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A NEW MODEL FOR COOPERATIVE MOBILITY IN SUPPORT OF QOS IN MANETS WITH HETEROGENEOUS AUTONOMY REQUIREMENTS

by

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A NEW MODEL FOR COOPERATIVE MOBILITY IN SUPPORT OF QOS IN MANETS WITH HETEROGENEOUS AUTONOMY REQUIREMENTS

Ghassen Ben Brahim, Ph.D.

Western Michigan University, 2007

Modern mobile ad-hoc networks (MANETs) frequently consist of nodes which exhibit a wide range of autonomy needs. This is particularly true in the settings where MANETs are model compelling, i.e. battlefield, response & rescue, and contexts requiring rapid deployment of mobile users. The time-critical nature of the underlying circumstances frequently requires deployment of both manned and unmanned nodes, and a coordination structure which provides prioritized tasking to them.

In classic ad-hoc networks settings, it is assumed that all nodes are autonomous and do not depend in any case on other nodes. In this research work, contrarily to this design, we propose introducing the notion of cooperation between nodes which results in a new design of an ad-hoc network: Non-Autonomous ad-hoc network. In such network, mobile nodes are classified into two classes: cooperative versus non-cooperative nodes. Cooperative nodes behave in such a way that they can either adjust their locations within the network based on pre-assigned movement budget, and/or switch to different radio frequency channel during data transmission in case of cognitive radio capable mobile nodes. The goal of this proposed cooperative model is to improve the overall network performance by providing better Quality of Services (QoS). The QoS parameter considered in this work is the Bit

Error Rate (BER) of the wireless channel, which is a good metric that accurately represents the wireless channel conditions.

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Ghassen Ben Brahim

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Mobile wireless ad-hoc networks (MANETs) are an important infrastructure building block, enabling the successful execution of both military and public safety operations. In the military setting, MANETs facilitate communication between mobile infantry units, command and control, field intelligence, aerial surveillance, etc. They can be built using Radio Frequency (RF) communication links both between and within infantry formations, ground armored vehicles (e.g., tanks), airborne units (e.g., fighters, bombers), and naval/amphibious platforms (e.g., destroyers, troop carriers). MANETs are particularly well-suited for rapid establishment of communications in battlefield and public safety settings, because they are comprised of mobile platforms that do not require a fixed infrastructure but rather operate over a shared wireless medium.

On the research side, the potential applications of MANETs have led, perhaps not surprisingly, to a surge in research breakthroughs addressing the many technological challenges which stand in the way of their wide scale adoption. These challenges include the limitations of wireless RF channels in terms of available bandwidth and relatively high bit error rates, energy-efficient communication to extend the network lifetime, QoS aware routing to meet application requirements, and the design of new protocols to support large networks and handle the limitations of the underlying wireless RF links.

On the applications side, the demanding requirements of end users in the military and public-safety sectors have led to the development of a variety of unmanned platforms [41]. More specifically, end-user demands have driven the development of Unmanned Ground Vehicles (UGVs) and Unmanned Air Vehicles (UAVs) for use within battlefield and public safety missions, e.g. the UAV-Ground Network [9]. These devices are mobile, mission-capable, and well-suited for use in dull, dirty, difficult, and dangerous settings, including collection of data from sensors [28]. In particular, UAVs and UGVs can be deployed to serve as relays, maintaining mobile communication links by optimizing the reception and the transmission of signals among end users. The capability of these vehicles to be maneuvered in small increments over a wide variety of terrains is a distinct advantage that makes them well-suited to serve as mobile relays. In addition, UAVs and UGVs are also capable of serving as mobile power supplies, since they can be easily deployed to travel to remote locations where power is most critically needed, or to support recharging of embedded devices and hardware carried by troops in the field.

The modern battlefield communications network is a MANET comprised of both manned and unmanned elements (e.g. UAVs [8]), the question remains as to the role of cooperation between nodes. Certainly, task-oriented cooperation is to be expected in such a setting, e.g. coordinating the activity of UAVs to achieve a joint objective like radio source localization [22]. Here, however, we pose a more fundamental question: What role can cooperation play in supporting *communication itself?*

Prior work on the question of how cooperation can benefit communication (e.g. See [42, 34, 11, 25, 54, 53] and others) has approached the issue from the vantage point of a node's willingness to forward messages to the next hop (toward the intended destination) along a multi-hop path. Almost all prior work was colored by the consumer model in which node mobility is considered the sacrosanct domain of the user, autonomously determined and non-negotiable. While this is an appropriate conception of current consumer applications (e.g. cell phone and laptop users) it fails to leverage the unique opportunities present in battlefield MANETs. In the latter setting, mobility is a fundamental resource of every MANET node, and cooperative nodes can potentially contribute their mobility towards the common good vis-a-vis systemic objectives. In this article, we develop a realistic model for cooperation in battlefield MANETs and evaluate the extent to which communications can be improved when constituent nodes are sometimes willing to *be moved* or to *switch* to different channel.

1.2 MANET Characteristics

MANETs have many special characteristics that distinguish them from other types of networks. These characteristics include: (1) multi-hop routing, (2) dynamic topologies, (3) self-organized architecture, (4) limited security, (5) limited resources, etc. Some details of each of these characteristics are:

1. **Multi-hop routing**: A node in a MANET can communicate with the nodes that are within its transmission range. So, each node only keeps in contact with a limited number of neighbors, regardless of the network size. If a node wants to send a message to another node that is outside its range, other nodes help in relaying the message to its destination. Unlike conventional cellular wireless networks, multi-hop radio relay is a fundamental property in MANETs.

In addition to saving radio transmission power of the nodes, multi-hop routing has other significant advantages. The first advantage is adaptability. Using a multi-hop path, packets can be routed in such a way to bypass: obstacles [39], security breached nodes, low energy nodes, etc. The second advantage is the spatial reuse [36], where neighboring nodes have the ability to use the same frequency. This allows for simultaneous communication to exist between nodes that are out of each other's range. The third advantage is energy conservation. Assume that 2 paths exist between a certain source and a certain destination where the first path is composed of many hops each using a small transmission radius, and the second path is composed of fewer number of hops each using a large transmission radius. It was proven that by choosing appropriate small radii, the path with more number of hops achieves higher throughput and less energy consumption [29].

2. **Dynamic topologies**: Nodes in a MANET are autonomous and free to move arbitrarily. Such properties result in a topology that is constantly and rapidly changing.

3. **Self-organized architecture**: Self organization plays a role in adapting to the network dynamics. It allows nodes to collaborate with each other to make appropriate decisions that lead to better network performance. One way to provide self organization is by using a central node that oversees the whole network. But such a central node is not usually present in a MANET. So, network designers resort to utilizing distributed self organization algorithms that are fast and efficient. Dynamic routing is one example of self-organization. Distributed self organization presents a real

challenge in MANETs and it constitutes a major part of this dissertation.

4. **Limited security**: MANETs are more vulnerable than wired networks. This is due to the wireless medium that is shared by all mobile nodes. MANETs are subject to attacks such as: eavesdropping, spoofing, denial-of-service, man-in-the-middle, etc.

5. **Limited resources**: Bandwidth and energy are two of the most important resource constraints in MANETs. MANETs have limited bandwidth because wireless link capacity is usually low. Also, wireless links have low throughput due to multiple access, fading, noise, and interference. MANETs are also energy constrained because most MANET nodes rely on batteries. When the node battery is drained, it dies and might bring the whole network to a halt. So, one of the most important system design criteria is energy conservation and it constitutes a major part of this dissertation.

Despite active research groups working on many of these MANET characteristics, major challenges still exist. These challenges include routing, security, quality of service (QoS) and power management. In fact, one of the goals of the Internet Engineering Task Force MANET Working Group (IETF MANET WG), which was formed in 1996, was to develop a framework for running IP based protocols in ad hoc networks [46]. Routing protocols that aim to to achieve this goal [49, 59] are constantly being analyzed and tested by MANET WG for possible standardization.

1.3 MANET Challenges

The characteristics discussed in the previous section differentiate MANETs from conventional networks. They also cause considerable challenges including scalability, energy-efficiency, and QoS requirements.

Scalability in MANETs can be defined as whether the network can provide an acceptable throughput when the network size increases. Scalability in a MANET is directly related to the network design and to the routing protocol used. For example, the network can become more scalable by reducing the routing protocol overhead [61]. Scalability can also be achieved by designing the network in a hierarchical fashion [57]. Scalability is still an open problem in MANETs and it is receiving much interest from researchers. A good survey discussing routing protocols' scalability can be found in [60].

Energy-efficiency is of considerable importance in MANETs since nodes rely on portable, limited power resources and they bear the duty of relaying packets for other nodes. The failure of some nodes due to battery drainage might bring the whole network down. Most existing solutions for reserving energy are done in the MAC Layer. They reserve energy by sending the nodes to sleep and then waking them up when it is time for them to send/receive packets. Other solutions for reserving energy are done in the Network Layer where routes with many short hops are chosen instead of routes with fewer longer hops [63]. Few researchers considered the MANET environment aspects (node properties and link properties) as deciding factors in reserving energy. Such factors include: the traffic pattern in the network, the mobility of the nodes, the residual energy of the nodes, and the density of certain regions in the network. Energy-efficiency remains one of the most important challenges in designing MANETs.

Satisfying the QoS requirements is a major challenge in both wired and wireless networks. In wireless networks, the problem is harder due to the unpredictability of the radio frequency (RF) characteristics and due to sharing the channel medium. Extensive research has been done on QoS provisions in ad hoc networks, such as QoS routing or admission control [15, 44, 45, 77]. Most of the existing research works deal with resource allocation (e.g., scheduling or buffering) or routing for QoS requests.

In this work, we focus on addressing the third challenge (self-organized architecture) in details and we present multiple solutions to these problems. The next section presents the problem description and the approaches used to address the above challenges.

1.4 Problem Description

The model of networking has evolved significantly over time. Classical networking presumed that link structure is essentially static and predetermined, with users at fixed locations. The cellular network paradigm, in contrast, allowed each user to roam and extend the classical network by making wireless connections to nearby base station nodes. In the purely mobile ad-hoc (MANET) setting, the classical network disappeared altogether; links are formed entirely by dynamic peer-to-peer wireless connections between users. Arising from historical context of consumer MANETs, users are envisioned in this model as being entirely autonomous with respect to their mobility. What we propose here is a significant modification of the conventional mobile ad-hoc network model.

In this work, we consider different wireless network models, where nodes can either make the decision to move to a different location, or can decide to switch to a different Radio Frequency channel during data transmission. We refer to wireless nodes of the latter type by Cognitive Radio (CR) capable.

The first model considers networks where mobility is a resource that can be used to ameliorate communication infrastructure. Our work begins with the model of Basu et al. [2], but rather than considering networks consisting of robots and non-robots, we consider the more general setting of *heterogenous* networks comprised of nodes which exhibit the entire spectrum of personalities: from defiant autonomy to self-sacrificial cooperativeness. We capture this viewpoint by adopting a cost model for mobility. That is to say, every node is willing to move for the sake of the common good, but *for a price*. Each node is assigned a *movement cost* (proportional to distance moved)—this is the price it charges to be moved, say, per meter. Defiant autonomy is exhibited when a node declares this cost to be infinite; self-sacrificial cooperativeness is manifest when this cost is set to zero. The relative extent of cooperativeness exhibited by battlefield MANET nodes is reflected by the ratios of their associated movement costs.

We see mobility planning (for cooperative nodes) as a core function of the network routing layer, which becomes responsible for allocating a fixed (periodically renewed) *mobility budget* towards paying for the movement of cooperative nodes. The model assumes that a node will execute any mobility request that has been adequately funded by an allocation of the mobility budget; such requests are interpreted as being from higher-level supervisors whose objective is to maintain a communication network that best supports the overall mission requirements. Nodes that are autonomous (i.e. unwilling to be subjected to the movement requests of the routing layer) simply declare their movement costs to be infinite.

The initial central problem to be addressed then is how best to utilize the movement budgets of nodes to defray the cost of for moving them, in a way that leads to meeting the end-to-end QoS requirements of a set of connections. The QoS parameter we consider is the bit error rate (BER) as it is gives a good estimate about the quality of the wireless connections.

The second model considers networks that uses Cognitive Radio technology, which offers a new mechanism for flexible usage of radio spectrum. Under this model, CR-capable nodes are allowed to operate in an under-utilized licensed frequency otherwise reserved to primary users, without violating their privileges. To achive this, CR-capable mobile nodes must be able to determine and predict available unused network capacity that they could potentially leverage. The next central problem to be addressed then is how to efficiently use the network Cognitive Radio capabilities by CR-capable nodes in order to meet the end-to-end QoS requirements of a set of connections. Similarly to the previous model, the QoS parameter we consider is the bit error rate (BER.)

In short, in this work we develop a realistic model for cooperation in mission-oriented rapid-deployment MANETs that leverages both cooperative mobility and cognitive radio paradigms. We present solutions to optimizing the performance of MANETs which consist of *CR-capable* nodes that are sometime able to *be moved*. We evaluate the extent to which the communications infrastructure can be improved by leveraging these two paradigms, and assess the extent to which the two optimization spaces interact with one another.

1.5 Dissertation Organization

The primary focus of this work is network design in MANETs. Specially, scalability, self network organization, and energy-efficiency are considered. The remainder of this dissertation is organized as follows:

Chapter 2 considers how cooperation between nodes can improve communication in battlefield mobile ad-hoc networks (MANETs). We present a taxonomy of the models of cooperation that have been manifested in MANET research efforts so far. These include the following: (1) Relay based cooperation models, (2) models of cooperation using Spatial-Diversity, (3) Cooperation Models based Reputation Management, (4) Power-based Topology Control cooperation models , (5) Mobility-based Topology Control cooperation models , (6) Cooperation Models for Distributed Control, and (7) Cognitive Radio based cooperation models.

Chapter 3 describes our new proposed cooperative models, which were build on the assets and limitations of prior models of cooperation. The proposed models capture the salient features of MANETs. In particular, the cost-benefit framework of our models is a significant advance in modeling heterogeneous networks whose nodes exhibit the complete range of autonomy with respect to mobility.

Chapter 4 outlines our design of *CoopSim,* a platform for conducting simulation experiments to evaluate the impact of parameters, policy, and algorithm choices on any system based on the proposed Cooperative Mobility Model

Chapter 5 depicts our Mixed-Integer Linear Programming (MILP) formulation of the model, which accurately captures its objectives and constraints. The MILP objectives are to use the mobility budgets of cooperative nodes to adjust the topology in a manner that: (1) *meets* end-user connection QoS requirements using minimal node movement, or (2) *optimizes* end-user connection QoS while not exceeding available movement budgets.

To make the proposed technique scale to large networks we develop a new technique for converting a large global MILP into a sequence of smaller local MILP optimizations, and demonstrate that the resulting approach is scalable and succeeds at efficiently moving cooperative nodes in a manner which optimizes connection bit error rates. This techniques is based on the divide & conquer principle.

Chapter 6 describes our proposed effective centralized algorithm for mobility planning based on multigrid techniques. We evaluate the performance of the proposed scheme and we demonstrate through simulation results that the communication infrastructure — specifically, connection bit error rate — can be significantly improved by leveraging this proposed scheme.

Chapter 7 defines our second proposed approach to node mobility planning. This approach suggests a natural analogy between finding the cooperative node movement direction and the problem of computing resultant forces. We evaluate the performance of the proposed scheme using the CoopSim platform and we show that the communication infrastructure — specifically, connection bit error rate — can be significantly improved by leveraging this proposed scheme.

Chapter 8 presents our model of cooperative mobility and algorithms for mobility planning, which were based on cognitive radio concept and node budgeted movement concepts. We start by describing our proposed traffic estimation and opportunistic channel selection strategies. Our proposed channel estimation strategy utilizes a combination of Exponentially-Weighted Moving Average (EWMA) and wavelet-based filters. Channel selection employs an extensible fuzzy rule-base to determine the overall cost of a cognitive radio channel, based on its estimated average and auto-correlation metrics. Then we describe policies for cooperative mobility and opportunistic channel selection. Finally, we evaluate the performance of the proposed scheme using the CoopSim platform and we show that the communication infrastructure can be significantly improved by leveraging this proposed scheme.

Chapter 9 presents an overall conclusions as well as the major contributions of this work and outlines the future trajectory of our research work.

CHAPTER 2

A TAXONOMY OF COOPERATIVE COMMUNICATION MODELS

2.1 Introduction

A fundamental objective of MANET operation is the efficient use of node resources towards the delivery of basic network functions, e.g. assuring timely data delivery among network nodes. This functionality is assured by the integrated operation of network, link, and physical layers of the MANET. Each of these layers presents its own scalability challenges, arising from inherent MANET characteristics such as node mobility and dynamics, harsh wireless channel conditions, scarce communication bandwidth, and limited energy resources. Naturally, in order to mitigate the difficult problems posed by the intrinsic constraints of MANET architectures, MANET designers have long considered schemes by which nodes might collaborate (at various levels of the protocol stack) so as to achieve better network and (ultimately most importantly) better application performance.

The notion of cooperative communication is itself quite old, appearing in the networking literature as early as the 1970's (e.g. papers on the relay channel model in information theory [17]). The phrase "cooperative communication" reflects the fact that each network node has two existential modalities:

(i) a *selfish* existence in which it seeks merely to maximize the transfer of its own data, and

(ii) an *altruistic* existence in which it is willing to cooperate with the ambient system and aid in the transfer of data to and from other nodes.

Indeed, a large fraction of the corpus of literature on networking is, in some sense, concerned with achieving and maintaining a balance between these two modalities in an efficient manner that is mutually agreeable to all participants. In the next section, we describe the different categories of approaches to MANET node cooperation that have been considered to date.

