmits its signal directly to the next destination (d), the received signal at d is given by

$$y_{sd} = \sqrt{p_s^D K r_{sd}^{-\gamma}} h_{sd} u + n_{sd}, \tag{6.1}$$

where p_s^D is the transmission power from the source in the direct transmission mode, K is a constant that depends on the characteristics of the transmitter, the receiver, and channel (e.g., the frequency and the antenna gain), r_{sd} is the distance between the two nodes (s and d), and u is the transmitted data with a unity power.

The criterion for a good detection is that the received signal-to-noise-ratio (SNR) must be greater than the detection threshold (β). Outage is defined as the status when the receiver is unable to detect data u. Hence, a link is considered to be in outage if the received SNR falls below β. Thus, the outage probability, when direct transmission is only used, Pr^D_{out}, is defined as $Pr(SNR_{sd} < \beta)$. It can be easily shown that the power that minimizes the collision probability subject to the outage probability constraint ($Pr^D_{out} \leq Pr^*_{out}$) is given by

$$p^D_s = -\frac{\beta N_o r^{\gamma}_{sd}}{K \ln(1 - Pr^*_{out})}, \tag{6.2}$$

where Pr^*_{out} is the maximum acceptable outage probability and N_o represents the noise power.

In cooperative transmission, the employed system model is similar to that used in [8]. As shown in Fig. 6.1, a cooperative link consists of three nodes: source (s), destination (d), and a potential relay node (l). The relaying technique used in this study is the incremental adaptive decode-and-forward. With this technique, the source sends its signal to the destination using the direct link. If the destination is unable to detect the signal using the direct link, the relay forwards the signal to the destination (provided that the relay was able to detect the signal). If the relay is unable to detect the signal, it remains silent and the destination will rely on the direct signal only. For cooperative transmission, the received signals from s at d and l can be respectively expressed as

$$y_{sd} = \sqrt{p^C_s K r^{-\gamma}_{sd}} h_{sd} u + n_{sd}, \tag{6.3}$$

$$y_{sl} = \sqrt{p^C_s K r^{-\gamma}_{sl}} h_{sl} u + n_{sl}, \tag{6.4}$$

where p^C_s is the transmission power from the source in the cooperative transmission. If the relay forwards the signal to the destination, the received signal at the destination from the relay node can be expressed as $y_{ld} = \sqrt{p^C_l K r^{-\gamma}_{ld}} h_{ld} u + n_{ld}$, where p^C_l is the transmission power of the relay node. In this case, the destination detects the signal using the relay signal only. Although combining schemes such as maximum ratio combining are more

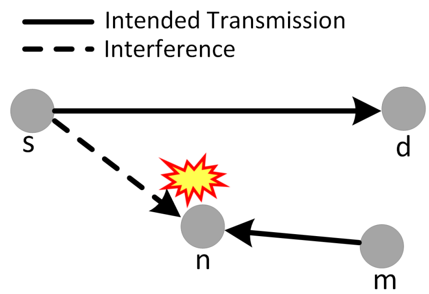


Figure 6.2: Collision Problem.

efficient, they require storage of the direct signal until the indirect signal is received. Also, combining schemes require more signal processing and perfect knowledge of the channel state information. Due to the limited power and processing capabilities in WSNs, such combining techniques are not employed in this work.

6.4 Problem Formulation

In this section, we present a mathematical model for our joint routing, relay node assignment, and power allocation. Denote $\mathbb{N}$ as the set of nodes in the network, with $\mid \mathbb{N} \mid= N$. In set $\mathbb{N}$, there are three subsets of nodes, namely, (i) the set of source nodes, $\mathbb{N}_s = \{s_1, s_2, ..., s_{N_s}\}$, with $\mid \mathbb{N}_s \mid= N_s$, (ii) the set of destination nodes, $N_d = \{d_1, d_2, ..., d_{N_d}\}$ with $\mathbb{N}_d =\mid N_d \mid$, and (iii) the set of remaining nodes that are available for serving either as intendant nodes in the route, or as relay nodes. Moreover, nodes i and j are disconnected from each other, $Con_{i,j} = 0$, if $y_{ij} \geq Y_d$, where Con is the connectivity indicator and Y_d is the connection distance threshold. Otherwise, node i and j are connected and $Con_{i,j} = 1$.

As illustrated in Fig. 6.2, a source node, s, will cause a collision to another node, n, if s is sending while n is simultaneously receiving (from another node, m), provided that the interference from s at n is high enough to cause a collision. As a result, in direct transmission, the probability that s will cause collision at n, given that m was unable to sense the transmission of s, $Pr(Coll._s^D(n))$, can be expressed as

$$Pr\left(Coll._s^D(n)\right) = Pr_{rx}(n)Pr(I_s(n) > I_{th}^{Coll.}), \tag{6.5}$$

where $Pr(I_s(n) > I_{th}^{Coll.})$ is the probability that the received interference from s by n, $I_s(n)$, is greater than the interference threshold, $I_{th}^{Coll.}$, above which the interference causes a collision and the desired signal is undetectable and $Pr_{rx}(n)$ is the probability that n will be receiving given by

$$Pr_{rx}(n) = \sum_{i \in \mathbb{N}}^{i \neq n} Pr_{tx}(i)\, E_{i,n} + \sum_{v \in \mathbb{N}}^{v \neq n} \sum_{w \in \mathbb{N}}^{w \neq n, w \neq v} Pr_{tx}(v)\, F_{v,w}^{n}, \tag{6.6}$$

where $E_{i,n}$ is a binary variable to specify whether the link between i to n is in the routing solution, i.e.,

$$E_{i,n} = \begin{cases} 1 & \text{if node } n \text{ is used as the next node in its route} \\ & \text{to destination,} \\ 0 & \text{otherwise.} \end{cases} \tag{6.7}$$

$F_{i,j}^n$ is another binary variable to specify whether n is used as a relay node for the link between i to j in the routing solution, i.e.,

$$F_{i,j}^n = \begin{cases} 1 \, \text{if node } n \text{ is used as the relay node on hop } i, j, \\ 0 \qquad \text{otherwise.} \end{cases} \tag{6.8}$$

$Pr_{tx}(n)$ is the probability that n is transmitting; hence, $Pr_{tx}(n) = \Lambda_t(n)\, T_p$, where T_p is the packet time duration and $\Lambda_t(n)$ is defined as the total packet transmission rate of node n. Therefore, $\Lambda_t(n)$ is the sum of the packet generation rate of node itself, $\Lambda_0(n)$, and the transmission rate of packets that node n forwards either as a next hop or a relay node, thus,

$$\Lambda_t(n) = \Lambda_0(n) + \sum_{m\in\mathbb{N}}^{m\neq n} \Lambda_t(m)\Big\{E_{m,n}\big(Pr\left(SNR_{mn} > \beta\right) +$$
$$Pr\left(SNR_{mn} < \beta\right) \sum_{l\in\mathbb{N}}^{l\neq n, l\neq m} Pr\left(SNR_{ml} > \beta\right) Pr\left(SNR_{ln} < \beta\right)$$
$$+ \sum_{k\in\mathbb{N}}^{k\neq n, k\neq m} F_{m,k}^{n} Pr\left(SNR_{mk} < \beta\right)\left(SNR_{mn} > \beta\right)\Big\}, \quad (6.9)$$

where SNR_{mn} is the SNR of the link between node m and node n.

Employing Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism for channel access, nodes that are within the sensing range of a transmitter are inhibited from transmitting. Therefore, the probability that s will cause a collision to one or more nodes in the network is given by

$$Pr(Coll._s^D) = \Big(1 - \prod_{n\,\in\,\mathbb{N}} \left(1 - Pr\left(Coll._s^D\left(n\right)\right)\right)\Big) Pr\left(NST_s\right), \quad (6.10)$$

where $Pr(NST_s)$ is the average probability of not sensing transmission of s by a node that has traffic to send to n, thus,

$$Pr\left(NST_s\right) = \sum_{m\in\mathbb{N}} Pr(I_s(m) < I_{th}^{Sens.})\big(Pr_{tx}(m)E_{m,n} +$$
$$\sum_{k\in\mathbb{N}}^{k\neq m,n} Pr_{tx}(k)F_{m,n}^{k} Pr\left(SNR_{mn} < \beta\right) Pr\left(SNR_{kn} > \beta\right)\big), \quad (6.11)$$

where $I_{th}^{Sens.}$ is the carrier sensing threshold above which the channel is deemed busy.