In our view, a *model of cooperation* consists of two distinct components:

(i) A lexicon of actions by which to express its altruistic tendencies,

(ii) A set of objective criteria by which the benefits of a node's altruistic behavior are to be assessed.

Our focus in this article is on mobile ad-hoc networks, and even within this narrow setting, several models of cooperation have been proposed to date (albeit at times only implicitly). Although these models came about in a somewhat ad-hoc manner over the past few years, each arose within concrete research efforts seeking to leverage some new observation or technological development, which in turn was motivated by the over-arching objective of making more efficient use of wireless network resources. In hindsight now, we are in a position to offer the following taxonomy of the models of cooperation that have been manifested in MANET research efforts so far.

2.2 Relay Based Cooperation Models

This fundamental class of models of cooperation begin with the central observation that if a transmitted signal is not strong enough to reach the intended destination, intermediate nodes may altruistically receive, process, and then retransmit (or relay) the signal toward the final destination. The lexicon of altruism is the willingness of a node to dedicate local resources (e.g. buffer storage, power and computational cycles) to engage in relay actions, while benefit is quantified in terms of the connection throughput of the network as a whole.

In the specific context of wireless communications, this model of cooperation relies intrinsically on the broadcast nature of the network, where the concrete implementation of the relay process requires repeating or amplifying the received signal. Kramer et al. [37] give a concise review of relay techniques proposed to date, most of which involve either extending routing protocols at level three of ISO model [11, 10, 72] or extending protocols at the MAC layer [27, 69, 62].

2.3 Spatial-Diversity Based Cooperation Models

The central observation underlying this class of models is that when multiple copies of a message are received by a node, a better estimate of the original signal can be determined by combining the received signals. These models refine the basic Relay Cooperation Models described above by extending the lexicon of altruistic behavior. Specifically, when acting as a relay, each node can determine whether to forward the entire received data or merely a part of it, as well as whether any compression should be applied before the forwarding. As before, the benefit of an altruistic act is quantified in terms of the connection throughput of the network as a whole.

Most of the concrete schemes within this class operate at the physical or MAC layers. For example, Liu et al. [47] describe a new MAC layer protocol to determine whether a relay node should forward the data in full or in part, so as to maximize the benefit of multiplicities at the receiver. Scaglione at al. [62] go further by introducing the concept of the opportunistic large array (OLA), in which network nodes respond to the signal of a node designated as the leading transmitter. The avalanche of responses from OLA nodes increases the signal-to-noise ratio (SNR) of the original transmission, permitting the strengthened signal to be detected and decoded by a far away receiver. Because each node in the OLA has a choice of whether to relay or not (depending on its local circumstances) these architectures are the natural spatially-diverse analogues of the standard techniques of Relay Cooperation Models (e.g. adaptive decode-and-forward or amplify-and-forward algorithms [64, 73]).

2.4 Reputation Management Based Cooperation Models

The central observation underlying this class of models is that the efficacy of any concrete instantiation of a Relay Cooperation Model can be easily subject to compromise and abuse by misbehaving nodes. Accordingly, this class of models extends the basic Relay Cooperation Model by augmenting the lexicon of altruistic behavior to include cooperation in identifying nodes which are not meeting communal expectations with respect to relaying responsibilities. Nodes that are not cooperating in the data forwarding process are often characterized in the literature [50, 16, 11] as “misbehaving” nodes, and their behavior is further classified as being either malicious or selfish in nature. A malicious node is one that does not cooperate because it wants to intentionally break the network functionality, while a selfish node is one that is simply not willing to spend local resources to forward data that is not intended for it.

Most research efforts which consider this form of cooperation focus on detecting and isolating misbehaving nodes through watchdog or reputation mechanisms. For example, Buchegger et al. [10] present the CONFIDANT protocol which extends standard Dynamic Source Routing [31]. This protocol is designed to detect and isolate misbehaving nodes by making use of experienced and reported behavior of other nodes.

The complimentary work of Machiardi et al. [50] culminates in the development of the CORE protocol, which seeks to amortize a node's access to network resources against its contribution to data routing and forwarding, thereby balancing self-interest against altruism. Every node within the CORE network monitors the behavior of neighboring nodes and assigns a reputation value for each of them. Routing and forwarding decisions take reputation into account. A misbehaving node can be re-integrated into the network if it resumes cooperative behavior with respect to relaying responsibilities. A closely related market-based approach is described by Hubauz et al. in [13, 12]. In their papers, the authors model a mobile ad-hoc network as a market in which relay services are exchanged in a virtual economy based on a virtual currency called the nuglet. Each node is forced to pay to have its data forwarded, and receives credit whenever it forwards some data on behalf of other nodes. Selfishness is avoided by self-regulation in the market: nodes are free to be selfish, but by behaving selfishly they reach a self-limiting state of bankruptcy, after which they can no longer send their own packets.

2.5 Power-Based Topology Control Cooperation Models

The central observation underlying this class of models is that using new technologies [53], nodes can adjust their transmission power levels. The concomitant models of cooperation arising from this observation, all extend the lexicon of altruism to include inter-node coordination of transmission power. Clearly, changes in node transmission power impacts both the network topology and the network's total energy consumption. Most of the prior research in this area measures the benefit of altruistic behavior in terms of minimizing the total energy consumption of the network, or minimizing the maximum energy consumption (over the set of network nodes). Other variants of the same problem that have received more limited attention include: minimizing node degree, minimizing the hop diameter of the network, minimizing the maximum transmission radius, guaranteeing connectivity, minimizing the number of biconnected components [4].

Exemplary research efforts within this cooperation paradigm include the work of Gerharz et al. [25], who considered the problem of adjusting transmission power in a manner that maintains strong connectivity of the induced network topology, while minimizing total energy consumption in the network. In their paper, the authors note that this can be done either by assigning a (suitably computed) uniform transmission power to all nodes, or via an appropriately chosen non-uniform power assignment. They note that the former approach presents a somewhat complex and unscalable task, since information has to be collected and distributed across the entire network at regular intervals, but demonstrate how efficient per-node transmission power levels can be determined in a distributed manner, using only the local neighborhood information. Along the same lines, Borbash et al. [4] resolve the problem of cooperatively setting transmission power levels so that each device has bidirectional links to its k (geographically) nearest stations. Jia et al. [30] consider a more general fine-grained scheme which adjusts power transmission levels in order to construct a network topology that satisfies a specified set of QoS requirements, while minimizing the maximum transmission power used (over all network nodes). The QoS specifications considered by Jia et al. includes minimum bandwidth requirements and maximum delay (in terms of hop count) between application-level endpoints.

2.6 Mobility-Based Topology Control Cooperation Models

The central observation underlying this class of models is node mobility can ameliorate network communication properties. Until quite recently, relatively little effort has been directed to communication-reactive mobility control for ad-hoc networks. Movement control for fault tolerance was investigated in by Basu and Redi [2] using a model which considered moving subsets of nodes to new locations in order to achieve biconnectivity in the network graph. Spanos et al. developed a geometric connectivity robustness metric to provide a means to quantify the motion constraints imposed by (range-based) connectivity requirements [65]. The work of Frew and others showed how decentralized mobility control can be used to achieve desirable network properties, e.g. a delay tolerance [23]. Finally, in [26] Goldenberg et al. present a self-adaptive distributed feedback control scheme to obtain desirable overall network properties such as connectivity and power efficiency. We note that all these research efforts were motivated by improving aggregate network properties, as opposed to maximizing the performance of an existing, dynamic set of application-layer connections. Only very recently, Dixon and Frew have made steps in this direction, showing how one can apply extremum seeking methods to decentralized mobility control [19], using these to form linked chains of mobile relays under nonholonomic constraints in a manner that maximizes total link bandwidth.

2.7 Distributed Control Based Cooperation Models

These models arise in the context of specific distributed applications, when application designers realize that coordination of node activities can facilitate the fulfilment of overall group objectives. These models have appeared frequently in recent years, partly in response to the prevalence of MANETs comprised of multiple independent dynamic nodes that are subject to coupled constraints. Such systems arise naturally in the context of dynamic control of group operations for UAVs, UGVs and robots, [3]. Altruistic action in such settings involves the sharing of information regarding evolving group objectives. The benefits of altruistic behavior are typically measured in application-specific metrics.

One example of a generic coordination challenge appearing at the core of many distributed applications [58] is the problem of specifying robust algorithms by which a group of MANET nodes can reach consensus on the shared information in the presence of limited and unreliable information exchange and dynamically changing interaction topologies. Such consensus algorithms are of crucial importance, e.g. they guarantee that all UGVs in a team can converge to a coherent state through only local interactions. A concrete instance of this is addressed, for example, in the work of Kuwata et al. [38] who describe how a group of UAVs can coordinate their activities by solving local optimization problems and then conveying aspects of these solutions to their neighbors. In describing their application-specific cooperation scheme, Kuwata et al. demonstrate how to coordinate the UAVs without replicating the global optimization problem at each agent. Their work is a marked improvement on prior approaches which achieved agreement between UAVs by relaxing the constraints and then increasing the penalty on constraint violation. In contrast, the authors achieve coordinated behavior by having MANET nodes engage in the cooperative exchange of Lagrange multipliers corresponding to active constraints, i.e. nodes exchange their preferences with other nodes in each local optimization iteration.

2.8 Cognitive Radio Based Cooperation Models

The central observation underlying this class of models is the fact that Cognitive radio technology can ameliorate network communication properties.

The potential applications of MANETs have led to a remarkable surge in research breakthroughs addressing the many technological challenges which stand in the way of their wide scale adoption. These challenges include: the limitations of wireless RF channels in terms of available bandwidth and relatively high bit error rates, inefficient use of available RF channels, energy-efficient communication to extend the network lifetime, and the difficulty of designing QoS aware routing protocols capable of meeting application requirements in a scalable way. We anticipate that as applications requiring new QoS classes arise, the RF environment will become increasingly variable, making it more challenging to optimize radio spectrum allocation and performance. *Cognitive Radio* (CR) technology has been recognized by both the regulatory and technical communities as a possible panacea to this increased variability, because of its capability to support sensing, knowledge formation, and adaptive channel allocation. CR technology [51] offers a new mechanism for flexible usage of radio spectrum. It allows secondary users to operate in an under-utilized licensed frequency otherwise reserved for primary users, without violating their privileges. To achieve this, *CR-capable* mobile nodes must be able to determine (and predict) available unused network capacity that they could potentially leverage.

In the next chapter, we present our first cooperation model for MANETs, which is based on the willingness of cooperative mobile nodes to move to a different location with the objecive of improving the quality of wireless communication channels in terms of bit error rate. We will also discuss in the same chapter possible network metrics that can be considered when evaluation the proposed cooperative scheme.

CHAPTER 3

BUDGETED BASED COOPERATIVE MODEL

3.1 Introduction

Application-level cooperation has been studied in the context of specific tasks (e.g., in [38], Kuwata et al. describe how a group of UAVs can coordinate their activities by solving local optimization problems and then conveying aspects of these solutions to their neighbors). The objective of such investigations is to determine how team members should share and exchange high-level information to best achieve team objectives. In this work, we consider more fundamental questions on the role that cooperation can play in supporting *communication itself.* Prior work on the question of how cooperation can benefit communication [42, 34, 11, 25, 54, 53] has approached this issue from the vantage point of a node's willingness to forward messages along the next hop (toward the intended destination) along a multi-hop path. Almost all prior research adopts the consumer MANET model, where node mobility is considered the sacrosanct domain of the user, autonomously determined and non-negotiable. While this is an appropriate conception of current consumer (e.g., cell phone and laptop) applications, it fails to leverage the unique opportunities present in mission-oriented MANETs. Here, we consider mobility to be a fundamental resource of every MANET node; cooperative nodes can potentially contribute their mobility towards the common good vis-a-vis systemic objectives. We extend this cooperative model to have cooperative nodes operate in Cognitive Radio network. Under this assumption, cooperative nodes, opportunistically switches to different unused radio frequencies which are reserved to primary users, with the goal of enhancing the network performance.

In the next sections, we describe our proposed cooperative models, which are based on the willingness of cooperative nodes to either move to a different location or to opportunistically switch to a different radio frequency. Then, we present a list of possible network performance metrics that the proposed cooperative model would enhance.

3.2 Budgeted Movement Cooperative Mobility

The classical networking model assumes that link structure is essentially static and predetermined, with users at fixed locations. The cellular network paradigm, in contrast, allows each user to roam and extend the classical network by making wireless connections to nearby base station nodes. In the purely mobile ad-hoc (MANET) setting, the classical network disappears altogether and links are formed entirely by dynamic peer-to-peer wireless connections between users. Arising from historical context of consumer MANETs, users are envisioned in this model as being entirely autonomous with respect to their mobility. What we propose here for the battlefield environment is a significant modification of the conventional mobile ad-hoc network model.

We motivate the model with a concrete, albeit fictitious user story: Consider a ground combat situation in a battlefield environment where both manned and unmanned vehicles are deployed. Assume that certain communication channels (with specifiable QoS) need to be maintained for a successful mission (e.g. between the central command and every manned vehicle). If any unmanned vehicles are presently untasked, could they not be used to contribute in maintaining the communication infrastructure? In doing so, an untasked unmanned vehicle would be acting altruistically, contributing it's mobility towards the betterment of the overall communication infrastructure. On the other hand, perhaps one of the unmanned vehicles is presently tasked to a high-priority objective, e.g. delivering fresh battery power to a specific troop deployment in the field. This latter tasked unmanned vehicle would likely not be amenable to contributing it's mobility towards the betterment of the communication infrastructure, because of the disruptive impact of such altruism to its present mission.

The above user story brings to light the central observation underlying our proposed model for cooperation: *In a battlefield MANET, different nodes exhibit different degrees of autonomy with respect to their willingness to be moved.* Stated another way, battlefield MANET nodes exhibit the entire spectrum of altruism with respect to contributing their mobility resources towards the improvement of the communication infrastructure. The models of cooperation described in the taxonomy presented in previous section were developed in the context of traditional MANETs, yet almost all of them assume that network nodes move entirely selfishly with regard to only their own personal objectives. In contrast, we consider mobility to be a fundamental property of every MANET node, and view mobility as a potentially contributable resource that is part of its altruistic lexicon. Given this vantage point, category (5)—Cooperation Models for Mobility-based Topology Control—can be seen as a special case of category (6)—Cooperation Models for Distributed Control—if one considers the entire network layer as the distributed control application.

Our model begins with the model of Basu et al. [2], but extends it by postulating that future MANETs will not be homogeneous in terms of node autonomy. While Basu et al.

consider networks consisting of robots and non-robots, we contend that the general setting requires us to consider *heterogeneous* networks comprised of nodes which exhibit the entire spectrum of personalities: from defiant autonomy to self-sacrificial cooperativeness. We capture this viewpoint by adopting a cost model for mobility. To wit, every node is willing to move for the sake of the common good, but *for a price*. Each node is assigned a **movement cost** (proportional to distance moved)—this is the price it charges to be moved, say, per meter. Defiant autonomy is exhibited when a node declares this cost to be infinite; self-sacrificial cooperativeness is manifest when this cost is declared to be zero.

The relative extent of cooperativeness exhibited by battlefield MANET nodes is reflected by the ratios of their associated movement costs. Mobility planning is added as a core function of the network routing layer, and is responsible for allocating a fixed (periodically renewed) **mobility budget** towards the movement of cooperative nodes. The model assumes that a node will execute any mobility request that has been adequately funded by an allocation of the mobility budget; such requests are interpreted as being from higher-level supervisors whose objective is to maintain a communication network that best supports the overall mission requirements. Nodes that are unwilling to be subjected to the movement requests of the routing layer (e.g. manned vehicles and tasked unmanned vehicles) simply declare their movement costs to be very large.

3.3 The Opportunistic Cognitive Radio Model

In contrast to the Cooperative Mobility Model, in which cooperative nodes are willing to move to a different location with the goal of improving the end-to-end communication channels bit error rates, the opportunistic channel selection cognitive radio Model aims to opportunistically benefit from the abundant spectrum that is not fully utilized by primary users, while seeking to enhance the QoS provided on all communication channels, vis-a-vis bit error rate (BER). The model assumes that all nodes operate in a Cognitive Radio network, and each node is able to scan the radio spectrum and determine the set of channels to be used by the primary and secondary users. Techniques for scanning and identifying the set of these channels are beyond the scope of this work.

We present a new wireless channel estimation technique based on the wavelet transform and flip-flop filter techniques. Each node estimates the utilization of each of the primary channels then decides whether exchanging traffic over unused primary channels is feasible and will enhance the quality of the communications*. First, we present techniques for estimating the status and utilization of the wireless channels.

3.4 Network Performance Metrics

From a global vantage point, cooperation can benefit not only the nodes involved, but also seemingly unrelated parts of the network, and in many orthogonal aspects. While Basu et al. [2] measured the benefits of altruistic behavior in terms of coarse-grained biconnectivity of the network as a whole, we consider a more fine-grained measure: the quality of service provided for the set of existing network connections. The adoption of a cost model permits us to quantify the impact of altruism demographics within the heterogeneous networks. In effect, it permits us to consider the extent to altruism (i.e. low movement costs

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*It is important to mention here that under our scheme, traffic opportunistically sent over the primary channel is preempted when a traffic generated by a primary user arrives—this is done by switching opportunistic traffic back to the secondary channel.

or high mobility budget) impacts the “quality” of existing connections. We list some of the ways in which “quality” can be interpreted:

(1) **Better network connectivity**: When a receiving node is outside the transmission region of the transmitting node, (i.e. received signal energy falls below receiver sensitivities) cooperation (e.g. Relay, Power-Based Topology Control) can sometimes yield connectivity to nodes that are otherwise unable to communicate directly. Mobility-based topology control can be employed when prohibitively high power levels are required to achieve connectivity, since multi-hop paths can be established through cooperative nodes that have been moved into suitable locations.

(2) **Higher throughput, Lower delay**: When having to transmit over a poor quality communication channel, cooperative approaches (e.g. Relay Cooperation, Power-Based Topology Control, Mobility-based Topology Control) can improve wireless channel quality by raising the Signal-to-Noise (SNR) ratio, thus yielding higher probability of successful transmission (hence raising throughput) and lowering retransmissions probabilities (hence lowering end-to-end transmission delay).

(3) **Extended coverage**: As noted previously, Cooperative Mobility can be used to maintain better network connectivity. By carefully selecting how connectivity is augmented, one can ensure higher probability for the existence of a route between specified source/destination nodes, thereby obtaining better coverage.

(4) **Longer network lifetime**: Cooperative approaches such as Power-Based Topology Control seek to minimize power consumption in order to extend network lifetime.

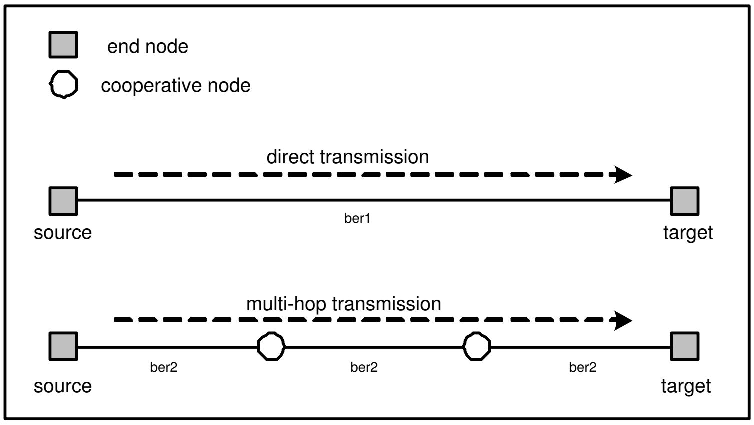


Figure 3.1 Direct transmission vs. multi-hop transmission.

Mobility-based topology control can be used to create multi-hop paths in place of paths with fewer longer hops. As the authors' previous work shows, this can reduce overall power consumption required to achieve comparable quality of service [5].

(5) **Better Wireless channel QoS**: Mobility-based topology control can be used to create multi-hop paths in place of paths with fewer longer hops. Even if the total power consumption is kept constant across scenarios, our previous work indicates that multi-hop configurations frequently achieve better quality of service even when subjected to the same power budget constraints [33]. To illustrate, consider Figure 3.1. Suppose direct signal transmission from the source to the target node results in a wireless channel with bit error rate equals to ber_1. Now consider multihop transmission through two cooperative nodes, dividing the original source signal transmission power between the source and the two relay nodes. If each hop attains a bit error rate of ber_2, the bit error rate of the 3-hop connection is equal to $1 - (1 - ber_2)^3$, which is easily shown to be less than ber_1 whenever $ber_2 < ber_1$.

Since the quality of the end-to-end communication between end users depends on the quality of the wireless channel, in this work, the network performance metric that we will be considering during our study of the proposed cooperative models is the wireless channel bit error rate (BER), which perfectly captures the quality of the wireless channels.

In the next chapter, we present our design of the CoopSim, a platform for conducting simulation experiments to evaluate the impact of parameters, policy, and algorithm choices on any system based on the proposed cooperative mobility model.

3.5 Scenario

Figure 3.2 illustrates a typical scenario in which the budgeted Cooperative Mobility Model improves the overall quality of wireless channels. The scenario depicts an 11 node network in which nodes 2-4 and 6-9 are cooperative. The bottom graph in the figure depicts the new network configuration after cooperative nodes 6,8 and 9 have been moved to new locations. The movement results in an improvement in the BER of many wireless channels, including: (6,9), (6,10), (7,9), etc. As described earlier, cooperative nodes 6, 8, and 9 require the Routing and Optimization Layer to pay for their declared movement costs using its residual mobility budget; the nodes will cooperate if this is done.

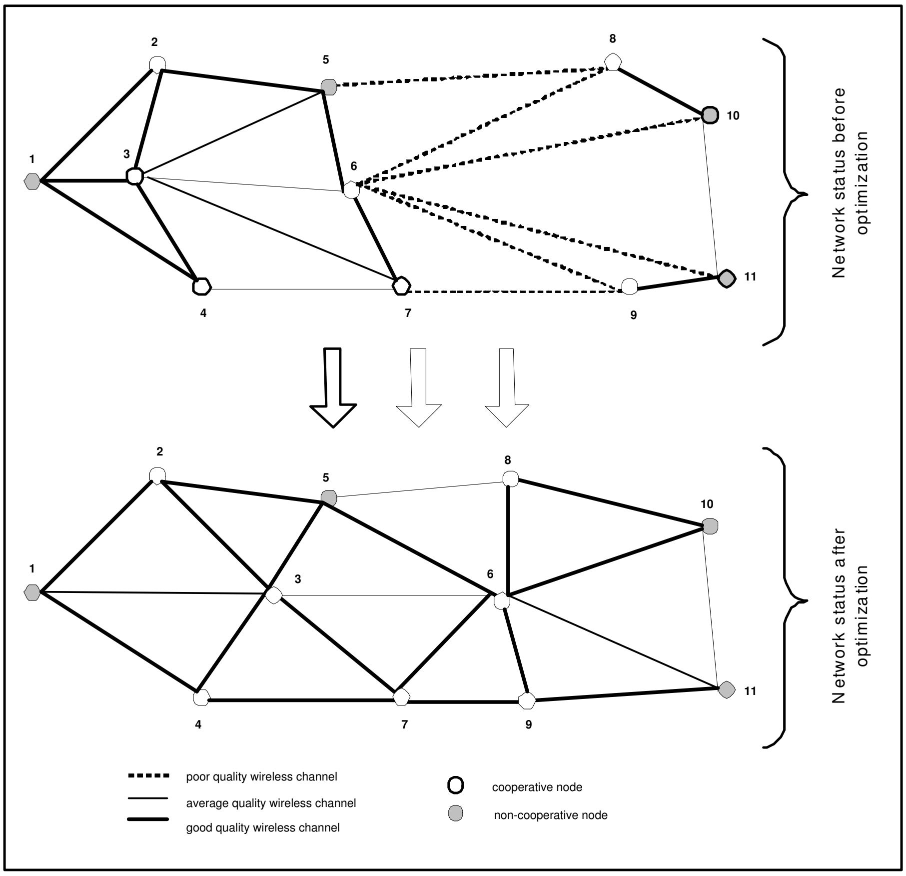


Figure 3.2 The utility of cooperative mobility.

CHAPTER 4

COOPSIM SIMULATION PLATFORM

4.1 Introduction

We have developed a simulation platform to investigate how parameter, policy and algorithm choices influence the efficacy of systems based on the proposed Cooperative Mobility Model. The CoopSim platform dynamically updates the communication infrastructure by manipulating its heterogeneous constituent network elements; network nodes are assumed to have a wide range of characteristics, including mobility costs and available transmission power. CoopSim continuously seeks to fulfill concrete end-to-end QoS requirements for a set of application level (multi-hop) connections between given endpoint pairs. CoopSim achieves this by leveraging cooperative mobility: it determines new locations for cooperative battlefield MANET nodes, while adhering to its mobility budget constraints. In this exposition QoS requirements are stated in terms of maximum acceptable end-to-end connection bit error rates (BER), but we note that CoopSim can seamlessly integrate arbitrary, richer QoS definitions. CoopSim can be used to evaluate both centralized approaches to mobility budget allocation (using global information) as well as distributed approaches that use only local information at each node.

4.2 CoopSim General Architecture

The CoopSim platform is implemented as a modular discrete event simulator that is naturally organized in layers. Figure 4.1 depicts the three-layer architecture, while Figure

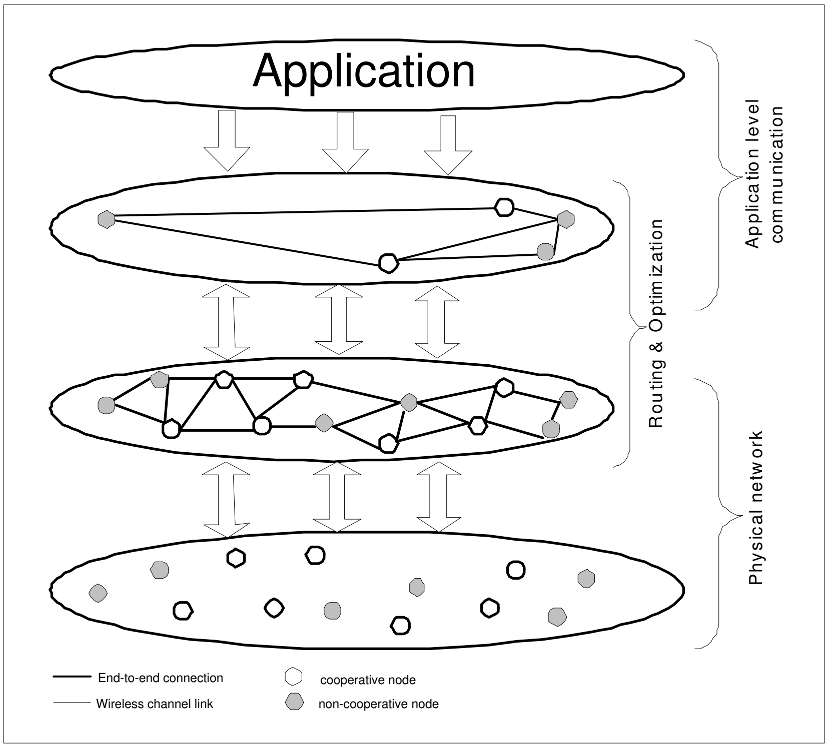


Figure 4.1 CoopSim layered design architecture.

4.2 presents a modular schematic diagram. Each modular building block that takes part in the discrete event simulation is called a simulation *entity*. Clearly, every battlefield MANET node is a simulation entity; in addition, there are the Physical Infrastructure Manager, the Routing Engine, Command & Control simulation entities. These correspond to each of the three layers. Additionally, an OutputHandler simulation entity serves as a collection point for the data recorded during a simulation experiment.

4.2.1 Physical Infrastructure Layer

The *lowest layer* of CoopSim represents the *Physical Infrastructure Layer*, which consists of a collection of wireless components such as UGVs, manned tanks, etc. Within

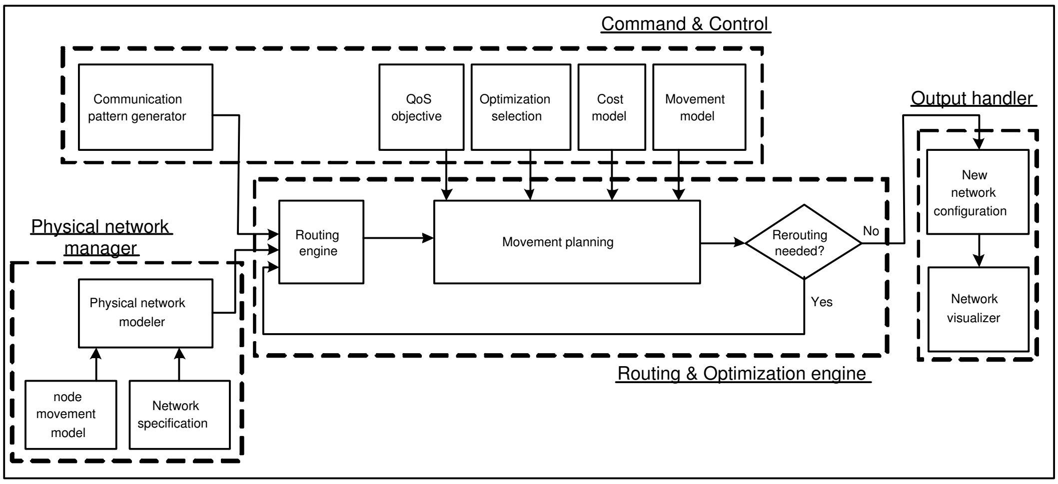


Figure 4.2 CoopSim modular architecture.

the CoopSim platform all functionality of the Physical Infrastructure Layer is implemented by a simulation entity called the *Physical Network Manager*. Important aspects of this layer/entity include:

- **Network Discovery**. These protocols are used to enable all nodes to discover their neighbors and establish wireless communication channels with them. The design of the network discovery protocol is beyond the scope of this article; a good reference can be found in [56]. For simulation purposes CoopSim assumes that a unidirectional channel connecting a transmitter to a receiver arises whenever the distance separating the two nodes is less than the communication range of the transmitter. A wireless channel forms between two battlefield MANET nodes whenever there is unidirectional channel in both directions.

- **Channel Characteristics**. Suppose we have a pair of nodes at distance D communicating using transmission signal power P over a wireless channel L with noise power P_{noise} through a medium with propagation constant α. The relationship between wireless channel bit error rate (BER) and the received power P_{rcv} is a function of the modulation scheme employed. CoopSim considers non-coherent Binary orthogonal Phase Shift Keying (BPSK) where $P_{rcv} = P/D^{\alpha}$, and the instantaneous channel BER is thus [40, 48, 55]:

$$BER(L) = \frac{1}{2}\, e^{-\left(\frac{P}{D^{\alpha}}\right)\frac{1}{P_{noise}}}.$$

4.2.2 Routing and Optimization Layer

The Routing and Optimization Layer forms the core of the CoopSim. It is the *middle layer* in Figure 4.1. This layer is responsible for routing the set of connections that need to be maintained and repositioning the cooperative nodes in order to better provide the required QoS. Within the CoopSim platform, the functionality of the Routing and Optimization Layer is implemented in a simulation entity called the *Routing and Optimization Engine*. Important aspects of this layer/entity include:

- **Routing**. Connections are routed along shortest paths in the graph using Dijkstra's algorithm, where the weight of link L is taken to be

  $$w_L = -\log(1 - BER(L)).$$

  It is easy to verify that shortest paths in this graph metric yield connections with minimal end-to-end BER. It is possible that in the course of the simulation two nodes move far apart, causing the channel between them to fail, and in turn causing some connections to break. CoopSim attempts to reroute connections that break due to link failures in this manner. The present version of CoopSim does not consider opportunistic rerouting of connections that are still intact but have become suboptimal because of node mobility.

- **Mobility**.

  Evaluating the performance of a mobile Ad Hoc network highly depends on the mobility model used. The mobility model should dictate the movement of the mobile nodes in a realistic way. Two of the most mobility models used by researchers are the Random Walk Mobility Model [18] and the Random Waypoint Mobility Model [7, 32]. Each one of these models generates unrealistic scenarios that make them inappropriate for mobile Ad Hoc network simulation. An alternative is to use the Gauss-Markov Mobility Model [67] that fixes the problem encountered by the previous two models.

  The Random Walk Mobility Model was developed to mimic the erratic movement of entities in nature that move in unpredictable ways [18]. A mobile node moves from one location to another by choosing two random values corresponding to speed and direction. Speed and direction are chosen to be within predefined ranges, [$speedmin$, $speedmax$] and $[0, 2\pi]$ respectively. After a certain time period t, or a distance d, new values for speed and direction are generated. No relation exists between the current and the past movements of the node. This might lead to unrealistic scenarios, where a node stops suddenly or makes sharp turns. Also, if the time period (t) or the distance (d) were small values, the node will be moving abruptly in a small region.

The Random Waypoint Mobility Model uses pause time between changes in speed and/or direction [7, 32]. A mobile node starts by pausing for a certain time period. Then it moves from one location to another by choosing two random values corresponding to speed and destination. Speed is chosen to be uniformly distributed between [$minspeed$, $maxspeed$]. The mobile node travels towards the new destination at the selected speed. Upon arrival, it pauses for a certain period of time and then starts the process again. The Random Waypoint movement is similar to the Random Walk movement when the pause time is 0. Hence, the Random Waypoint Mobility Model suffers from the same problems that the Random Walk Mobility Model suffers from.

To eliminate the problems (sudden stops and sharp turns) encountered by the Random Walk and the Random Waypoint mobility models, we use the Gauss-Markov Mobility Model. The Gauss-Markov Mobility Model was originally proposed for the simulation of a personal communications service (PCS) [43]; however, this model has been used for the simulation of an ad hoc network protocol [67]. The main advantage of this model is allowing past velocities (and directions) to influence future velocities (and directions). A mobile node starts moving using a current speed and direction. At fixed intervals of times, n, new speed and direction values are assigned to the mobile node. These values are calculated based on the values used in the previous time interval and a random variable. The speed and direction at the n^{th} instance are given by the following equations:

$$s_n = \alpha s_{n-1} + (1-\alpha)\overline{s} + \sqrt{(1-\alpha^2) s_{x_{n-1}}} \tag{4.1}$$

$$d_n = \alpha d_{n-1} + (1-\alpha)\overline{d} + \sqrt{(1-\alpha^2) d_{x_{n-1}}} \tag{4.2}$$

where s_n and d_n are the new speed and direction of the mobile node at time interval n; α, $0 \leq \alpha \leq 1$, is the tuning parameter used to vary the randomness; $\overline{s}$ and $\overline{d}$ are constants representing the mean value of speed and direction as $n \rightarrow \infty$; $s_{x_{n-1}}$ and $d_{x_{n-1}}$ are random variables from a Gaussian distribution. Totally random values (or Brownian motion) are obtained by setting $\alpha = 0$ and linear motion is obtained by setting $\alpha = 1$. Intermediate levels of randomness are obtained by varying the value of α between 0 and 1.