Since incremental relaying is used, the average collision probability caused by the cooperative link to all other nodes in the network is equal to the collision probability caused by the source, $Pr(Coll._s^D)$, if the direct signal (from the source) is detectable at the destination or if the relay node is unable to detect the source signal. Otherwise, collision happens by either the source or the relay; hence, the collision probability is the probability of the union of two events: 1) collision caused by the source and 2) collision caused by the relay. Thus, the per node collision probability caused by the cooperative transmission (from s and l) to all other nodes in the network is given by

$$\begin{aligned} Pr\left(Coll._{s,l}^{C}\right) &= Pr(Coll._{s}^{D}) \\ &\Big[Pr\left(SNR_{sd} > \beta\right) + Pr\left(SNR_{sd} < \beta\right) Pr\left(SNR_{sl} > \beta\right)\Big] + \\ &\Big[1 - \left(1 - Pr(Coll._{s}^{D})\right)\left(1 - Pr(Coll._{l}^{D})\right)\Big] \\ &Pr(SNR_{sd} < \beta) Pr(SNR_{sl} > \beta). \end{aligned} \tag{6.12}$$

Inserting the exponential distribution due to the Rayleigh fading and after mathematical manipulation, Eq. (6.12) can be rewritten as in Eq. (6.13).

$$\begin{aligned} Pr\left(Coll._{s,l}^{C}\right) = &\left(1 - \prod_{i\in\mathbb{N}}^{i\neq s}\left[1 - Pr_{rx}\left(i\right) exp\left(-\frac{I_{th}\, r_{si}^{\gamma}}{K\, p_s}\right)\sum_{j\in\mathbb{N}}^{j\neq s, j\neq i} Pr_{tx}\left(j\right)\left(1 - exp\left(-\frac{I_{th}'\, r_{sj}^{\gamma}}{K\, p_s}\right)\right)\right]\right) \\ &+ \left(1 - \prod_{i\in\mathbb{N}}^{i\neq s}\left[1 - Pr_{rx}\left(i\right) exp\left(-\frac{I_{th}\, r_{si}^{\gamma}}{K\, p_l}\right)\sum_{j\in\mathbb{N}}^{j\neq s j\neq i} Pr_{tx}\left(j\right)\left(1 - exp\left(-\frac{I_{th}'\, r_{sj}^{\gamma}}{K\, p_l}\right)\right)\right]\right) \\ &\left(1 - exp\left(-\tfrac{N_o\, \beta_d\, r_{sd}^{\gamma}}{Kp_s}\right)\right) * exp\left(-\tfrac{N_o\, \beta_d\, r_{sl}^{\gamma}}{Kp_s}\right) \\ &- \left(1 - \prod_{i\in\mathbb{N}}^{i\neq s}\left[1 - Pr_{rx}\left(i\right) exp\left(-\frac{I_{th}\, r_{si}^{\gamma}}{K\, p_s}\right)\sum_{j\in\mathbb{N}}^{j\neq s, j\neq i} Pr_{tx}\left(j\right)\left(1 - exp\left(-\frac{I_{th}'\, r_{sj}^{\gamma}}{K\, p_s}\right)\right)\right]\right) \\ &\left(1 - \prod_{iin\mathbb{N}}^{i\neq s}\left[1 - Pr_{rx}\left(i\right) exp\left(-\frac{I_{th}\, r_{si}^{\gamma}}{K\, p_l}\right)\sum_{j\in\mathbb{N}}^{j\neq s, j\neq i} Pr_{tx}\left(j\right)\left(1 - exp\left(-\frac{I_{th}'\, r_{sj}^{\gamma}}{K\, p_l}\right)\right)\right]\right) \\ &\left(1 - exp\left(-\tfrac{N_o\, \beta_d\, r_{sd}^{\gamma}}{Kp_s}\right)\right) exp\left(-\tfrac{N_o\, \beta_d\, r_{sl}^{\gamma}}{Kp_s}\right) \end{aligned} \tag{6.13}$$

Therefore, the probability that the entire route causes collision can be expressed as

$$Pr(Coll._{route}) = 1 - \prod_{h=1}^{H}\left(1 - Pr\left(Coll._{s_h, l_h}^{C}\left(h\right)\right)\right), \tag{6.14}$$

where h is the hop number and H is the total number of hops in the route.

In a cooperative transmission link with incremental adaptive decode-and-forward relaying, outage probability is given by

$$Pr_{out}^{C} = Pr(SNR_{sd} < \beta)Pr(SNR_{sl} < \beta) + Pr(SNR_{sd} < \beta)Pr(SNR_{sl} > \beta)Pr(SNR_{ld} < \beta). \tag{6.15}$$

Employing the exponential SNR in Eq. (6.15), outage probability of a cooperative link can be expressed as

$$Pr_{out}^{C} = 1 - exp\left(-\frac{k1}{p_s}\right) - exp\left(-\frac{k2}{p_s} - \frac{k3}{p_l}\right) - exp(\frac{k1+k2}{p_s} + \frac{k3}{p_l}), \tag{6.16}$$

where $k1 = \frac{N_o \beta r_{sd}^{\gamma}}{K}$, $k2 = \frac{N_o \beta r_{sl}^{\gamma}}{K}$, and $k3 = \frac{N_o \beta r_{ld}^{\gamma}}{K}$.

In addition to that, the end-to-end outage probability of a certain route is defined as the probability that outage takes place in one of the H hops of the route, i.e.,

$$Pr_{out}(route) = 1 - \prod_{h=1}^{H} \left(1 - Pr_{out}^{C}(h)\right), \tag{6.17}$$

where $Pr_{out}^{C}(h)$ is the outage probability of the h-th link in the route.

The goal of the algorithm is to find the route from each source to the sink such that each route minimizes the collision probability per node due to the route to other nodes in the network, while satisfying the end-to-end outage probability constraint. Therefore, the optimization problem can be formulated as below

$$\underset{p_{s_h},\, p_{l_h},\, E_{i,j},\, F_{i,j}^k}{Min.} \quad Coll_T, \tag{6.18}$$

$$s.t.\ Pr_{out}(route_r) \leq Pr_{out}^*, \qquad \forall r \in \mathbb{N}_s$$

$$C1 : 1 \leq \sum_{i\in\mathbb{N}} \sum_{j\in\mathbb{N}}^{j\neq i} E_{i,j} + \sum_{i\in\mathbb{N}} \sum_{j\in\mathbb{N}}^{j\neq i} \sum_{k\in\mathbb{N}}^{k\neq i, k\neq j} F_{i,j}^k \leq 2N_s\left(N-1\right),$$

$$C2 : \qquad E_{i,j} - F_{i,j}^k \geq 0, \qquad \forall i,j,k \in \mathbb{N} \quad i \neq j \neq k$$

$$C3 : \qquad E_{i,j} - \sum_{k\in\mathbb{N}}^{k\neq i} E_{j,k} \geq 0,$$

$$C4 : \qquad \sum_{i\in\mathbb{N}}^{i\neq D} E_{i,D} \geq 1,$$

$$C5 : \qquad \sum_{i\in\mathbb{N}}^{i\neq D} E_{S,i} \geq 1,$$

where p_{s_h}, p_{l_h}, $E_{i,j}$, and $F_{i,j}^k$ are the optimization variable. $Coll_T$ is the objective function, which is the total collision probability per node in the network and can be expressed as

$$Coll_T = 1 - \prod_{r=1}^{N_s}(1 - Pr(Coll._{route_r})). \tag{6.19}$$

As explained earlier, each node in a cooperative routing can receive data from the previous node and can work either as the relay node or the next hop. Constraint $C1$ in (6.18) forces the range for the number of links involved in the source-destination paths in the network with N_s source nodes (i.e., N_s flows in the network). A cooperative relay node may be assigned to hop (i, j) only if the hop is included in the path solution. Otherwise, no relay node will be assigned to that hop (i, j); $C2$ in Eq. (6.18) characterizes this constraint. Constraint $C2$ also holds when j is not a next hop and in that case all E variables in (6.18) are equal to zero. Constraint $C3$ formulates the flow balance at an intermediate node along the path between each source, s_i, and the destination node, D.