At each time interval, the next location is calculated based on the current location, speed, and direction of movement. Specifically, at time interval n, the mobile node's position is given by the equations:

$$x_n = x_{n-1} + s_{n-1} cos(d_{n-1}) \tag{4.3}$$

$$y_n = y_{n-1} + s_{n-1} sin(d_{n-1}) \tag{4.4}$$

where (x_n, y_n) and (x_{n-1}, y_{n-1}) are the x and y coordinates of the mobile node's position at the n^{th} and $(n-1)^{st}$ time intervals, respectively, and s_{n-1} and d_{n-1} are the speed and direction of the mobile node, respectively, at the $(n-1)^{st}$ time interval [14]. The Gauss-Markov Mobility Model can eliminate the sudden stops and sharp turns encountered by the models discussed above by allowing past velocities (and directions) to influence future velocities (and directions).

The routing and optimization engine, will be extended in order to support the cognitive radio capabilities of the CoopSim. This extension will be presented in details in chapter 8.

4.2.3 Application Layer

The application layer is responsible for generating a set of connections and associated QoS requirements. It is the *topmost layer* in Figure 4.1. This layer is responsible for generating a set of connections and associated QoS requirements. Within the CoopSim platform, the functionality of the Application Layer is implemented in a simulation entity called the *Command & Control*. Important aspects of this layer/entity include:

- **Connections**. A connection is defined by a pair of distinct nodes which serve as the source and destination. The Application Layer can generate arbitrary connection topologies based on the structure of the distributed application that is being simulated. In this article, we consider applications in which communication needs are represented by a random set of source-destination pairs.

- **QoS Requirements**. In this exposition, we consider QoS requirements to be defined in terms of maximum acceptable end-to-end BER, but we note that CoopSim can incorporate any computable definition of QoS.

- **Connection QoS**. We compute the BER of multi-hop connections under an end-to-end retransmission scheme. The bit error rate of a connection C which traverses links

L_1, L_2, ... L_k can then be computed as follows:

$$BER(C) = \prod_{i=1}^{k} BER(L_i).$$

- **Movement Costs**. Command & Control maintains information about each node: whether it is a manned or unmanned asset. Unmanned nodes are further categorized as either tasked or untasked, with tasked nodes having priorities. Every node i declares its movement cost C_i. Manned vehicles and tasked unmanned vehicles are considered quasi-autonomous because they typically declare high movement costs and have their own objective-driven movement; high movement costs make it unlikely they will be moved by the Routing and Optimization Layer. Vehicles that are both unmanned and untasked are considered essentially cooperative; their declared costs reflect the relative logistical expense involved in their deployment.

- **Mobility budget**. This is the amount of credit to issued by Command & Control to the Routing and Optimization Layer, for funding the movement of cooperative battlefield MANET nodes. The mobility budget is replenished periodically, every T_m time units. In the current simulation, mobility budgets do not accumulate across time intervals.

The CoopSim platform also implements an *Output Handler* simulation entity, which interacts with the Network Manager, Routing Engine, and Command & Control to analyze the evolving topology and network characteristics.

Figures 4.3-4.5 show the interactions between the entities within the CoopSim platform. Figure 4.3 illustrates the CoopSim startup procedure. Figure 4.4 shows the actions per-

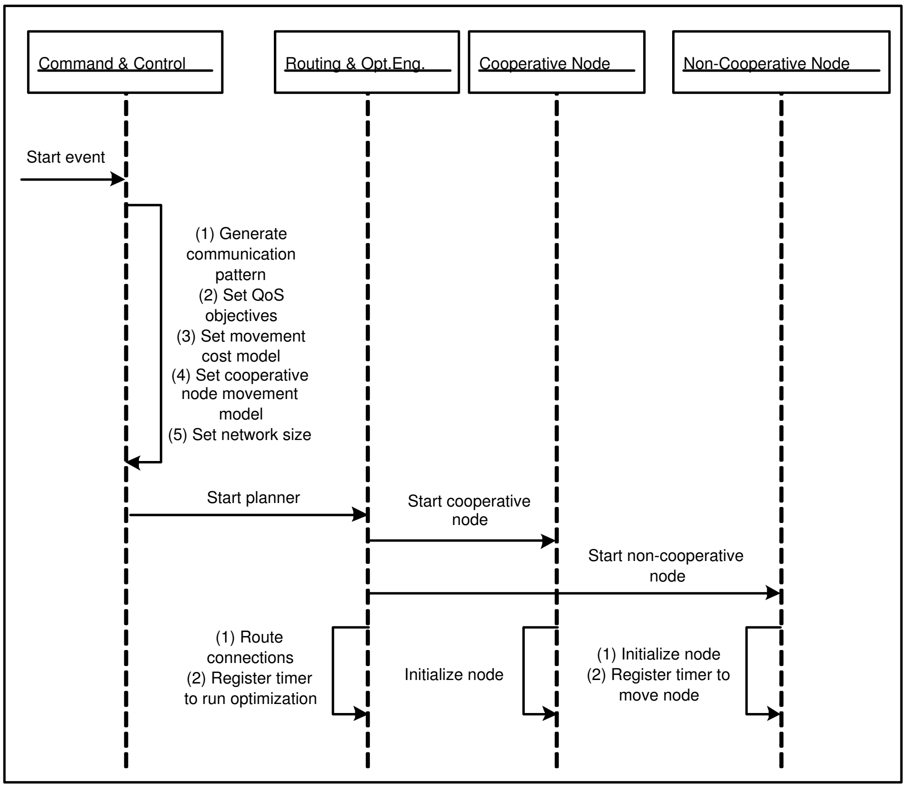


Figure 4.3 Event sequence diagram: CoopSim startup.

formed by the planner upon computing the best location of a cooperative node. After being instructed to move to different locations, the cooperative nodes update their current location, then update the Output Handler entity. Similar action is taken by the non-cooperative nodes when moving to a new locations based on the Gauss-Markov mobility model. These actions are illustrated in Figure 4.5.

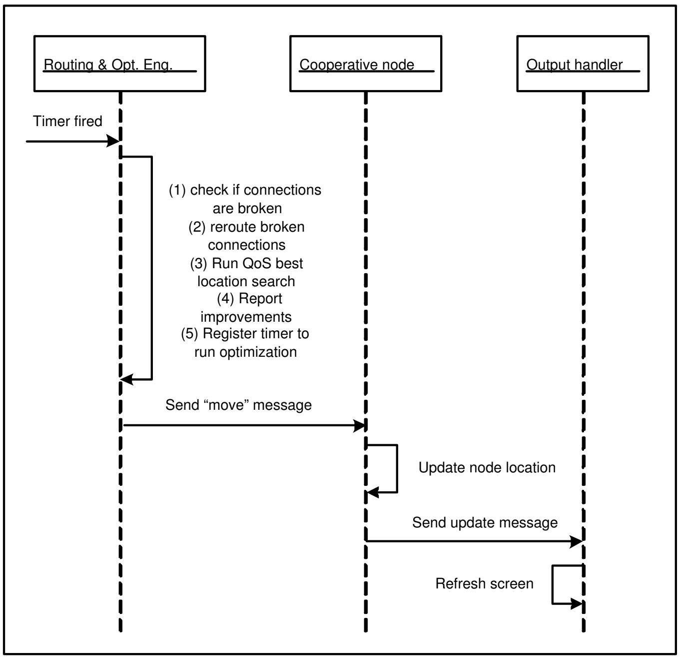


Figure 4.4 Event sequence diagram: updating cooperative nodes.

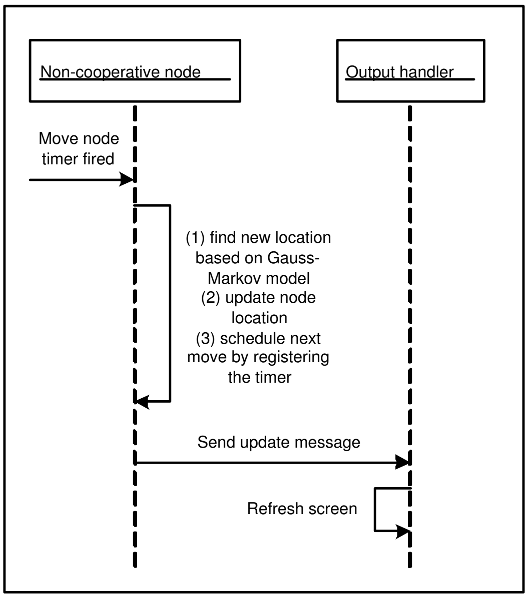


Figure 4.5 Event sequence diagram: updating non-cooperative nodes.

CHAPTER 5

MIXED INTEGER LINEAR PROGRAMMING FORMULATION

5.1 Introduction

As we mentioned in chapter 3, the goal of this research is to develop new schemes based on our proposed definition of cooperation between mobile nodes with the goal of improving the communication in MANETs. The first scheme we propose is based on nodes location management under budget constraints aiming at the improvement of the QoS of a connection set. Mixed-Integer Linear Programming (MILP) provides a framework for solving optimization problems of this form. In this chapter we propose an (MILP) formulation that accurately depicts the proposed cooperative model. Our formal description of this model describes both cases: (1) minimizing the movement budget used by all nodes while meeting the end-to-end QoS requirement of all connections, and (2) minimizing the BER of all connections under movement budget constraints. The MILP model was evaluated through simulations and found to be very effective, albeit for small networks. To make the proposed technique scale to large networks we propose a new technique for converting a large global MILP into a sequence of smaller local MILP optimizations.

The rest of this chapter is organized as follows. In section 5.2 we present a brief overview about Mixed Integer Linear Programming (MILP). In section 5.3 we specify the network model we are considering. In section 5.4, we present our formulation of both aforementioned problems as well as the complexity of the proposed MILP formulation in terms of number of variables. We verify the correctness of our formulation in section 5.5

through small network size networks. In section 5.6, we describe our approach in using the developed MILP for large scale networks, then we study its performance in section 5.7. Finally, in section 5.8 we draw some conclusions about the proposed approaches.

5.2 Mixed Integer Linear Programming Overview

Linear programming (LP) is an important field in operations research that deals with solving optimization problems of a particular form. Linear programming problems consist of a linear cost function (consisting of a certain number of variables) which is to be minimized or maximized subject to a certain number of constraints. The constraints are linear inequalities of the variables used in the cost function (also called the objective function).

If the unknown variables in the linear programming problem are all integers, the problem is called an "*integer programming (IP)*" or "*integer linear programming (ILP)*" problem. If only a subset of the variables are integers, the problem is called a "*mixed integer programming problem*". If all the variables are restricted to 0 or 1, the problem is called "*binary integer programming*" problem [70].

In contrast to linear programming, which can be solved efficiently in the worst case, MIP problems are in the worst case undecidable, and in many practical situations NP-hard. Every MILP problem falls into one of three categories:

1. Infeasible: The problem is infeasible if a feasible solution to the problem does not exist.

2. Unbounded: The problem is unbounded if the constraints do not sufficiently restrain the cost function so that for any given feasible solution, another feasible solution can

be found that makes a further improvement to the cost function.

3. Optimal solution: The problem has an optimal solution when the cost function has a unique minimum (or maximum) cost function value. This does not mean that the values of the variables that yield that optimal solution are unique. A problem that has an optimal solution is a problem that is not infeasible and not unbounded.

The *simplex* method is usually used to solve LP problems. It is composed of two basic steps. The first step is to find a feasible solution to the problem. The second step is to iteratively improve the value of the cost function. This is accomplished by finding a variable in the problem that can be increased, at the expense of decreasing another variable, such that the cost function is improved.

To illustrate this, let us consider the traveling salesperson (TSP), which a famous problem that can be easily modeled as an ILP problem. The TSP problem can be stated as follows. Consider a traveling salesperson who must visit each of n cities, numbered from 1 to n. For each pair of cities (i, j), let c_{ij} be the cost of going from city i to city j (and vice versa). Let $x_{ij} = 1$ if the person travels from city i to city j (and vice versa). This problem is known as the symmetric TSP. In the asymmetric TSP, the cost to travel in one direction may differ from the cost to travel in the other. Clearly the asymmetric problem is the more general. The TSP can be modeled as an ILP problem as follows [68]:

$$Min \qquad \sum_{i=1}^{N} \sum_{j=1}^{i-1} c_{ij} x_{ij}$$

Subject to

$$\sum_{j \neq i} x_{ij} = 2 \qquad \forall i \tag{5.1}$$

$$\sum_{i \in S} \sum_{j \notin S} x_{ij} \geq 2 \qquad \forall S \subset N \tag{5.2}$$

$$x_{ij} \in \{0, 1\} \qquad \forall i, \forall j \tag{5.3}$$

Constraint 5.1 indicates that every city must be visited. This constraint is not sufficient to ensure that TSP is satisfied because it is possible to have multiple cycles (subtours), rather than one big cycle (tour) through all the cities. Constraint 5.2 handles this situation by eliminating subtours. It indicates that for any subset of cities, S, the tour must enter and exit that set. Constraint 5.3 limits the solution space (values of x_{ij}) to either “0” or “1”.

Before we present our MILP formulation of the cooperative model under movement budget constraints, we describe the network model we are considering, which includes the specifications of wireless channel characteristics.

5.3 System Model

We consider a wireless ad-hoc network consisting of n nodes equipped with omni-directional antennas with different transmition power. Wireless propagation suffers severe attenuation [20] and [66]. If node i transmits with power P_t(i), the power of the signal received by node j is given by

$$P_{rcv}(j) = \frac{P_t(i)}{c \times d_{ij}^{\alpha}}, \tag{5.4}$$

where d_{ij} is the distance between nodes i and j. α and c are both constant, and usually $2 \leq \alpha \leq 4$ (See [20]).

Each wireless channel L between two nodes has a computable Bit Error Rate, $BER(L)$, that is the probability of the occurrence of an error during data transfer over that link. The relationship between the BER of a wireless channel and the received power level P_{rcv} is a function of the modulation scheme. Since we are only interested in studying the general dependence of the BER on the received signal power, we will consider the non coherent binary orthogonal Frequency Shift Queying (FSK) modulation scheme. Other modulation schemes can be analyzed in similar way, though closed-form analysis may not be always possible. For this specific modulation scheme, the instantaneous channel BER is given by [48, 55, 40] to be:

$$BER = 0.5\, e^{-\frac{P_{\text{rcv}}}{2P_{\text{noise}}}} \tag{5.5}$$

Let ρ be a *connection* defined by a source node s and a target node t and consisting of a sequence of links $L_1, \ldots, L_r$. In this case, the connection (under an end-to-end retransmission scheme) witnesses

$$BER(\rho) = 1 - \prod_{\ell=1}^{r} 1 - BER(L_\ell). \tag{5.6}$$

To minimize (5.6), we maximize $\prod_{\ell=1}^{r} 1 - BER(L_\ell)$, which by monotonicity of logarithms, is equivalent to maximizing $\sum_{\ell=1}^{r} \log(1 - BER(L_\ell))$ or minimizing

$$\sum_{\ell=1}^{r} -\log(1 - BER(L_\ell)). \tag{5.7}$$

Accordingly, if each link L in a graph is weighted by its *quality*

$$w_{i,j} = -\log(1 - BER(L)) \tag{5.8}$$

Then minimum cost paths correspond to minimum routes with minimal end-to-end bit error rates.

In our model, we assign for each cooperative node i a non-negative movement budget b_i. We assume that each node can move to a different location based on the available budget. When a node runs out of budget, it is no longer able change its location.

From the network model, we can see that the quality of the wireless channels within the network can be affected by the location of all nodes. For a given connection, having the many intermediate nodes on the segment between the endpoints would result in lower connection bit error rates; this is deducible from (5.6). Therefore, our goal(s) are to use the mobility budgets of cooperative nodes to adjust the topology in a manner that:

(I) *meets* end-user connection QoS requirements using minimal node movement, or

(II) *optimizes* end-user connection QoS while not exceeding available movement budgets.

In the rest of this chapter, we present our MILP formulation of this online optimization problem, evaluate it through experiments, and propose enhancements to make it scalable to real-world settings.

5.4 MILP Formulation

In this section, we present our formulation of the optimal mobility planning using MILP.

Assumptions.

(i) The set of mobile nodes $V = \{1, 2, \dots, n\}$ consists of nodes which all have the same sensitivity (minimum receivable signal power P_{min}) and the same transmission power P_{tx}; thus all links in the network are bidirectional.

(ii) The physical environment is discretized by selecting a set of "mesh points" $M = \{1, 2, \ldots, N\}$, and declaring that cooperative nodes must be placed only at mesh points'.

(iii) Fast routing convergence occurs and that connections are routed using Dijkstra's shortest path algorithm over the actual topology.

Input

For each node $i \in V$, we are given:

(a) its present *location* $w_i \in M$;

(b) its *mobility budget* $b_i \in \mathbb{R}$;

(c) the *desired BER* $\text{ber}_{i,j}$ between i and $j \in V$.

Preprocessing

- For each pair of positions $p, q \in M$, we compute the channel quality $m_{p,q}$ as $-\log(1-ber)$, where ber is the bit error rate of a direct transmission between locations p and q. These quantities are stored in *channel quality matrix* $[m] = [m_{p,q} \,|\, p, q \in M]_{N \times N}$.
- For each pair of nodes i and j, we compute the desired QoS $q_{i,j} = -\log(1 - \text{ber}_{i,j})$ and construct the QoS *requirements matrix* $[q] = [q_{i,j} \,|\, i, j \in V]_{n \times n}$.

- Using pairwise distances, expression (5.5), and the parameters of assumption (i), we construct the *network graph* $G = (V, E)$. Then, for each pair of nodes i and j, find a shortest route in G from i to j, defining the indicator variable $r_{k,l}^{(i,j)}$ to be 1 iff there is a link from node k to node l ($k, l \in V$) and it was used to route the connection from i to j. These are stored as n^2 distinct *route matrices* $[r]_{i,j} = [r_{k,l}^{(i,j)} \,|\, k, l \in M]_{N\times N}$ ($i, j \in V$).

- For each node $i \in V$, we compute the distances $d_p^{(i)}$ from w_i to each $p \in M$. These are stored as n distinct *distance vectors* $\vec{d}^{(i)} = [d_p^{(i)} \,|\, p \in M]_{1\times N}$ ($i \in V$).

Variables

- *Node movement vectors* $\vec{s}^{(i)} = \left[s_p^{(i)} \,|\, p \in M\right]_{1\times N}$ where $s_p^{(i)} = 1$ iff node i moves to location p (0 otherwise).

- *Link movement variables* are derived from the node movement vectors, where $g_{l,q}^{(k,p)} = 1$ iff nodes k and l are at mesh locations p and q (0 otherwise).

Objective

The actual quality of the connection between nodes i and j (after all nodes have moved) can be computed as

$$X_{i,j} = \sum_{p,q=1}^{N} m_{p,q} \sum_{l,k=1}^{n} r_{k,l}^{(i,j)} g_{l,q}^{(k,p)}. \tag{5.9}$$

To see this, note that the expression identifies all links (k, l) which are used in connection (i, j) and uses the location p (of k) and q (of l) to determine the quality of each constituent link (k, l); these are then aggregated appropriately to determine the quality of the entire connection (i, j). On the other hand, the distance that node i moves is simply $\vec{d}^{(i)} \cdot (\vec{s}^{(i)})^T$.

We consider an objective function that is a linear combination of these two quantities as sub-objectives:

$$\min \alpha \sum_{i=1}^{n} \vec{d}^{(i)} \cdot (\vec{s}^{(i)})^T + \beta \sum_{i=1}^{n} \sum_{j=1}^{n} X_{i,j} \tag{5.10}$$

Here, we report on investigations of the pure objective cases, **(Objective I)** when $\alpha = 1, \beta = 0$ and **(Objective II)** when $\alpha = 0, \beta = 1$; in general settings taking both $\alpha, \beta \neq 0$ could be used to implement a mixed objective.

Constraints

- *Movement budget constraints*: To ensure that each node does not violate its movement budget we require that for each $i \in V$:

$$0 \leq \vec{d}^{(i)} \cdot (\vec{s}^{(i)})^T \leq b_i. \tag{5.11}$$

- *QoS requirement constraints*: To ensure that the quality of service requirement is met, we require for all $i, j \in V$:

$$X_{i,j} \geq q_{i,j}. \tag{5.12}$$

- *Route constraints*: Since the variables are binary, we require that for all $i, k, l \in V$ and $p, q \in M$:

$$s_p^{(i)}, g_{l,q}^{(k,p)} \in \{0, 1\}. \tag{5.13}$$

To ensure that node and link movement variables are coherent, we require for all $i \in V$:

$$\left(s_p^{(k)} + s_p^{(l)}\right) - 1 \leq g_{l,q}^{(k,p)} \leq \min\{s_p^{(k)}, s_p^{(l)}\}. \tag{5.14}$$

- *Selector constraints*. Since node can only move to one place, for all $i \in V$,

$$\sum_{k=1}^{N} s_p^{(i)} = 1. \tag{5.15}$$

MILP complexity. The complexity of any MILP problem depends on the number of variables and constraints in that problem. In the proposed formulation, the factors that determine the number of variables and constraints are the mesh size (N), the network size (n), and the connections set C. The number of variables in the proposed MILP formulation is $\sharp vars = (Nn)^2 + Nn$, while the number of constraints involved is $|C| \cdot \sharp vars$.

5.5 Initial Experiment

We begin by presenting the benefits of cooperative mobility planning using the MILP formulation using the results of some small but very illustrative simulations. The simulations are conducted in $1280m \times 800m$ field. The mesh used was a cartesian grid with cell geometry of $6m \times 6m$. The initial coordinates of the mobile nodes were uniformly randomly distributed within the network. All nodes were given the same transmitting power and the a uniform movement budget (ranging from low values of $50m$ to high values $300m$ in the different experiments). We conducted our optimization on a connection set C of size 3 where the endpoints were chosen at random. We considered both scenarios where the randomly generated connections were edge-disjoint (no contention) and cases where shortest path routes shared edges (contention). We used the MILP solver `lp-solve` which is based on the simplex and branch-and-bound techniques. Figure 5.1 represents the initial network topology and the set of connections. We analyzed the movement plans determined by MILP in both large ($300m$) and small ($50m$) movement budget settings.

Figure 5.2 shows the new topology output by the MILP solver with Objective I. Table 5.5 indicates that the connection required BER was met (corresponding to a 60% improvement from the initial value) for all connections while using a total movement budget of 128. For example, for connection $C2$, a total budget of 64 units was used to lower the end-to-end BER from $1.52 \cdot 10^{-3}$ to $5.72 \cdot 10^{-4}$, which corresponds to an improvement of more than 60%.

Figure 5.3 shows the new topology output by the MILP solver with Objective II. Table 5.5 shows that the average BER per connection was improved from 10^{-3} to 10^{-9}, an improvement of more than 100%. Under this scheme, a total movement budget of approximately 1000 units was used. For example, for connection C2, a total budget of 568 units was used to lower the end-to-end connection BER from $1.52 \cdot 10^{-3}$ to $2.27 \cdot 10^{-9}$.

In considering the effect of increasing the movement budget on the connection performance we found, as expected, that higher budgets consistently yield better QoS. For example, for connection $C1$, increasing the movement budget from 50 to 300 units, results in lowering BER from $2.45 \cdot 10^{-5}$ to $2.44 \cdot 10^{-7}$.

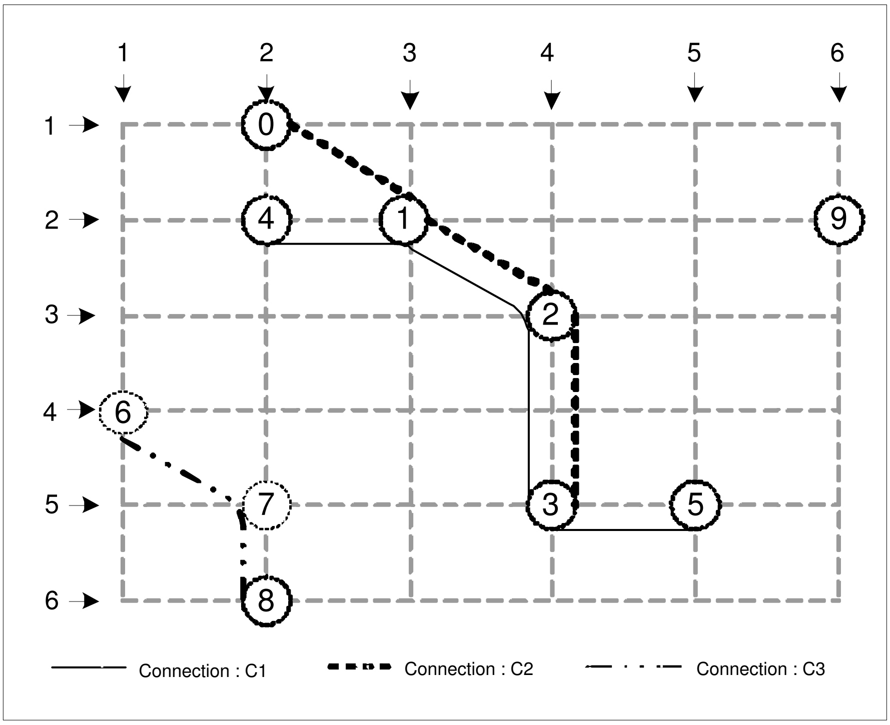


Figure 5.1 Initial topology and connection set.

5.6 Divide And Conquer Approach

In general, the difficulty of any MILP problem depends on the number of variables and constraints in that problem. We found that MILP problems having more than 2000 variables or 4000 constraints were essentially intractable with commodity hardware. Thus, the initial formulation (above) would be helpful only as long as the number of variables and the number of constraints are below these figures. In order to address larger network sizes, we require a strategy for reducing the search space.

Our approach is to replace the global network MILP whose goal is to attain end-to-end connection quality using minimal mobility, by converting it into a set of local MILPs at the link level. This yields scalability by decreasing the computational complexity, providing an improvement of the wireless links, which then indirectly result in an improvement in

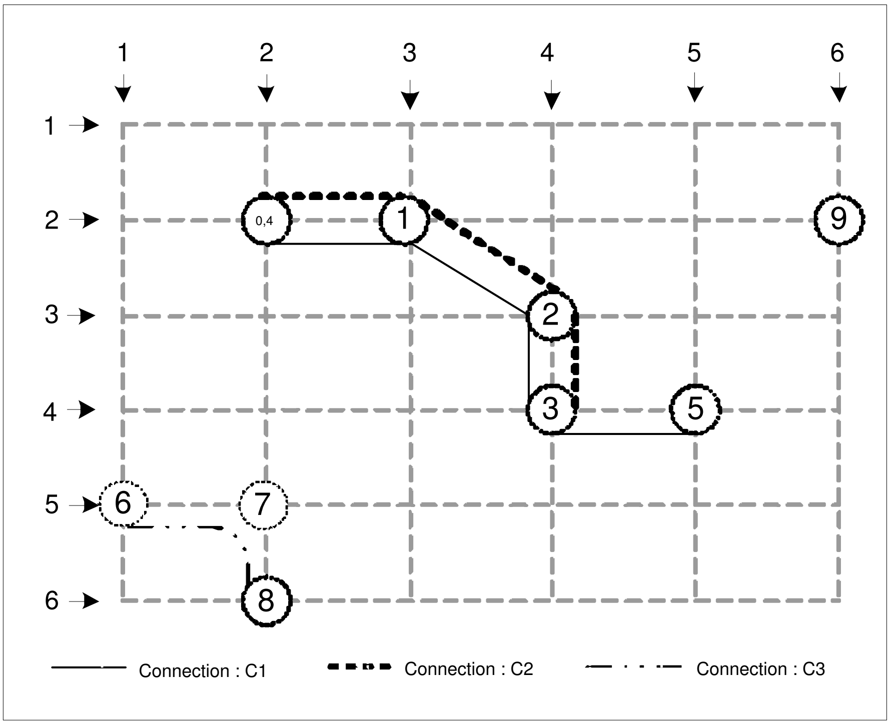


Figure 5.2 Objective I, movement budget = 300/node.

the end-to-end connection quality. The approach is shown in Figure 5.6 and is described in detail below:

Each round of the algorithm begins by determining which connections still do not meet their end-to-end bit error rate requirements. For each of these "violating connections" we determine the poorest *improvable* wireless link (s, d), i.e. the link with the highest bit error rate whose endpoints have movement budgets above a predefined threshold.

The algorithm then designs a local mesh around link (s, d) by making a uniform cartesian grid around the smallest axis-parallel bounding box which contains s, d and all of their neighbors. The density of the grid is taken to be the same as that for the global MILP, but because the bounding box is typically much smaller than the ambient space, the local MILP involves far fewer mesh points $N' \ll N$.

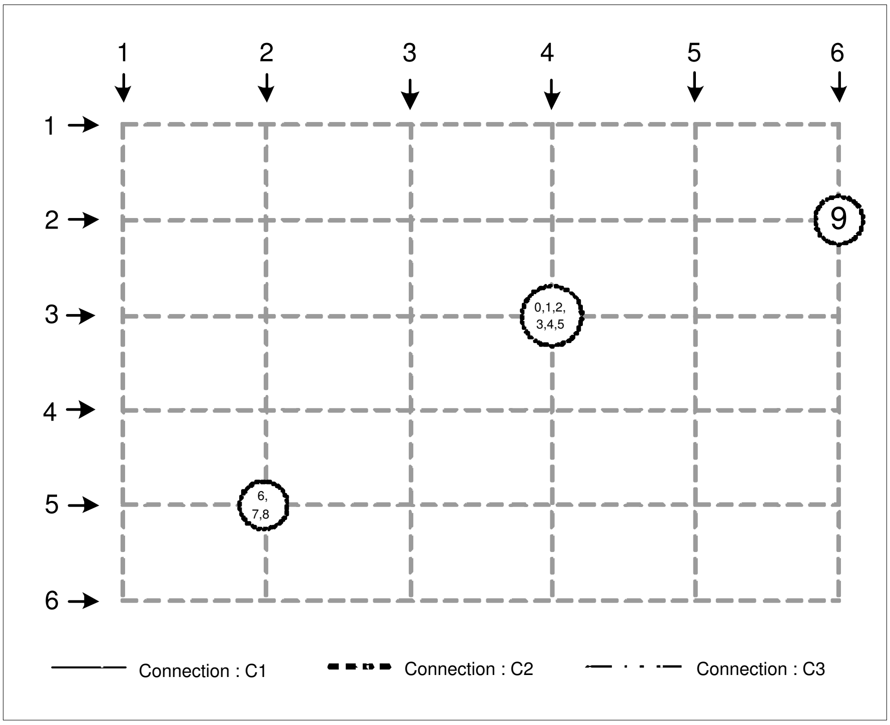


Figure 5.3 Objective II, movement budget = 300/node.

The procedure then constructs a local MILP using this grid, but considers only those cooperative nodes which both (i) lie within the bounding box and (ii) participate in some connection that does not meet its bit error rate requirements. Because the bounding box is typically much smaller than the ambient space the local MILP considers far fewer nodes $n' \ll n$. Finally, the connection constraints of the local MILP include only the bit error rate requirements of connections going through the link (s, d). The local MILP is solved and node positions updated as prescribed; this completes one round of the algorithm.

The procedure executes additional rounds until convergence; either (i) all connections meet their BER requirements, (ii) the connections which do not meet their requirements contain no improvable links, or (iii) the consideration of all improvable links yields connection BER improvements that are "insignificant", i.e. fall below a chosen threshold.

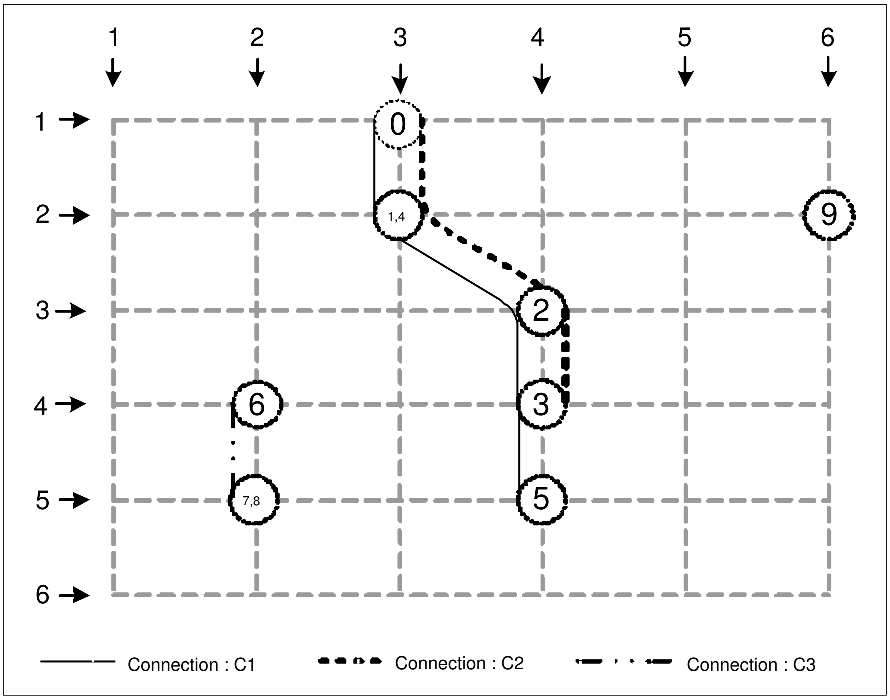


Figure 5.4 Objective II, movement budget = 50/node.

5.7 Results

In this section we give some experimental results to illustrate the performance of the proposed MILP for large network size. The scenario consists of a network size of 25 uniformly distributed nodes, where 10 autonomous nodes are moving according to a Gauss-Markov process, and 15 cooperative nodes operate, each with a uniform mobility budget; all nodes reside inside a one square kilometer grid. Node transmit power and receiver sensitivities are set so that wireless channels arise whenever two nodes are at distance less than $100m$. We establish 15 random connections that we propose BER requirements for the connections equal to 60% of their initial values.

The first experiment investigates the impact of the proposed scheme on improving the average BER of the connection set. The top curve in figure 5.7 represents the average BER

	Connection (src, dst)	Route	Used budget	Initial BER	Final BER
Min(dis): large budget	(0,3)	0 → 1 → 2 → 3	64	1.912 E-3	5.391 E-4
	(4,5)	4 → 1 → 2 → 3 → 5	64	1.525 E-3	5.713 E-4
	(6,8)	6 → 7 → 8	32	2.45 E-3	4.894 E-4
Min(BER): large budget	(0,3)	0 → 1 → 2 → 3	316	1.912 E-3	0
	(4,5)	4 → 1 → 2 → 3 → 5	568	1.525 E-3	0
	(6,8)	6 → 7 → 8	116	2.45 E-3	0
Min(BER): limited budget	(0,3)	0 → 1 → 2 → 3	84	1.912 E-3	5.631 E-7
	(4,5)	4 → 1 → 2 → 3 → 5	155	1.525 E-3	2.455 E-5
	(6,8)	6 → 7 → 8	84	2.45 E-3	5.674 E-8

Figure 5.5 Initial experiment outcomes.

of an ad-hoc network where the cooperative nodes remain stationary over time. The bottom curve represents the same measure in the presence of cooperative nodes manipulated according to the proposed MILP scheme. By looking at the *slope* of the bottom chart, we conclude that the routing and optimization scheme were able to maintain a fairly constant low connection set BER. By analyzing the difference of both curves, we conclude that with our proposed scheme, we were able to achieve an improvement of the overall connection set BER by almost 300%.