Moreover, the destination node must be reached and each source node must transmit data to some other nodes. These constraints are expressed by $C4$ and $C5$, respectively.

Obviously, (6.18) is a *Mixed Integer Non-Linear Programming* problem, since the binary variables ($E_{i,j}$, $F_{i,j}^k$) and real variables (p_{s_h}, p_{l_h}) are involved in the non-linear objective and the constraints.

Lemma 1. *The minimum collision cooperative routing problem is NP-Hard.*

The proof of Lemma 1 is given in the Appendix.

6.5 Proposed Solution Procedure

The Branch and Bound (BnB) algorithm is by far the most widely used tool for solving integer optimization problems. Obviously, the optimal value of cost function in a continuous linear relaxation of a problem will always be a lower bound on the optimal value of the cost function. Moreover, in any minimization, any feasible point always specifies an upper bound on the optimal cost function value. The idea of the BnB is to utilize these observations to subdivide MINLP's feasible region into more-manageable subdivisions and then, if required, to further partition the subdivisions. These subdivisions make a so-called enumeration tree whose branches can be pruned in a systematic search for the global optimum.

6.5.1 Branch and Bound Space Reduced algorithm

We enhance the BnB algorithm and develop a *BnB Space Reduced* algorithm to solve the MINLP. This proposed algorithm reduces the BnB area of a search and implements the

BnB relaxation and separation strategy to solve the problem.

The pseudocode of the proposed framework, using the BnB-Space Reduced, is described in Table 1. In this algorithm, Ω represents optimization problem set and Ω^* denotes the global minimum of the cost function $Coll_T$. Therefore, the algorithm provides a (1- ϵ) optimal solution Ω_ϵ, which means Ω_ϵ is close enough to Ω^* such that $\Omega^* \geq (1-\epsilon)\Omega$. Initially, Ω includes the original problem, i.e., $Coll_T$ denoted by $\omega 0$. A lower bound of the cost function is first derived through solving a linear relaxation of $Coll_T$ denoted by (B_L) (line 3 in Table 1. Construction of the linear relaxation is described in the next subsection. Since any feasible solution of ω can serve as an upper bound, the one obtained by rounding under the satisfaction of all constraints is used and denoted as B_U.

The process of finding the lower and upper bound for the cost function, is called *bounding*. If the derived upper and lower bounds are within the ϵ-vicinity of each other, the algorithm terminates (line 10, 11). Otherwise, it divides the feasible region of the problem into two narrower subsets (*branching* step), and the problem ω will be replaced with two subproblems $\omega 1$ and $\omega 2$ constructed by branching binary variable $E_{i,j}$, respectively (see line 17). Simultaneously, other variables are fixed according to the constraints in Eq. (6.18).

The developed feature of BnB, reduces the feasible integer variable space. In this phase of the algorithm, all subsets that include the disconnected integer variables (i.e., disconnected next hop $(E_{i,j} = 1 \& Con_{i,j} = 0)$ or disconnected relay node $\left(F^k_{i,j} = 1 \& Con_{i,k} = 0\right.$ or $\left.Con_{k,j} = 0\right)$ are removed and the subsets area of search is reduced.

Through an iterative branching procedure, subsets are further divided into smaller ones to build the enumeration tree. The structure of the enumeration tree allows the algorithm to remove some branches and search for the solution in a very effective way.

Moreover, narrowing down the subsets of the optimization variables makes the linear relaxations tighter (i.e., increases B_L) and provides the next local search processes with a closer starting point to the optimal solution (i.e., reduces B_U). Hence, the gap between B_L and B_U is reduced as the process continues. More precisely, the global lower bound B_L is updated in each iteration, in order to contain the minimum of the lower bounds of all subsets (lines 5, 6). The global upper bound B_U is also updated at each iteration (lines 8, 9) and the branches with a lower bound greater than $(1-\epsilon)B_U$ are pruned (line 13). This approach is continued until the difference between the global lower and upper bounds satisfy the accuracy ϵ (lines 10, 11). Clearly, we may lose the global optimum by pruning the branches. However, if the global optimum is in a pruned branch with the lower bound is B_{L_ω}, then $\Omega^* \geq B_{L_\omega}$, and consequently, $\Omega^* \geq (1-\epsilon)B_U$. Therefore, the current best feasible solution with objective value B_U is already an $(1-\epsilon)$ optimal solution, and the optimality is still guaranteed $(1-\epsilon)$. In fact, this guarantee is the key feature of the algorithm, which makes it very effective in solving the MINLP.

6.5.2 A lower bound for the collision problem

To obtain the exact solution using a branch-and-bound algorithm in a reasonable computation time, computation of the lower bound of the cost of each branch are important. The stronger bound decreases the number of enumerations for searching the most promising branch. In order to derive the lower bound of the collision problem the linearization technique along with relaxation of the integer variables are used and the non-linear objective and constraint are replaced by the linear-relaxed form. Firstly, we approximate the exponential expression in the objective function ($Coll_T$) and constraint in Eq. (6.17)

Table 1: Proposed Cooperative Routing Algorithm using MINLP.

INPUT An arbitrarily located set of nodes, $\mathbb{N}$, set of source nodes, N_s, and a destination node, D.
- define set Ω of sub-problems;
- $\Omega \leftarrow \omega 0; B_U \leftarrow \infty$;
- solve linear relaxation of $Coll_T$ and denote its minimum cost function by B_L.

while $\Omega \neq \emptyset$ **do**
    - select a problem $\omega \in \Omega$ with the minimum B_{L_ω};
    - let $B_L \leftarrow B_{L_\omega}$;
    - set B_{U_ω} a feasible solution for ω via local search;
    if $B_{U_\omega} < B_U$ **then**
        - $B_U \leftarrow B_{U_\omega}$, $\Omega^* \leftarrow \Omega$;
        if $B_L \geq (1-\epsilon)B_U$ **then**
            - **return** B_{U_ω};
        else
            - remove all problems $\omega i \in \Omega$ with $B_{L_\omega} \geq (1-\epsilon)B_U$;
        end if
    end if
    - remove all problems that includes disconnected link;
    - select two sub-problem $\omega 1$ and $\omega 2$;
    - solve linear relaxation of $\omega 1$ and $\omega 2$ and denote their cost functions by$B_{L_{\omega 1}}$ and $B_{L_{\omega 2}}$;
    if $B_{L_{\omega 1}} \leq (1-\epsilon)B_U$ **then**
        - $B_L \leftarrow B_L \cup \{\omega 1\}$;
    end if
    if $B_{L_{\omega 2}} \leq (1-\epsilon)B_U$ **then**
        - $B_L \leftarrow B_L \cup \{\omega 2\}$;
    end if
end while

OUTPUT the $(1-\epsilon)$ optimal solution B_U.

using a first order Taylor polynomial approximation. Then, due to the fact that the logarithm function can transfer the multiplication and divisions operations of the variables into linear form, we define the new variable θ and we apply the logarithmic operation to the non-linear functions. Therefore, the following operations are used for linearisation and relaxation of the non-linear functions ($Coll_T$ and Pr_{out}).

$$exp(-z_{i,j}) = 1 - z_{i,j} \tag{6.20}$$

$$\theta_{i,j} = \ln(v_{i,j} \times w_{i,j}) = \ln v_{i,j} + \ln w_{i,j} \tag{6.21}$$

where z, v, and w are the optimization variables. For instance, using Eq. (6.20), the term $exp\left(-\frac{I_{th} r_{si}}{K p_s}\right)$ in Eq. (6.13), can be written as $\left(1 - \frac{I_{th} r_{si}}{K p_s}\right)$, and doing a simple change of variable $\frac{I_{th} r_{si}}{K p_s} = K' X_s$, the term can be rewritten as $\left(1 - K' X_s\right)$ which is in a linear expression.

6.5.3 Complexity

The worst case computational complexity of the MINLP grows exponentially with the number of integer variables. In other words, a problem with b_r binary variable requires solving 2^{b_r} non-linear programming problems [14]. Although actual run-time is reduced, due to the search space reducing, the complexity of the algorithm remains exponential. Therefore, low-complexity near-optimal (sub-optimal) approach is provided in the next section.