The second experiment investigates the effects of increasing the node mobility budget and number of connections. The network is constructed in the same manner as before but the same autonomous movement node sequence is responded to by cooperative node which have mobility budget of $50m$ (top curve) and $20m$ (bottom curve). By considering the *difference* between the curves curves of the top graph, we notice that for a higher node

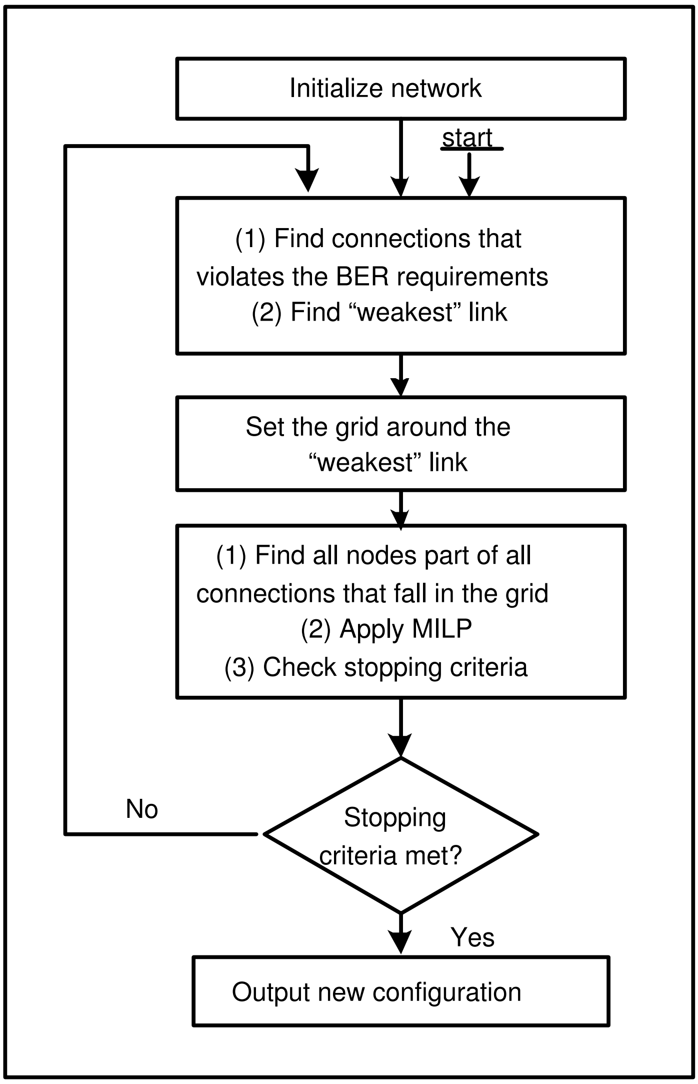


Figure 5.6 Converting a global MILP as a sequence of local MILPs.

movement budget corresponds a better improvement in the overall percentage BER improvement. For example, for a connection set size, corresponds a 20% improvement when using 50 units of budget compared to the case where each node has only 20 units. Considering the *slope* of the curves in the top graph, we conclude that the average percentage BER improvement decreases as the connection set size increases.

The bottom graph of figure 5.8, illustrates the impact increasing the movement budget on the percentage of the connections that do not meet the BER requirement by the time the optimization terminates. By looking at the *slopes*, we conclude that this percentage increases as the connection set size increases. For example, 13% of the connections did not meet the BER requirement when the connection set size equals to 17. By considering the *difference* between both curves of the bottom graph, we conclude the percentage of connections that did not meet the BER requirement is much less in the case of higher movement budget available per node. For example, for 17 connections, increasing the movement budget from 20 to 50 units results in a 40% improvement in the percentage of connections not meeting the BER requirement.

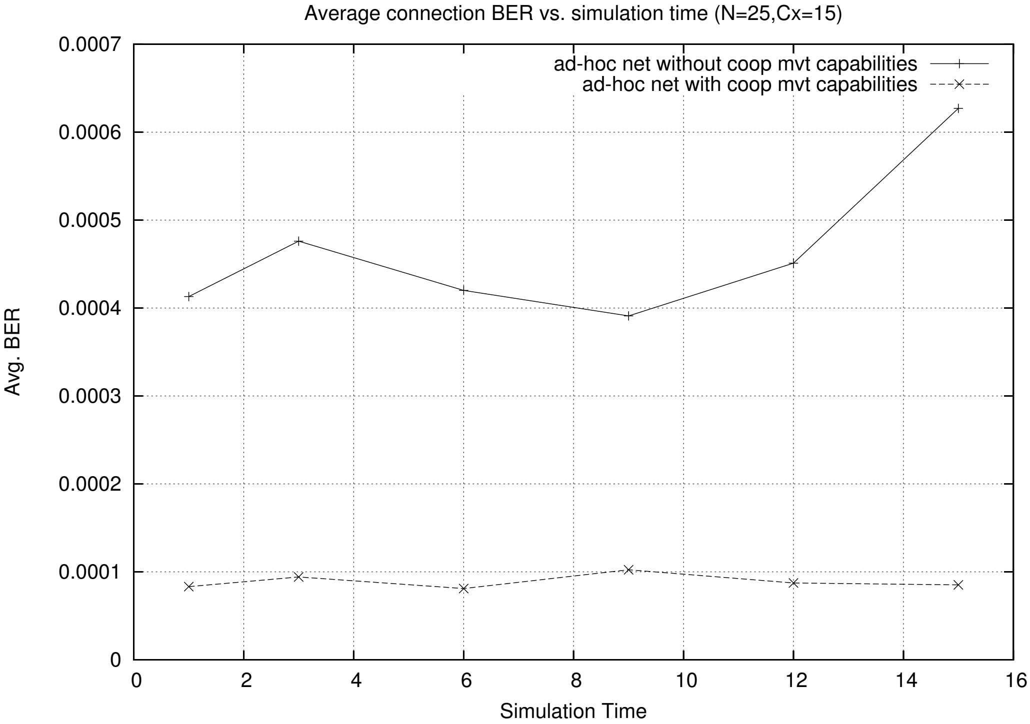


Figure 5.7 Using localized MILPs to minimize connection BER.

5.8 Summary

In this chapter we demonstrate new strategies to improve MANET communications, based on inter-node cooperation with respect to node mobility under movement budget constraints. We develop a Mixed-Integer Linear Programming (MILP) formulation of the model, accurately capturing its objectives and constraints. The MILP model is evaluated through simulations and found to be very effective, although for small networks. To make the proposed technique scale to large networks we develop a new technique for converting a large global MILP into a sequence of smaller local MILP optimizations. This technique is based on divide and conquer concept. We demonstrate that the resulting approach is scalable and succeeds at efficiently moving cooperative nodes in a manner which optimizes connection bit error rates.

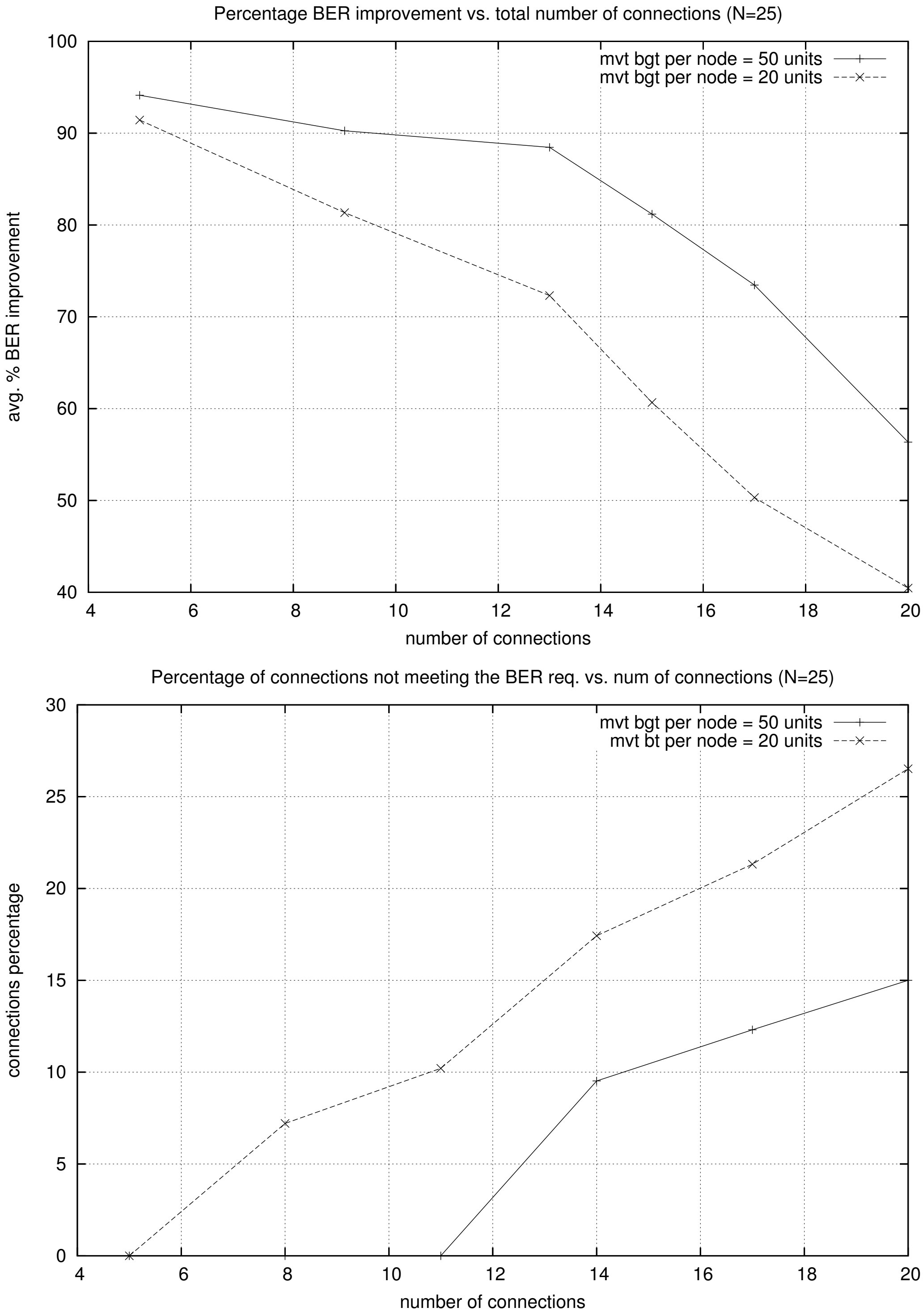


Figure 5.8 The benefit of increasing the mobility budget.

CHAPTER 6

OPTIMAL MOVEMENT PLANNING: MULTIGRID APPROACH

6.1 Introduction

Finding the optimal solution of the nodes location problem with the objective of meeting the connection set bit error rate requirements is very difficult because of the huge search space. Therefore, we propose the multigrid approach with the goal of finding a close to optimal solution of the current node search location problem, which will serve as a reference algorithm to which our next proposed algorithms based on heuristics will be compared to.

The multi-grid approach consists of having all cooperative nodes that are part of any connections under optimization visit as many locations as possible within its neighborhood area. Therefore, we assumes that the whole space is divided into a grid of variable size and we assume that each cooperative node can only be placed in either of the four corners of its surrounding grid cells. This would definitely prune the huge search space related to the possible location of cooperative nodes within the MANET network. Once a cooperative node is moved to a new location, a new space subdivision is performed by minimizing the granularity of the grid size. This guarantees that the connection bit error rate requirements are met while having the cooperative nodes consume a minimum movement budget.

The rest of this chapter is organized as follows. In section 6.2 we provide more details about the multigrd approach. We will introduce the concept of slack, we present the node control ligic procedure, then we discuss the complexity of the proposed algorithm. In section 6.3 we describe our simulation setup and interpret its outcome. Finally, in section

6.4 we draw some conclusions about the proposed approach.

6.2 Multigrid Approach

An initial approach to finding the optimal solution to the nodes location problem might consider using continuous function minimization techniques. However, several difficulties arise immediately: (i) the dimensionality of the space is large ($2N$ dimensions for networks of N nodes), (ii) the objective function (mean bit error rate per connection) is highly non-linear, and (iii) the objective function has many local minima. One way to systematize the search process is to discretized the search space. However, in discrete approaches, the grid resolution parameter introduces an inefficient tradeoff between solution optimality and compute time. We seek to mitigate this tradeoff using grids of varying resolution.

Multigrid (MG) techniques have gained significant popularity in computing numerical solutions for differential equations [6]. Following the general MG paradigm, we define a hierarchy of successively finer grids, based on an original "fine" grid. This process of defining the finer grids inverts the standard MG process of agglomeration [71]. At each phase, all cooperative nodes (that are part of any connections requiring optimization) successively consider moving to nearby grid locations. Specifically, here we assume that each cooperative node may consider moving to one of the four corners of its surrounding grid cell. Once all cooperative nodes have considered moving, the grid is refined (if necessary) according to a *grid refinement schedule*. In this approach, we consider an arithmetic grid refinement schedule, by considering a sequence of grids having $n, n + c, n + 2c, \ldots$ cells; in phase i, we consider a grid of $\sqrt{n + ic}$ by $\sqrt{n + ic}$ cells the grid has $n + ic$ cells .

In the next section, we present more details about the multigrid algorithm.

6.2.1 Node Control Logic

Before we describe the procedure that each cooperative node follows to select its next location, we define the notion of *slack* of a connection:

$$slack = \text{ current BER} - \text{ required BER.}$$

This is depicted in Figure 6.1.

When a node contemplates moving to a new location, it considers two quantities: its current slack, and the slack it will have if it moves to the new location; the latter quantity is referred to as the *projected* slack. The *slack differential* for a proposed move is defined by:

$$\begin{aligned} \text{slack differential} &= \text{current slack} - \text{projected slack}, \\ &= \text{current BER} - \text{projected BER}. \end{aligned}$$

We distinguish between scenarios based on whether a node sees a connection having negative or positive projected slack. On the one hand, if the projected slack is positive, two sub-possibilities arise: if the slack differential is positive, the projected cooperative node movement will result in better connection performance; if the slack differential is negative, moving the cooperative node to the new location will result in worse connection QoS. On the other hand, a negative projected slack indicates that the proposed movement will yield an improvement in the connection bit error rate that will *exceed* the required QoS. In such settings, the algorithm tries to minimize the *magnitude* of negative slack using minimal movement budget. The scenarios are depicted in Figures 6.1 and6.2.

The procedure to select the next location of the cooperative node is illustrated by the following pseudocode. The new location of the cooperative node is chosen in a way that results in an overall improvement of the bit error rate of all underlying connections while utilizing a minimum amount of the movement budget.

```
begin
    for each coop. node $C$ part of any connection do
        Find $C$'s boundary cell
        foreach grid cell's corner do
            (1) Compute projected BER of connections that transit $C$
            (2) Compute slack differential of all connections that transit $C$
        endforeach
        Find new location of coop. node $C$ such that:
        (1) Sum slack differential (over all transit connections) is positive and significant, and
        (2) There is sufficient movement budget to make projected move.
        (*) If more than one candidate corner exists, we choose the one which minimizes the sum of (the magnitudes of) the negative slacks
    endfor
    Move $C$ to the best corner, if one was found
    Decrease the residual movement budget suitably
end
```

Algorithm 6.1 Cooperative node control algorithm.

Failure to find a grid cell corner that satisfies (1) implies that average BER cannot be improved by moving. Failure to find a grid cell corner that satisfies (2) implies that insufficient movement budget is available. In the event that multiple grid corner's satisfy (1) and (2), the condition (*) is used to break ties, ensuring that we minimize the extent to which connection QoS is over satisfied. If a node fails to find a corner satisfying both (1) and (2), the node leaves the optimization process. We formalize each node's stopping criteria in pseudocode as follows:

```
begin
    if for all four grid cell corners:
    (1) Average slack differential (over all transit connections) is negative/insignificant
    OR
    (2) Not enough movement budget is available  then
        Node exits optimization process
    else
        Increase grid granularity and re-iterate
    endif
end
```

Algorithm 6.2 Multigrid algorithm stopping criteria.

In practice, the stopping criteria procedure is implemented by interpreting the phrase *"significant"* to mean a threshold encoding the notion of convergence. In our experiments convergence was assumed for a node when its slack differential was less than μ =1% of the *initial* slack at the beginning of the entire optimization process.

Initially, we divided the whole space into a grid of $n \times n$ cells. Within a phase, the movement of a cooperative node is restricted to be to one of the surrounding corners of the grid cell in which it resides, according to the previously described logic. If not all nodes have left the optimization process yet, the algorithm is rerun again over a successively finer granularity grid, as mandated by the refinement schedule. Figure 6.3 illustrates the algorithm.

6.2.2 Multigrid Algorithm Complexity

In this section, we study the complexity of the proposed algorithm in terms of the number of cooperative nodes in the connection set (N) and the number of connections (m).

Since in each phase, a node is guaranteed to reduce its slack by $\mu = 1\%$, the number of rounds required is bounded $1/\mu$. In each round, a node performs $O(m)$ work evaluating the

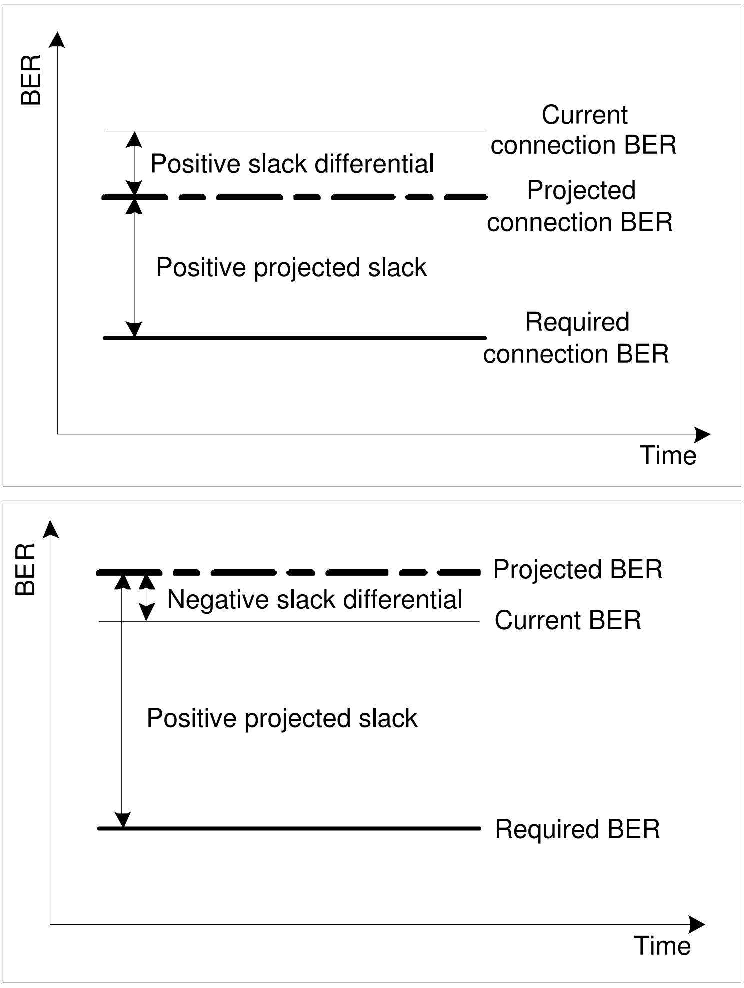


Figure 6.1 Positive projected slack.

four corners of its grid cell. Thus the algorithm converges in sequential time $O(Nm/\mu)$; a parallel implementation in which nodes operate concurrently requires $O(m/\mu)$ time. Note that the run time of the algorithm is independent of the initial grid size (n), and increment (c) which determine the grid refinement schedule; these parameters affect the quality of the solution because they alter the algorithm's susceptibility to local minima; they do not significantly impact upper bounds on the convergence time.

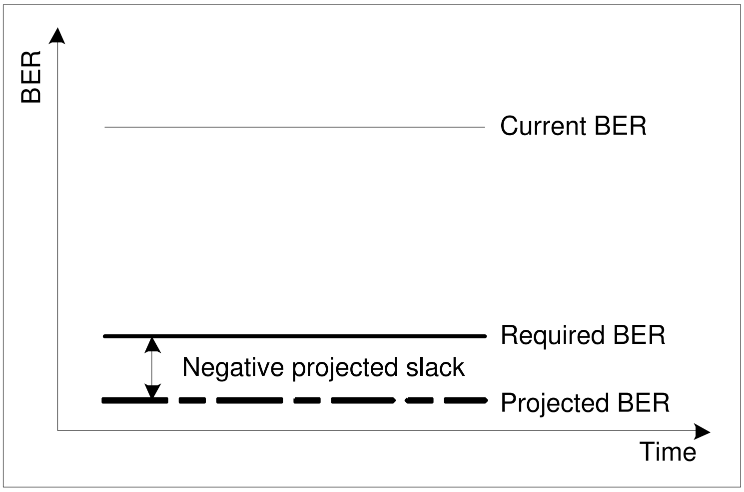


Figure 6.2 Negative projected slack.

6.3 Multigrid Algorithm Performance

In this section we describe our simulation setup, then we give some experimental results to illustrate the performance of the proposed multigrid approach.

6.3.1 Simulation Setup

We use the CoopSim platform to setup the following scenario. we consider an average network size of 30 uniformly distributed nodes, where 15 autonomous nodes are moving according to a Gauss-Markov process, and 15 cooperative nodes operate, each with a uniform mobility budget; all nodes reside inside a one square kilometer grid. Node transmit power and receiver sensitivities are set so that wireless channels arise whenever two nodes are at distance less than $100m$. We establish 15 random connections that we propose BER requirements for the connections equal to 60% of their initial values. We consider an initial grid size equal to 10.

6.3.2 Analysis

The first experiment investigates the effects of increasing the total mobility budget while keeping the number of cooperative nodes fixed. The top graph shows that having higher mobility budgets permits the routing and optimization layer to achieve lower connection BER over time. The bottom chart of Figure 6.4 depicts this effect in greater detail by considering the same experimental scenario but with varying mobility budget. The graph shows that a mobility budget of 50 units permits the routing and optimization layer to lower average connection BER by almost 8%, and that increasing the mobility budget to 200 units enables BER reduction of almost 40% over time. The results indicate that connection BER can be improved almost linearly as the mobility budget increases, even under constant numbers of cooperative nodes.

The second experiment investigates the effects of increasing the number of cooperative nodes while keeping the total mobility budget fixed. The simulation setup for the graph in Figure 6.5 consists of 15 autonomous nodes, 0, 3 or 8 cooperative nodes, mobility budget is fixed at 200 units, and a total of 7 random connections with a target Quality of Service to be 60% of their initial BER value for each connection. The top graph shows that having more cooperative nodes permits the routing and optimization layer to lower BER more effectively over time, even when the mobility budget is not increased. The bottom chart of Figure 6.5 depicts this effect in greater detail by considering the same experimental scenario but with varying numbers of cooperative nodes. For example, with 4 cooperative nodes, we can lower average connection BER by almost 8%, while increasing the number of cooperative units to 12 enables BER reduction of almost 40%. The results indicate that connection BER can be improved almost linearly as the number of cooperative nodes increases, even under constant total mobility budgets.

The next experiment investigates the impact of the proposed scheme on improving the average BER of the connection set. The top curve in Figure 6.6 represents the average BER of an ad-hoc network where the cooperative nodes remain stationary over time. The bottom curve represents the same measure in the presence of cooperative nodes manipulated according to the proposed multigrid scheme. By looking at the *slope* of the bottom chart, we conclude that the routing and optimization scheme were able to maintain a fairly constant low connection set BER. By analyzing the difference of both curves, we conclude that with our proposed scheme, we were able to achieve an improvement of the overall connection set BER by almost 300%.

The next experiment investigates the effects of increasing the node mobility budget and number of connections. The network is constructed in the same manner as before but the same autonomous movement node sequence is responded to by cooperative node which have mobility budget of $50m$ (top curve) and $20m$ (bottom curve). By considering the *difference* between the curves curves of the top graph, we notice that for a higher node movement budget corresponds a better improvement in the overall percentage BER improvement. For example, for a connection set size, corresponds a 35$\%$ improvement when using 50 units of budget compared to the case where each node has only 20 units. Considering the *slope* of the curves in the top graph, we conclude that the average percentage BER improvement decreases as the connection set size increases.

The bottom graph of Figure 6.7, illustrates the impact increasing the movement budget on the percentage of the connections that do not meet the BER requirement by the time the optimization terminates. By looking at the *slopes*, we conclude that this percentage increases as the connection set size increases. For example, 13% of the connections did not meet the BER requirement when the connection set size equals to 17. By considering the *difference* between both curves of the bottom graph, we conclude the percentage of connections that did not meet the BER requirement is much less in the case of higher movement budget available per node. For example, for 17 connections, increasing the movement budget from 20 to 50 units results in a 50% improvement in the percentage of connections not meeting the BER requirement.

6.4 Summary

In this chapter, we explained a new approach based on the multigrid techniques under movement budget constraints. This approach uses the cooperative mobility concept to improve the quality of communication channels in mobile ad-hoc network (MANETs). Simulation experiments indicate conclusively that the resulting approach is scalable and succeeds at efficiently moving cooperative nodes in a manner which optimizes connection bit error rates.

Despite the fact that the multigrid approach is quite costly in terms of the number of operations involved, it provides close to optimal solution for the cooperative nodes placements. Therefore, it could serve as a good reference to which we will be comparing our heuristic based cooperative node movement planning techniques.

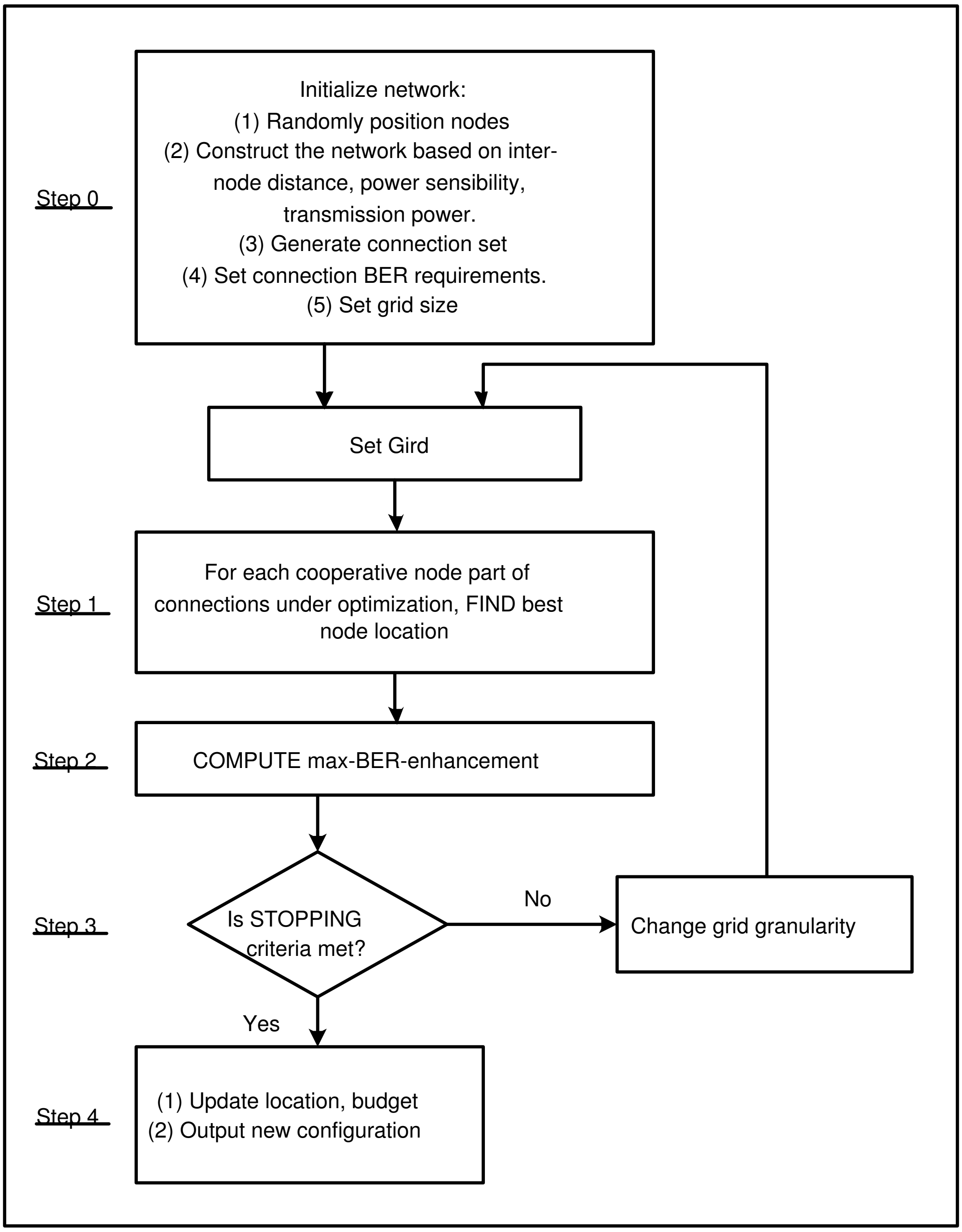


Figure 6.3 Flowchart of the multigrid algorithm.

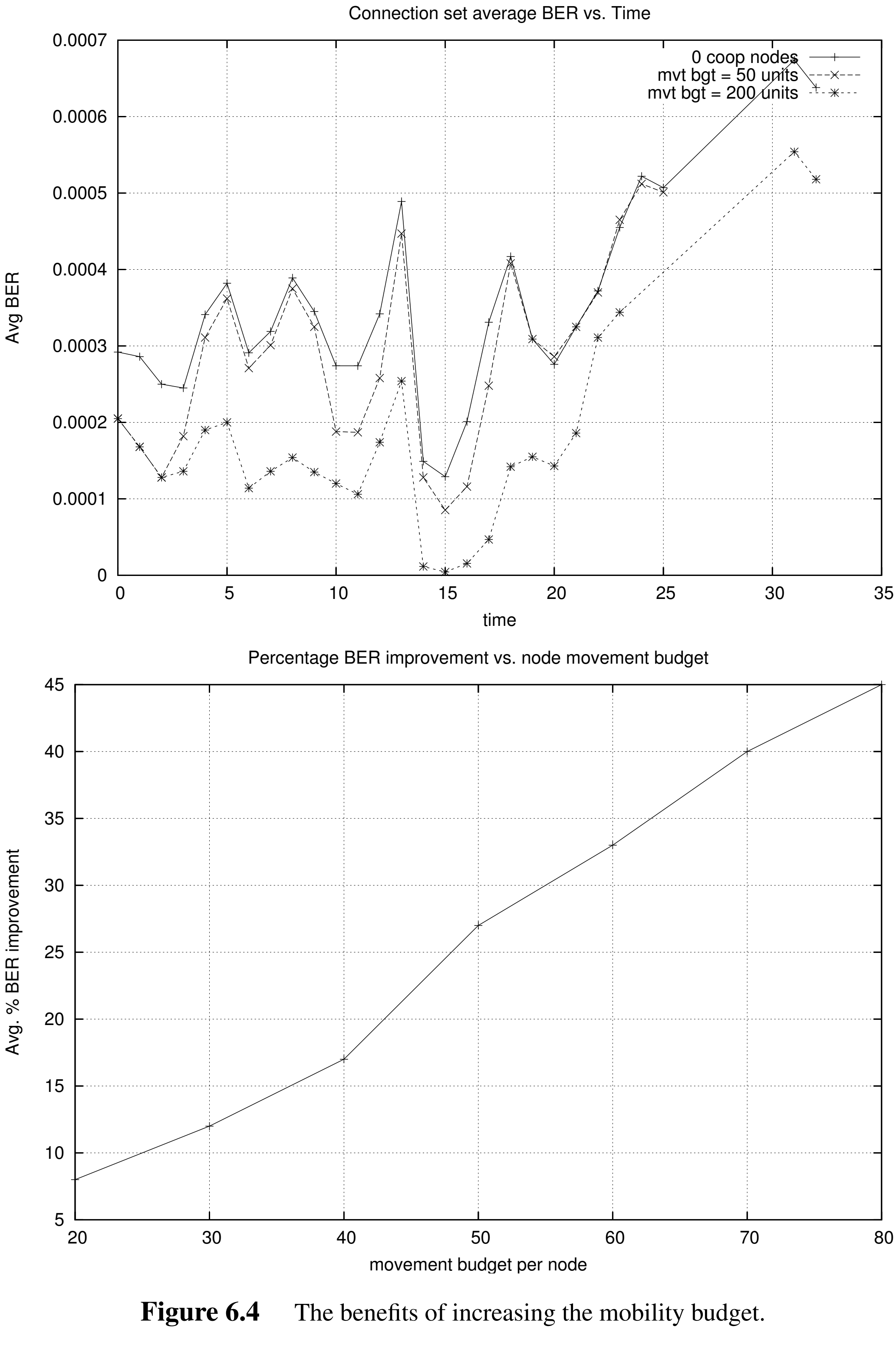
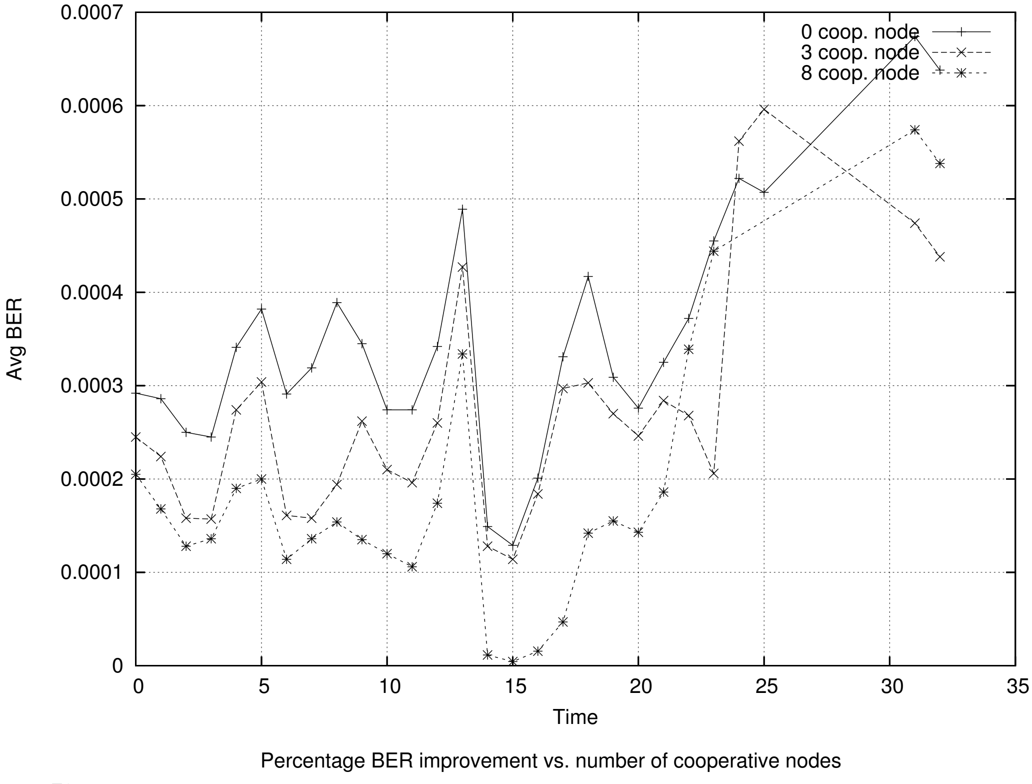


Figure 6.4 The benefits of increasing the mobility budget.