6.6 Near-optimal Cooperative Routing for Collision Minimization

In order to reduce the computational complexity, we propose a new algorithm in which the optimal transmission power (for the source and relay nodes of each link) is allocated separately, and the optimal power allocation is assigned after the routing solution.

The proposed sub-optimal cooperative routing algorithm is presented in Table 2. This algorithm uses equal, fixed transmission power in the objective function and the constraints. This value is assumed to be 0 dBm, that is the standard value in IEEE 802.15.4 devices [15]. Therefore, the problem is simplified to an INLP problem. The cost function of the algorithm is defined as $Coll_T \mid_{p_s=p_l=0\ dBm}$. The BnB Space Reduced algorithm, which is discussed in subsection 6.5.1, is employed to solve the INLP problem as well (line 3). After optimal path selection using BnB Space Reduced algorithm, the optimal power allocation is obtained by solving a constrained optimization problem using the Lagrange Multipliers method.

Table 2: Proposed Cooperative Routing Algorithm using INLP Pseudo code.

1 **INPUT** An arbitrarily located set of nodes, $\mathbb{N}$, set of source nodes, N_s, and a destination node, D.
2 - $p_s \leftarrow 0$ dBm, $p_l \leftarrow 0$dBm ;
3 - $Coll'_T = \{Coll_T \mid p_s = p_l = 0dBm\}$;
4 - solve the relaxed problem using BnB space reduce algorithm in Table 1 and denotes its results as $P^*_{N_s}$.
5 - apply Lagrange Multiplier function on $P^*_{N_s}$;
6 - obtain optimal power allocation for each transmitter and relay from Eqs. (6.24)-(6.26);
7 **OUTPUT** Near-Optimal path with optimal power allocation.

The constraint optimization problem for each selected cooperative link can be formulated as follows.

$$\begin{aligned} &\underset{p_s,p_l}{Min} \quad Pr\left(Coll._{s,l}^{C}\right), \\ &s.t.\ Pr_{out}^{C} \leq Pr_{out}^{*}. \end{aligned} \tag{6.22}$$

In a cooperative transmission link, the constrained optimization problem can be solved using the Lagrange Multipliers method as follows

$$\begin{aligned} &\tfrac{\partial}{\partial\, p_s}(\, Pr(Coll._{s,l}^{C}) \,+\lambda\, Pr_{out}^{C}) = 0, \\ &\tfrac{\partial}{\partial\, p_l}(\, Pr(Coll._{s,l}^{C}) \,+\lambda\, Pr_{out}^{C}) = 0, \\ &Pr_{out}^{C} = Pr_{out}^{*}\ , \quad \lambda > 0, \end{aligned} \tag{6.23}$$

where λ is the Lagrange multiplier. By substituting Eqs. (6.13), (6.14), (6.16), and (6.17) in Eq. (6.23), we get Eqs. (6.24)-(6.26).

$$\sum_{n\in\mathbb{N}}\left[\frac{I_{th}^{Coll.}r_{sn}^{\gamma}}{Kp_s^2}\,\phi\left(p_s,n\right)-\theta\left(p_s,n\right)\right]\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_s,m\right)\right] \tag{6.24}$$

$$\begin{gathered} \left[1-\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(exp\left(-\tfrac{k2}{p_s}\right)-exp\left(-\tfrac{k1+k2}{p_s}\right)\right)\right] \\ -\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(\tfrac{k1}{p_s^2}\right)exp\left(-\tfrac{k1+k2}{p_s}\right)+ \\ \left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(exp\left(-\tfrac{k2}{p_s}\right)-exp\left(-\tfrac{k1+k2}{p_s}\right)\right)\tfrac{k2}{p_s^2}+\left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_s,n\right)\right]\right) \\ \left(1-\prod_{n\in\mathbb{N}}\left[1-\phi\left(p_l,n\right)\right]\right)\left(\tfrac{k1+k2}{p_s^2}exp\left(-\tfrac{k1+k2}{p_s}\right)+\tfrac{k2}{p_s^2}exp\left(-\tfrac{k2}{p_s}\right)\right)- \\ \tfrac{\lambda k1}{p_s^2}exp\left(-\tfrac{k1}{p_s}\right)-\tfrac{\lambda k2}{p_s^2}exp\left(-\left(\tfrac{k2}{p_s}+\tfrac{k3}{p_l}\right)\right)-\tfrac{\lambda(k1+k2)}{p_s^2}exp\left(-\tfrac{k1+k2}{p_s}-\tfrac{k3}{p_l}\right)=0, \end{gathered}$$

$$\sum_{n\in\mathbb{N}}\left\{\frac{I_{th}r_{sn}^{\gamma}}{Kp_l^2}\,\phi\left(p_l,n\right)-\theta\left(p_l,n\right)\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_l,m\right)\right]\right\} \tag{6.25}$$

$$\times\left[exp\left(-\tfrac{k2}{p_s}\right)-exp\left(-\tfrac{k1+k2}{p_s}\right)\right]\prod_{m\in\mathbb{N}}\left[1-\phi\left(p_s,m\right)\right]$$

$$-\tfrac{\lambda k3}{p_l^2}\left[exp\left(-\tfrac{k2}{p_s}-\tfrac{k3}{p_l}\right)+exp\left(-\tfrac{k1+k2}{p_s}-\tfrac{k3}{p_l}\right)\right]=0,$$

$$1-exp\left(-\tfrac{k1}{p_s}\right)-exp\left(-\tfrac{k2}{p_s}-\tfrac{k3}{p_l}\right)-exp(\tfrac{k1+k2}{p_s}+\tfrac{k3}{p_l})=Pr_{out}^{*}, \tag{6.26}$$

where $\phi\left(p,n\right)$ and $\theta\left(p,n\right)$ are defined as follows

$$\phi\left(p,n\right)=Pr_{rx}\left(n\right)exp\left(-\tfrac{I_{th}^{Coll.}r_{sn}^{\gamma}}{K\,p}\right)Pr\left(NST_s\right),$$

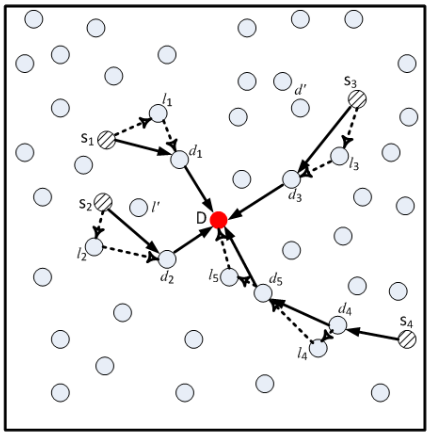
$$\theta\left(p,n\right)=Pr_{rx}\left(n\right)exp\left(-\tfrac{I_{th}^{Coll.}r_{sn}^{\gamma}}{K\,p}\right)\sum_{m\in\mathbb{N}}\frac{I_{th}^{Sens.}\,r_{sm}^{\gamma}}{K\,p^2}Pr\left(NST_s\right).$$

These three expressions (Eqs. (6.24) - (6.26)) are solved simultaneously to determine p_s and p_l.

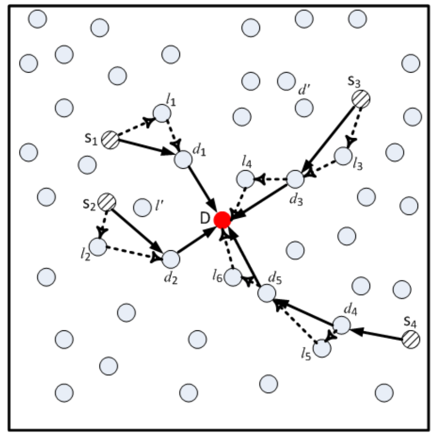
6.7 Performance Evaluation

In this section, we evaluate the performance of the proposed algorithms. We consider a random topology consisting of 10 to 50 sensor nodes (i.e., N varies from 10 to 50) and 3 or 4 flows (with randomly selected sources) within an area of 250m $\times$ 250m. The evaluation scenario is similar to the one used in [11].

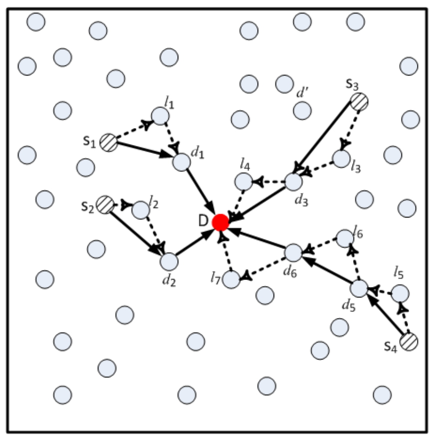
We assume that the path-loss exponent (γ) equals 4, the noise power (N_o) equals -103.8 dBm, and the detection SNR threshold (β) equals 10 dB. The interference threshold equals αN_o, where α is a design parameter. In this chapter we assume $\alpha=1$, which



(a) Cooperative routing using MINLP



(b) Cooperative routing using INLP

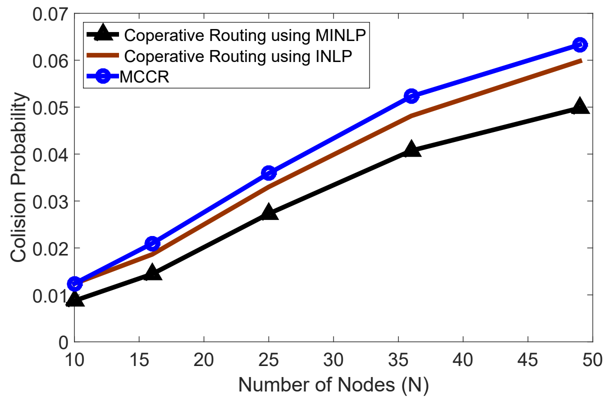


(c) MCCR

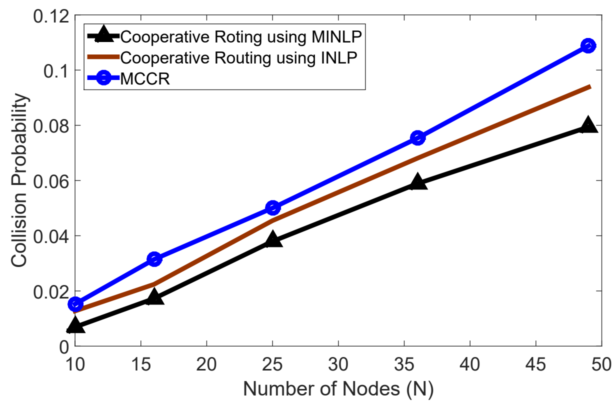
Figure 6.3: Proposed algorithms for the 50-Node network with 4 flows.

means the collision interference threshold is equal to the noise power ($I_{th}^{Coll.} = N_o$). We also assume the sensing threshold equals the noise power, i.e., $I_{th}^{Sens.} = N_o$ [15]. The packet generation rate (Λ_0) at each source node follows Poisson traffic model with a rate of 4 pkt/s. The end-to-end outage probability constraint (Pr_{out}^{*}) is set to 0.1.

To deal with the practical aspects of the presented framework, the algorithm can be implemented in an off-line manner during the initialization phase.



(a)



(b)

Figure 6.4: Comparing collision probability of the proposed routing with (a) 3 flows in the network, (b) 4 flows in the network.

6.7.1 Comparison between the proposed collision minimization cooperative routing algorithms

The proposed routing solutions: cooperative routing solution using MINLP, cooperative routing using INLP, and the MCCR algorithm presented in [13] are compared in Fig. 6.3 (a)-(c), respectively for a network with 50 sensor nodes. As shown in this figure, there are 4 source nodes, $N_s = 4$, and one sink node in the network. It can be seen that the proposed routing solutions select the nodes as far as possible from the high traffic load areas. In other words, the algorithms avoid selecting nodes near the active nodes to minimize collision probability. For example, in Fig. (6.3) (a)-(c), node $d^{'}$ is not selected as the next hop, since it is near the active nodes. Moreover, in the cooperative routing solution using the MINLP and INLP algorithms, unlike MCCR, the selected relay nodes are also located far from the high traffic load areas. As can be seen in Fig. (6.3) (a) and (b), node $l^{'}$, which is near the active nodes, is not selected as the relay node in MINLP and INLP routing algorithms.

The Collision probability caused by optimal cooperative routing using MINLP solution and that of INLP, and the MCCR algorithm are compared in Fig. 6.4 (a) and (b), respectively. From this figure, it is evident that cooperative routing using MINLP solution outperforms the other schemes and has the lowest collision probability. It can be seen that, at $N = 50$ and 4 flows in the network, the collision probability of cooperative routing using MINLP solution is reduced by 21%, and 43% compared with INLP and MCCR, respectively. This collision probability reduction is expected because in cooperative routing using MINLP, unlike INLP and MCCR, optimum power allocation is involved (from the initial routing decision process) in the routing selection to minimize collision probability. Moreover, unlike MCCR, the cooperative routing algorithms using MINLP and INLP assign the optimal relay node to each cooperative link. In the MINLP, the collision probability is the cost function during the route selection and power is allocated to the transmitters, in each hop, to minimize the collision probability caused by selected links across the route. However, the price for achieving optimal performance is the higher computational complexity of MINLP.

6.7.2 Evaluating the effect of cooperative routing parameters

To investigate the effect of each of the cooperative routing parameters (cooperative path selection, relay selection, and cooperative power allocation) separately in minimizing the collision probability (i.e., one technique is used, while the other two are not employed), we developed two additional routing algorithms. In the first one, called Cooperative Along Minimum Collision Direct path (CAMCD), cooperation is employed after constructing the route with the minimum collision probability using direct links only. Therefore, it does not take into account the possibility of using cooperative links during route selection. However, after route selection, it may use cooperative transmission over the links of the selected route. The second algorithm, called Minimum Collision Non-cooperative (MCN), considers only direct links during both the route selection and signal transmission. CAMCD and MCN use optimal power allocation, as explained in Section 6.6.

As shown in the Fig. 6.5, taking into account the possibility of using cooperative link during the route selection in cooperative routing using MINLP contributed 42% in minimizing collision probability. Moreover, comparing the performance of cooperative routing using MINLP and MCN to minimize collision reveals that cooperation transmission contributes 57% in collision reduction of the cooperative routing using MINLP algorithm.

Furthermore, in order to gain insight into the effect of the optimal power allocation to minimize the caused collision probability with cooperative routing using MINLP, we compare the performance of the algorithm with optimal power allocation with that of the algorithm with equal power allocation (i.e., $p_s = p_l = 0$ dBm for all nodes in the route). As shown in Fig. 6.5, the contribution of optimal power allocation in the collision

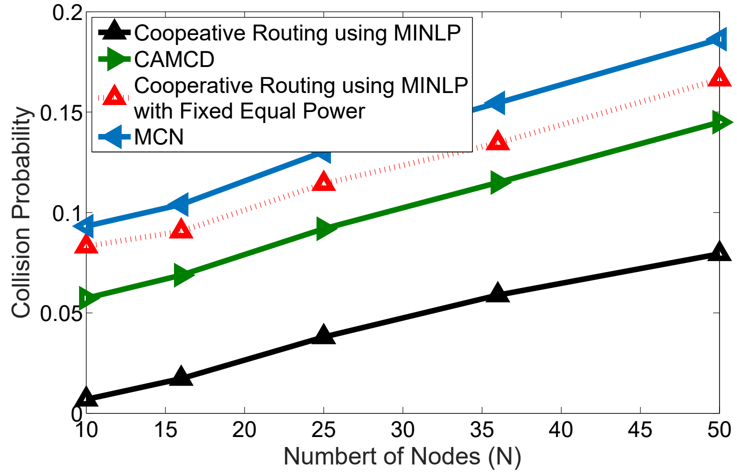


Figure 6.5: Evaluating the contribution of the cooperative routing parameters.

probability reduction ranges from 39% to 47% for $N = 9$ to 50.

6.7.3 Comparison between the proposed cooperative routing and minimum power cooperative routing algorithms

We compare the performance of the proposed cooperative routing using the MINLP solution algorithm with that of OKCR [16], EP-H1 [9], MPCR [8], and CAN-L [5]. These algorithms are the common and well-known cooperative routing algorithms, in which the assuming scenario is compatible with our proposed cooperative routing algorithm. The objective of the OKCR, EP-H1, MPCR and CAN-L algorithms is to minimize total transmission power in cooperative routing. Fig. 6.6 compares the collision probability caused by cooperative routing using the MINLP solution algorithm and that of the OKCR, EP-H1, MPCR and CAN-3 algorithms versus the number of nodes in the network. It is evident that the cooperative routing using the MINLP solution algorithm outperforms the other schemes and has the lowest collision probability. At N = 49, the collision probability of cooperative routing using MINLP solution is reduced by 82%, 78%, 56%, and 93% compared with OKCR, EP-H1, MPCR, and CAN-3, respectively. This collision probability reduction is expected because cooperative routing using MINLP solution selects the cooperative route that minimizes the collision probability by employing the collision probability as the cost function during the route selection and also by allocating the power (in each hop) to minimize the collision probability caused by the selected links across the route. By doing that, the cooperative routing using MINLP solution avoids selecting nodes that can cause high collision probability either because of the large number of neighbors or because some of these neighbors have a high probability of being used as the receiver or transmitter.

The required transmission power of the selected routes by different routing algorithms, in the network with 4 flows, is shown in Fig. 6.7. A larger number of nodes increases the distance between source-sink nodes; therefore, the total transmission power increases. In contrast, the CAN-3 algorithm first constructs the shortest-path route then it applies the cooperative transmission on the last 3 links of the established route. Therefore, the CAN-3 algorithm is limited in applying the cooperative transmission on a certain number of nodes, while the other algorithms can consider any node in the network to be a part of cooperative routing. Thus, the CAN-3 algorithm consumes more transmission power than the other algorithms in Fig 6.7. Moreover, the objective in MPCR is to minimize transmission power; therefore, MPCR is slightly more energy efficient than cooperative routing using MINLP solution. Comparing Figs. 6.6 and 6.7 show that minimizing the transmission power does not necessarily minimize the collision probability in the cooperative routing.

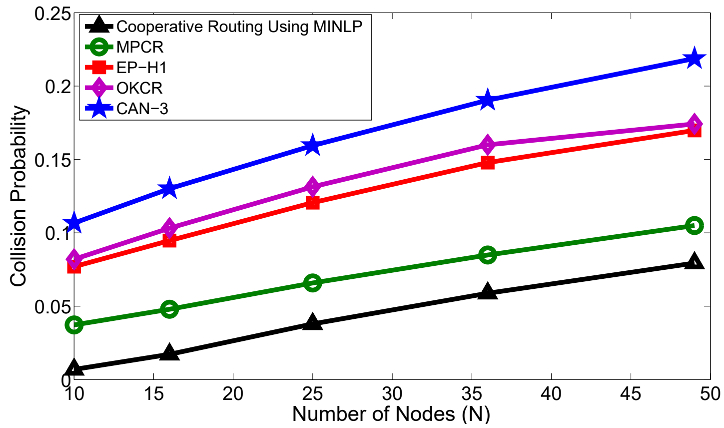


Figure 6.6: Comparing collision probability of the proposed cooperative routing and that of minimum power cooperative routing algorithms.

6.7.4 Evaluating the total power consumption, considering retransmission of collided packets

It was shown in the previous subsection that, although the algorithm that minimizes the collision probability requires more transmission power than the minimum-power cooperative routing, the former algorithm has significantly less collision probability. Therefore, the collision probability in minimum-power cooperative routing leads to frequent packet retransmissions. In the previous subsection, the total transmission power was calculated without taking the packet retransmission into account. In this section, we consider packet retransmission into consideration. The packet is retransmitted, if it is collided in the first round of transmission. We assume that the collided packet can be retransmitted for three times at most (after that the packet is dropped). This number is the default retransmission times for the IEEE 802.15.4 devices [15]. Therefore, the total transmission power is can be calculated as

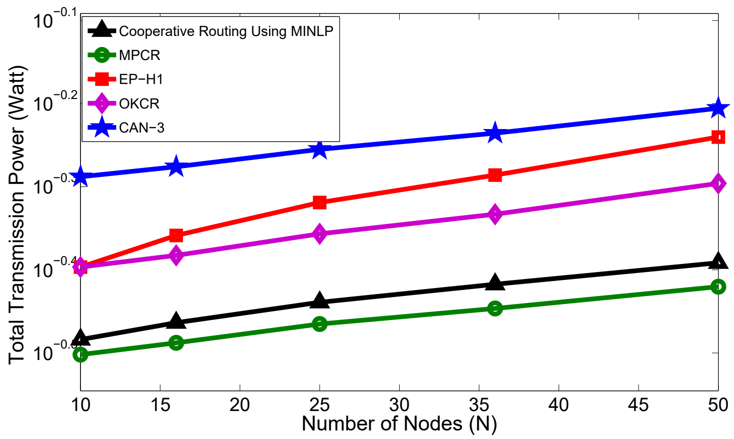


Figure 6.7: Comparing total transmission power of the proposed cooperative routing and that of minimum power cooperative routing algorithms.

$$P_T^{re} = P_T \left(1 + Coll_T + Coll_T^2 + Coll_T^3\right), \tag{6.27}$$

where P_T^{re} is the total transmission power by taking the retransmission into consideration.

The required transmission power of the selected routes by different routing algorithms, in the network with 4 flows and considering retransmission of collided packets, is shown in Fig. 6.8. It is evident that by considering the retransmission of collided packet, our cooperative routing scheme that minimizes collision probability saves considerably more energy compared to EP-H1, CAN-3, and OKCR and saves slightly more energy than the MPCR algorithms.

6.8 Conclusion

In this chapter, we presented the optimal cooperative routing to minimize collision probability in wireless sensor networks by joint use of optimal power, relay node allocation, and route selection. This optimization problem is inherently hard due to its mixed-integer

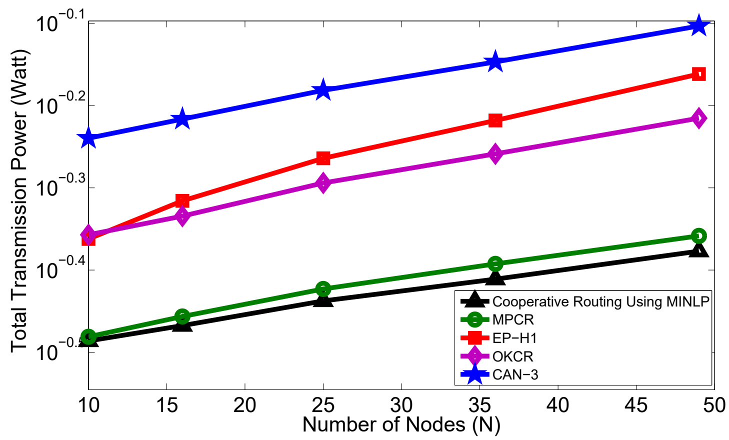


Figure 6.8: Comparing total transmission power of the proposed cooperative routing and that of minimum power cooperative routing algorithms, taking retransmission into consideration.

nature, non-linearity of the problem, and a very large solution space. We developed an efficient solution procedure based on the branch-and-bound technique augmented with a space reduction algorithm to speed up the computation. Then, we proposed the heuristic sub-optimal cooperative routing algorithms to speed up the computational complexity by decoupling transmission power allocation in the cooperative routing algorithm from the optimal route selection. Results reveal that cooperative routing using MINLP outperforms the heuristic routing algorithm. The performance of the proposed routing algorithms is compared with existing cooperative routing algorithms and the results demonstrate the significant rate gains that can be achieved by incorporating cooperative transmission in route selection for minimizing collision in wireless sensor networks. There are several directions for future work, including development of a flexible cooperative routing algorithm with multiple cost functions (for example collision probability and energy consumption) to optimize multiple routing objectives, simultaneously.

Appendix

In [17], for a given source-destination pair with N nodes in the network, the number of possible broadcasting trees from the source node to the destination node with zero transmitters and zero relaying nodes (i.e., only the source node is transmitting the packet) is given by

$$R(0) = \binom{N}{N} = 1, \tag{6.28}$$

The number of possible broadcasting trees with one relay node is given by

$$R(1) = \binom{N}{1} \sum_{i=1}^{N-1} \binom{N-1}{i}, \tag{6.29}$$

the above formula means that we first need to pick one node as the relay node and then decide how many nodes are reached directly by the relay node (the remaining nodes are directly reached by the source node). The case of possible broadcasting trees with two relay nodes is more complicated and is given by

$$R(2) = \binom{N}{2} \sum_{i=1}^{N-2} \left(\binom{N-1}{i} \sum_{j=1}^{N-2} \binom{N-1-i}{j} \right). \tag{6.30}$$

Therefore, the number of possible broadcasting trees with i relay nodes is given by

$$R(i) = \tag{6.31}$$

$$\binom{N}{i} \sum_{k_1=1}^{N-i} \left(\binom{N-1}{k_1} \sum_{k_2=1}^{N-1} \left(\binom{N-1-k_1}{k_2} \right.\right.$$

$$\left.\left. \dots \sum_{k_j=1}^{N-i} \left(\binom{N-1-\sum_{j=1}^{i-1} k_j}{k_i} \right) \right) \dots \right).$$

The above formula means that we first need to pick i nodes as the relay nodes with a number of possibilities of $(\binom{N}{i})$ and then decide how many nodes are reached directly by the relay node (the remaining nodes are directly reached by the source node). Therefore, the total number of possible broadcasting trees in the network is given by

$$T = \sum_{i=0}^{N-1} R(i) . \tag{6.32}$$

For example, for $N = 15$ (15 nodes in the network), the number of broadcasting trees is more than 8.7 billion [17]. Since cooperative paths are mapped as broadcasting trees, for the network with N_s there are $N_s T$ possible cooperative paths from the source nodes to the destination node. Therefore, selecting the best path out of all possible paths is *NP-hard*

REFERENCES

[1] J. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[2] R. Madan, N. Mehta, A. Molisch, and J. Zhang, "Energy-efficient decentralized cooperative routing in wireless networks," *IEEE Trans. Autom. Control*, vol. 54, no. 3, pp. 512–527, Mar. 2009.

[3] W. Zhuang and M. Ismail, "Cooperation in wireless communication networks," *IEEE Trans. Wireless Commun.*, vol. 19, no. 2, pp. 10–20, Apr. 2012.

[4] A. Nosratinia, T. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[5] A. E. Khandani, J. Abounadi, E. Modiano, and L. Zheng, "Cooperative routing in static wireless networks," *IEEE Trans. Wireless Commun.*, vol. 55, no. 11, pp. 2185–2192, Nov. 2007.

[6] F. Mansourkiaie and M. Ahmed, "Cooperative routing in wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. PP, no. 99, pp. 1–1, 2015.

[7] C. Pandana, W. Siriwongpairat, T. Himsoon, and K. Liu, "Distributed cooperative routing algorithms for maximizing network lifetime," in *Proc. IEEE Wireless Communications and Networking Conference, (WCNC)*, Apr. 2006, pp. 451–456.

[8] A. Ibrahim, Z. Han, and K. Liu, "Distributed energy-efficient cooperative routing in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3930 –3941, Oct. 2008.

[9] M. Dehghan, M. Ghaderi, and D. Goeckel, "Minimum-energy cooperative routing in wireless networks with channel variations," *IEEE Trans. Wireless Commun.*, vol. 10, no. 11, pp. 3813–3823, Nov. 2011.

[10] J. Zhang and Q. Zhang, "Contention-aware cooperative routing in wireless mesh networks," in *Proc. IEEE International Conference on Communications (ICC)*, June 2009, pp. 1–5.

[11] ——, "Cooperative routing in multi-source multi-destination multi-hop wireless networks," in *Proc. IEEE INFOCOM*, Apr. 2008, pp. 306–310.

[12] B. Han, J. Li, J. Su, and J. Cao, "Self-supported cooperative networking for emergency services in multi-hop wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 2, pp. 450–457, Feb. 2012.

[13] F. Mansourkiaie and M. Ahmed, "Joint cooperative routing and power allocation for collision minimization in wireless sensor networks with multiple flows," *IEEE Wireless Communications Letters*, vol. 4, no. 1, pp. 6–9, Feb 2015.

[14] J. Habibi, A. Ghrayeb, and A. Aghdam, "Energy-efficient cooperative routing in wireless sensor networks: A mixed-integer optimization framework and explicit solution," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3424–3437, Aug. 2013.

[15] *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specications for Low-Rate Wireless Personal Area Networks (WPANs)*, IEEE Std. 802.15.4, 2011.

[16] P. Ahmadi and B. Jabbari, "An outage-aware power saving cooperative routing algorithm in wireless networks," in *Wireless Telecom. Symp. (WTS), 2013*, Apr. 2013, pp. 1–5.

[17] F. Li and I. Nikolaidis, "On minimum-energy broadcasting in all-wireless networks," in *Proc. IEEE 26th Conference on Local Computer Networks, (LCN)*, Nov. 2001, pp. 193–202.

Chapter 7

Conclusions and Future Work

7.1 Introduction

Cooperative routing is a cross-layer design approach that combines the network layer and the physical layer to transmit packets through cooperative links. The goal of this dissertation is to minimize collision probability subject to the outage probability constraint, employing optimal cooperative routing, power allocation and relay selection. In this chapter, we summarize the contributions presented in this dissertation, draw main conclusions, and discuss several potential extensions to our work.

7.2 Conclusions

The following conclusions can be drawn from this dissertation:

- We started with a basic mathematical model for collision probability, in which the probability of being in receiving mode for each node is obtained assuming the Poisson arrival process. Then, we proposed a sub-optimal cooperative routing algorithm to minimize collision probability in WSNs. The results revealed that, at $N = 49$, the collision probability of the proposed cooperative routing algorithm using the Poisson arrival traffic is reduced by 85%, 48%, and 70% compared with EP-H1 [1], MPCR [2], and CAN-3 [3], respectively. Moreover, the results revealed that taking into account the possibility of using cooperative links during the route selection in the proposed sub-optimal cooperative routing algorithm, which used the Poisson arrival traffic, contributed 40% in minimizing collision probability. Moreover, comparing the performance of the proposed algorithm and that of the MCN algorithm revealed that cooperation transmission (employing relay node for transmission) contributes 54% in collision reduction of the proposed cooperative routing algorithm.

- We mathematically formulated the per-node traffic load in a cooperative link. The traffic load of each node includes the traffic generated by the node itself and the traffic generated by other nodes, which is forwarded by the node either as a next hop of the route or as a relay node. We verified the accuracy of the proposed mathematical model for the per-node traffic load using the simulation results. We illustrated that there is a close match between analytical and simulation results. Therefore, the proposed mathematical formula can accurately model the traffic load of each node in cooperative routing. The results also confirmed that traffic load increases as a function of the node's vicinity to the sink node.

- We employed the proposed model of per-node traffic load to obtain the mathematical model for collision probability of direct and cooperative transmission. For a cooperative transmission, we started with a simple cooperative transmission link, where each link consists of a source, destination, and a potential relay node. For this three-node cooperative transmission model, we mathematically analysed the collision probability caused by a cooperative link to all nodes in the network.

- We developed an optimization framework to obtain the cooperative route that causes minimum collision to other nodes of the network. The problem was formulated as the mixed integer non-linear programming problem. The complexity of the problem is discussed and we proved that the minimum collision cooperative routing problem is NP-Hard.

- To solve MINLP, we enhanced the BnB technique and developed the space reduction BnB algorithm which reduced the searching space of the branch and bound algorithm and increased the speed of convergence in BnB. The algorithm applied a joint optimization approach for power allocation, relay node assignment, and path selection which are the main optimization issues in cooperative routing. By doing that, the cooperative routing using MINLP solution avoids selecting nodes that can cause high collision probability either because of the large number of neighbors or because some of these neighbors have a high probability of being used as the receiver or transmitter.

- Due to the computational complexity of solving MINLP, two near-optimal heuristic cooperative routing algorithms were proposed by decoupling the optimization variables. In the first near-optimal cooperative routing, namely, cooperative routing using INLP, optimal power was allocated after route selection and relay node assignment. Therefore, optimal cooperative routing selection and rely node assignment were deployed in the first phase and the optimal power was allocated in the second phase. In the second near-optimal cooperative routing, namely, Minimum Collision Cooperative Routing (MCCR), firstly, the optimal cooperative routing selected and secondly, optimal power allocated and relay node assigned.

- We illustrated that the MINLP solution serves as the benchmark and we evaluated the quality of the solution obtained by any sub-optimal algorithm of this problem. The simulation results revealed that cooperative routing using MINLP outperforms the near-optimal heuristic routing algorithms. We illustrated that for a network with 50 sensor nodes including 4 source nodes, the collision probability cased by the routing using MINLP was reduced by 21% and 43% compared with INLP and MCCR, respectively. However, the price of achieving optimal performance in cooperative routing using MINLP is the higher computational complexity.

- We illustrated that the computational complexity of cooperative routing using MINLP and INLP grow exponentially with the number of nodes versus the polynomial complexity of the MCCR algorithm.

- We developed two additional routing algorithms to investigate the effects of each cooperative routing optimization variables in minimizing the collision probability of cooperative routing using MINLP. The simulation results, for a network with 50 nodes and 4 source nodes, revealed that taking into account the possibility of using cooperative link during the route selection in cooperative routing using MINLP contributed 42% in minimizing collision probability. Moreover, cooperation transmission (employing relay node for transmission) contributed 57% in collision reduction of the cooperative routing using MINLP algorithm. Furthermore, in order to gain insight into the effect of the optimal power allocation to minimize the caused collision probability with cooperative routing using MINLP, we compared the performance of the algorithm with optimal power allocation with that of the algorithm with equal power allocation. The results reveal that the contribution of optimal power allocation in the collision probability reduction ranges from 39% to 47% for a network with 9 to 50 nodes.

- We compare the performance of the proposed cooperative routing using the MINLP solution algorithm with that of EP-H1, MPCR, and CAN-3, where the objective of the algorithms is to minimize total transmission power in cooperative routing. We illustrated that the cooperative routing using the MINLP solution algorithm outperforms the other schemes and has the lowest collision probability. For a network with 50 nodes in the network including 4 source nodes, the collision probability of cooperative routing using MINLP solution is reduced by 93%, 56%, and 78% compared with EP-H1, MPCR, and CAN-3, respectively.

- We illustrated that the MPCR algorithm is slightly more energy efficient than the cooperative routing using the MINLP solution. Comparing collision probability as well as the required transmission power of the proposed algorithm with the existing energy efficient cooperative routing algorithms, such as MPCR, EP-H1, and CAN-3, proved that minimizing the transmission power does not necessarily minimize the collision probability in the cooperative routing.

7.3 Future Work

In Chapter 2 of this dissertation, we have presented a comprehensive review of existing cooperative routing protocols. The main challenges associated with optimal route selection and the design requirements of cooperative routing protocols are discussed to provide an insight into the objectives of routing protocols. An accurate classification of the protocols is given and the merits and disadvantages of the protocols are determined. Despite the large number of research activities and the rapid and significant progress that being made in cooperative routing in recent years, numerous avenues for further research remain. The following research issues are outlined for future investigation:

- Multiple Objectives: While offering a single objective supports one goal, routing algorithms should be flexible to support various application-specific requirements, such as throughput, capacity, coverage, end-to-end delay, real-time delay, and collision. So, designing flexible cooperative routing protocols with multiple cost functions to optimize multiple objectives can be reckoned as an interesting area for future research.

- Multi-constrained QoS guarantee: Cooperative routing algorithms should be flexible enough to support different application-specific QoS requirements, such as outage probability, end-to-end delay, delay jitter, and bandwidth consumption. Thus far, outage probability has been the main QoS requirement considered in cooperative routing algorithms. Although diverse QoS constraints need to be considered, satisfying some QoS metrics in certain wireless networks is in contradiction with achieving other constraints or objectives. For instance, in vehicular ad hoc networks, satisfying QoS is in contradiction with achieving more energy efficiency [4].

Therefore, designing a flexible cooperative routing with adaptive cost functions to provide multi-constrained QoS guarantee is viewed as an interesting area for future investigation.

- Nodes Mobility: Almost in all proposed cooperative routing algorithms, the nodes are assumed to be static. Recently, there has been an increased interest in applications that support the mobility of users, such as cellular networks and Vehicular Ad Hoc Networks (VANET). An example for this application is the medical-care application, where the mobile wireless network nodes are attached to the patients and need to send continuous data from the patient to the doctor. There is only one cooperative routing protocol that covers mobility (i.e., [5]) and there is much potential for future research in this area. On the other hand, mobility can pose some challenges in cooperative protocol design, such as dynamic relay node assignment methods.

- Security: It has been shown in the literature that the appropriate design of cooperative routing can extend the coverage and improve the performance of the network. However, the security issues raised by increasing the network coverage and allowing nodes to manipulate the signals of other nodes at the signal level (e.g., signal detection by the DF relays and signal combining at each receiving node) are not well-studied. Secure routing is an issue that needs further attention. Moreover, although security was not an objective in the design of recent cooperative routing algorithms, it is important to analyze the performance of these algorithms when security concerns are incorporated.

- Energy Harvesting (EH): Energy is harvested using solar, vibration, and other physical phenomena [6]. EH nodes harvest energy from the environment to carry out their communication tasks. Use of energy harvesting nodes as the relay nodes in cooperative diversity is proved to be a promising and emerging solution in energy-limited wireless networks [7,8]. However, none of the proposed cooperative routing algorithms are energy harvesting aware.

- Applications: Although there has been extensive work on employing cooperative routing in WSNs, there have been very few works that consider cooperative routing in other network applications, such as delay-sensitive applications and bandwidth-limited applications. Therefore, potential applications of cooperative routing, such as cognitive radio networks, LTE networks, wireless LANs, and cellular networks are an interesting area for future investigation.

- Implementations: Most of the cooperative routing algorithms surveyed in this paper have been evaluated through theoretical analysis and simulation; only one proposed algorithm, namely EERWSN [9], deals with the practical aspects of cooperative routing. The authors in [9] used parametric programming in an off-line manner to reduce the computational requirements for the sensor nodes to very simple operations during network functioning. Further investigation and improvements to the current implementation approaches are identified as an area for future work.

REFERENCES

[1] M. Dehghan, M. Ghaderi, and D. Goeckel, "Minimum-energy cooperative routing in wireless networks with channel variations," *IEEE Trans. Wireless Commun.*, vol. 10, no. 11, pp. 3813–3823, 2011.

[2] A. Ibrahim, Z. Han, and K. Liu, "Distributed energy-efficient cooperative routing in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3930–3941, Oct. 2008.

[3] A. Khandani, J. Abounadi, E. Modiano, and L. Zheng, "Cooperative routing in static wireless networks," *IEEE Trans. Commun.*, vol. 55, no. 11, pp. 2185–2192, Nov. 2007.

[4] Z. Sheng, Z. Ding, and K. Leung, "Distributed and power efficient routing in wireless cooperative networks," in *Proc. IEEE International Conference on Communications (ICC)*, June 2009, pp. 1–5.

[5] W.-H. Chen, A.-C. Pang, A.-C. Pang, and C.-T. F. Chiang, "Cross-layer cooperative routing for vehicular networks," in *Proc. IEEE International Computer Symposium (ICS)*, Dec. 2010, pp. 67–72.

[6] J. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive Comput.*, vol. 4, no. 1, pp. 18–27, Jan 2005.

[7] B. Medepally and N. Mehta, "Voluntary energy harvesting relays and selection in cooperative wireless networks," *Wireless Communications, IEEE Transactions on*, vol. 9, no. 11, pp. 3543–3553, November 2010.

[8] L. Liu, R. Zhang, and K.-C. Chua, "Wireless information transfer with opportunistic energy harvesting," *IEEE Transactions on Wireless Communications*, vol. 12, no. 1, pp. 288–300, January 2013.

[9] J. Habibi, A. Ghrayeb, and A. Aghdam, "Energy-efficient cooperative routing in wireless sensor networks: A mixed-integer optimization framework and explicit solution," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3424–3437, Aug. 2013.