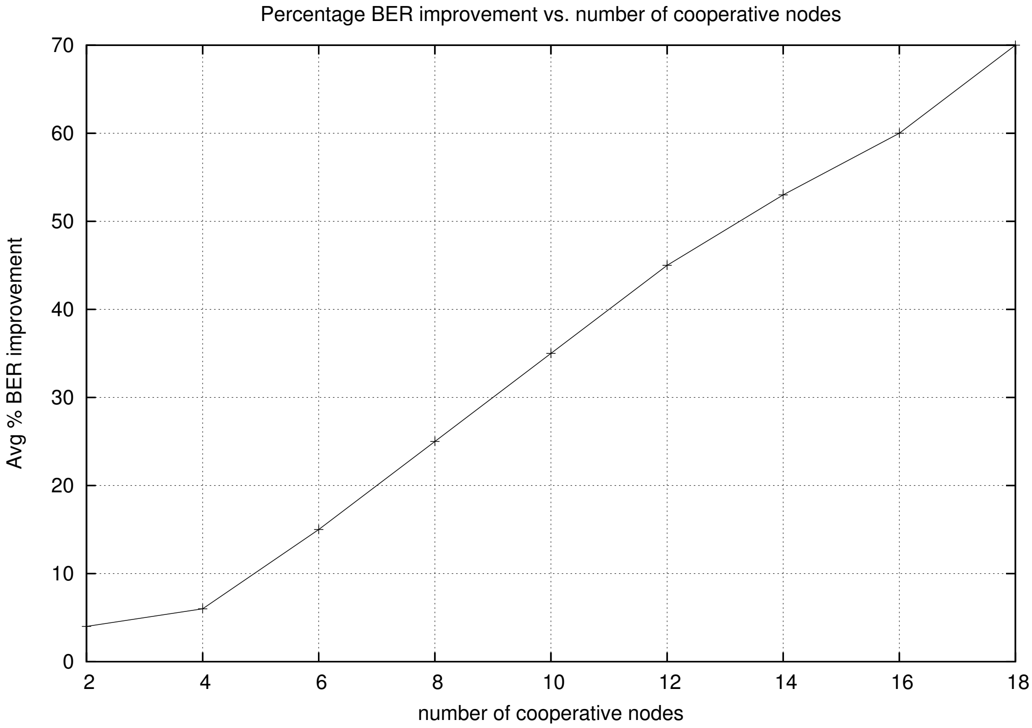


Figure 6.5 The benefits of increasing the number of cooperative nodes.

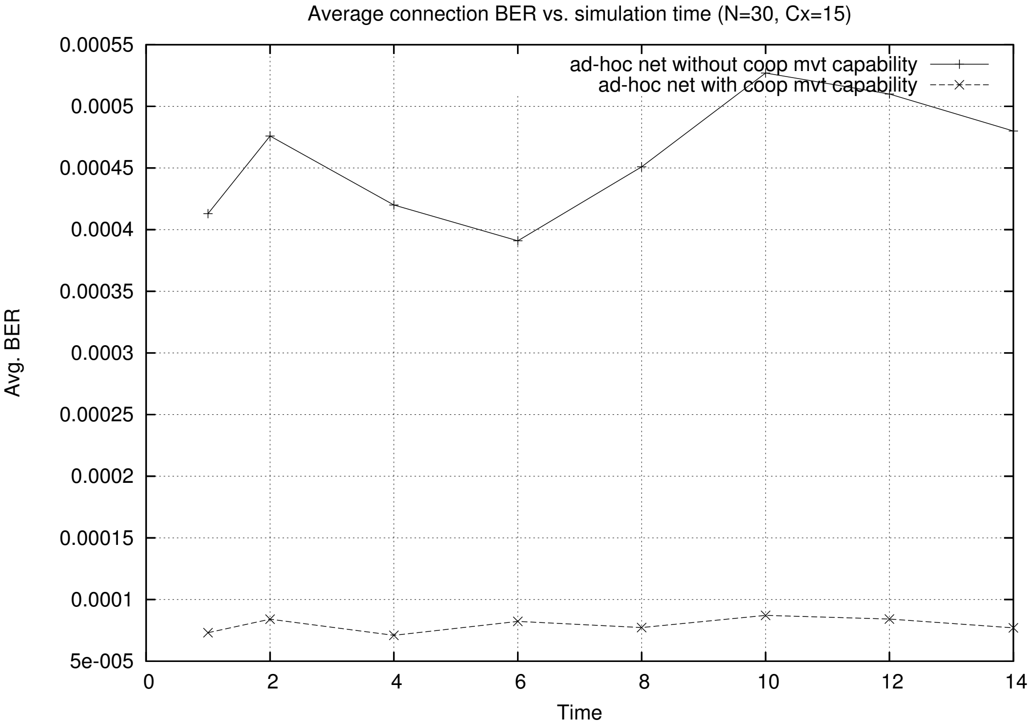


Figure 6.6 Using the multigrid scheme to reduce the average BER.

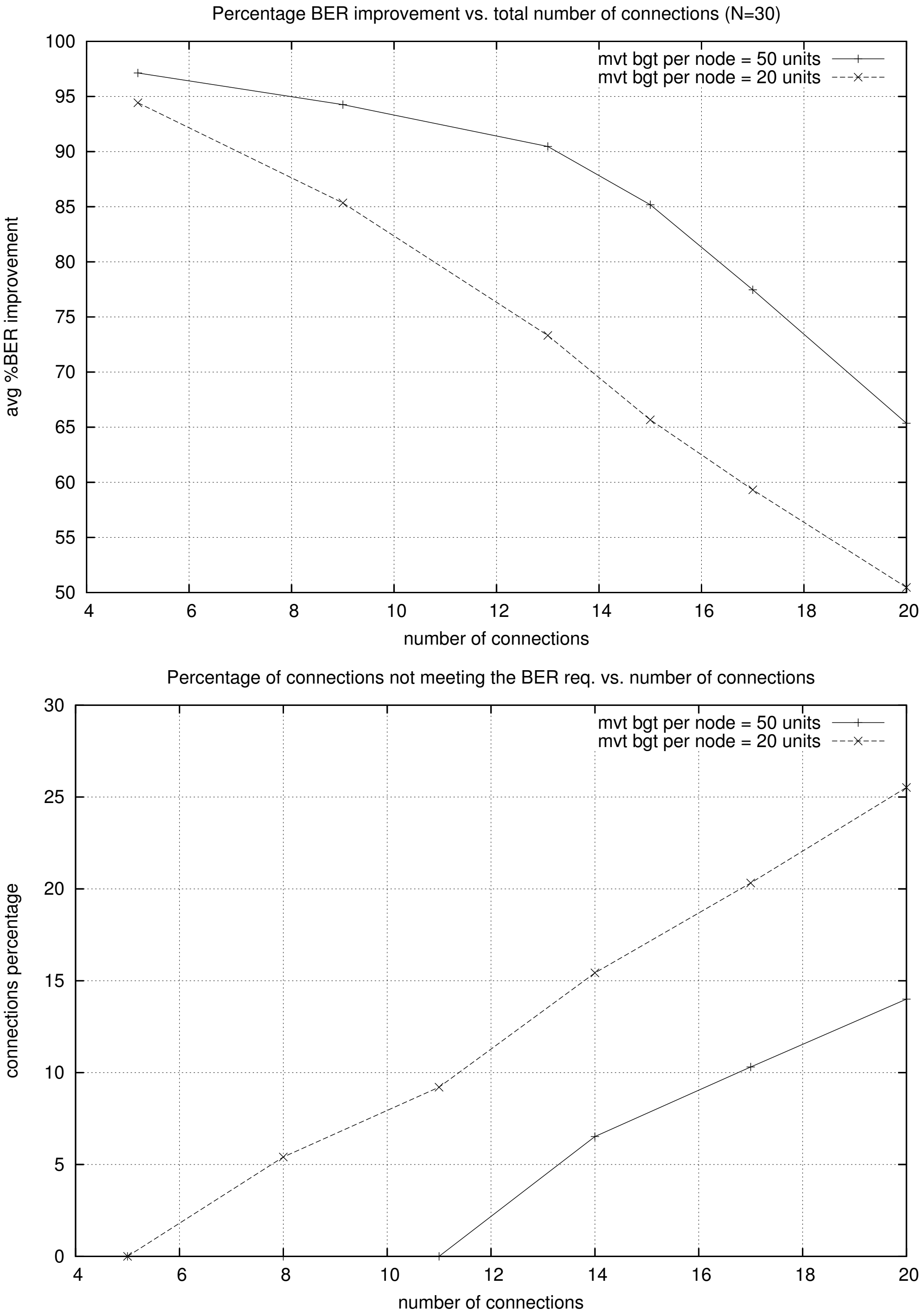


Figure 6.7 The benefit of increasing the mobility budget.

CHAPTER 7

OPTIMAL MOVEMENT PLANNING: RESULTANT APPROACH

7.1 Introduction

In this chapter, we describe our new approach for nodes location problem with the objective of meeting the connection set bit error rate requirements, which is based on the concept of concurrent resultant forces problem.

Our approach to node mobility planning is based on the following observations. Consider a single two-hop connection between a source node s and a destination node t, and assume that this connection goes through a cooperative node c. The following two observations are easily be proved by using the well-known Friis' formula [24]:

1. If node c is in line (s, t), then it moves towards s if $BER(c, s) \geq BER(c, t)$, and towards t otherwise; moving node c in a direction that is outside of line (s, t) yields worse connection performance.
2. If node c is not on the line (s, t), then it should move in a direction towards line (s, t).

The rest of this chapter is organized as follows. In section 7.2 we provide more details about the our proposed resultant approach. We present an analytical study of the concurrent resultant force method. Then we present the node control logic procedure. In section 7.3, we describe the distributed version of the resultant approach, the we discuss its complexity in terms of number of exchanged control messages. In section 7.4 we describe our experimental results. Finally, in section 7.5 we draw some conclusions about the proposed approach.

7.2 The Resultant Algorithm

Consider a single connection of size 3 between a source node s and a destination node t, and assume that this connection goes through a cooperative node c. Let us also assign weights $w(c, s)$ and $w(c, t)$ for connections (c, s) and (c, t) respectively, which represent the bit error rate of both wireless channels. Under the proposed cooperative scheme, cooperative node c repositions itself by moving in a direction that would improve the total end-to-end connection BER from s to t (see Figure 7.1). Finding the direction of node c would depend on its current location with respect to nodes s and t as well as the the weights $w(c, s)$ and $w(c, t)$, which depends on the following 2 observations: (1) if node c is in line (s, t), then it should move either towards s or t depending on the current weights. In this case, moving node c in a direction that is outside of line (s, t) would, definitely results in a worst connection performance. (2) if node c is not in line (s, t), then it should move in a resultant direction towards line (s, t). This guarantees the improvement of the total connection BER because moving in this direction would increase the received signal power by minimizing the distance c, s and c, t, which guarantees a lower connection BER. This can easily be proved by friis formula [24].

Under the aforementioned observations and assumptions, we make the analogy between finding the cooperative node movement direction and the resultant force problem. In this case, the cooperative node c is under 2 concurrent forces from c to s and form c to t with magnitude $w(c, s)$ and (c, t) respectively. The direction of the cooperative node c is simply

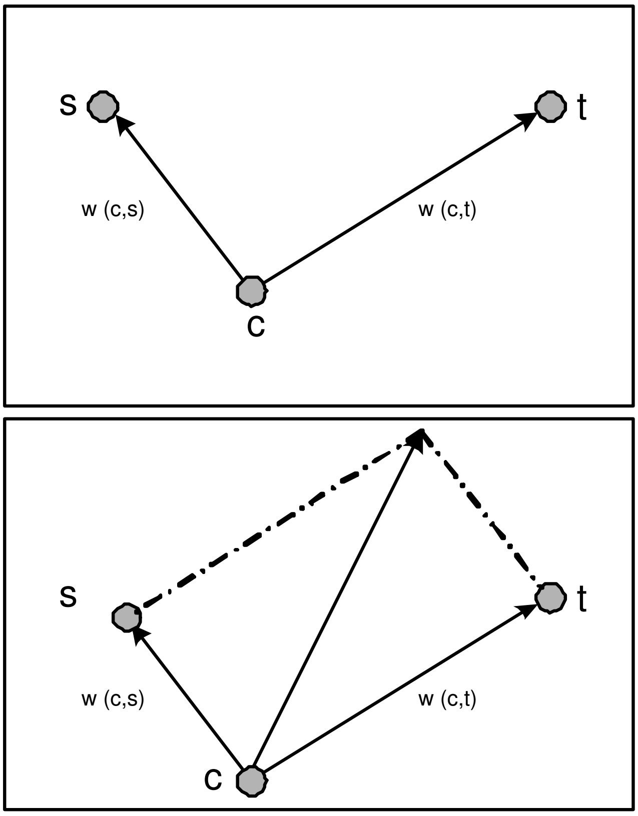


Figure 7.1 A gedanken experiment on node mobility: case scenario.

the direction of the resultant force of both forces acting on node c, which is a single force whose effect is the same as the sum of both forces (see Figure 7.1). This approach can be generalized to more than 2 forces acting on node c, which is equivalent to more than 2 connections are going through the same node.

Solving the Multiple resultant force problems can be done in several ways including the graphical method which can be parallelogram or triangle or polygon based approach. Unfortunately these approaches are not accurate in case we are dealing with large number of concurrent forces. Therefore, we will consider an analytical approach that would solve the more general case, where we have multiple concurrent forces. In the next section, we will overview the analytical approach to find the resultant force.

7.2.1 Concurrent Resultant Force: Analytical Method Overview

In this section, we illustrate the basic steps in finding the direction and the magnitude of the resultant force of a set of concurrent forces that pass through the same point. We will consider the following example. Assume a cooperative node c that is part of four different connections as depicted in figure 7.2. Based on the discussion in the previous section , finding the movement direction of the cooperative node c that would result in a better end-to-end connection BER can be achieved by finding the resultant force of all 4 concurrent forces from nodes (c to n_1), (c to n_2), (c to n_3), and (c to n_i) with magnitude w_1, w_2, w_3, and w_i respectively which represents the actual BER of the wireless channel from node c to all 4 nodes n_1, n_2, n_3, and n_i. Figure 7.2 illustrates the described notation conventions.

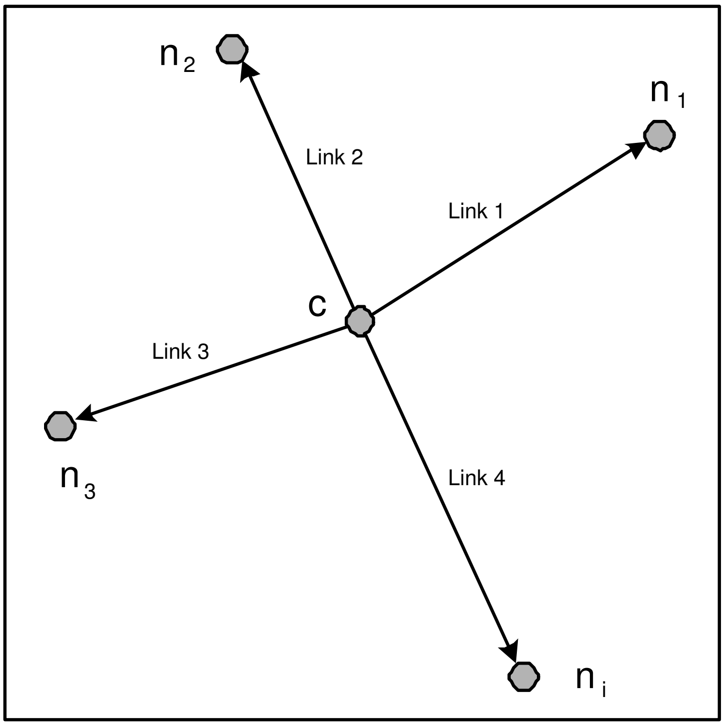


Figure 7.2 Resultant approach illustration: initial configuration.

In order to find the resultant force of set a of concurrent forces, we consider the combinations of components of each of these forces. The most useful ones are the rectangular components, which are parallel to the X and Y axes. These are usually indexed with x and y, for components parallel to X axis and Y axis, respectively. They are also known as H for horizontal, and V for vertical components. The resultant horizontal and vertical components can then be obtained by summing up all forces Horizontal components and all forces vertical components, respectively. Figure 7.3 depicts all X and Y component of all forces acting on cooperative node c.

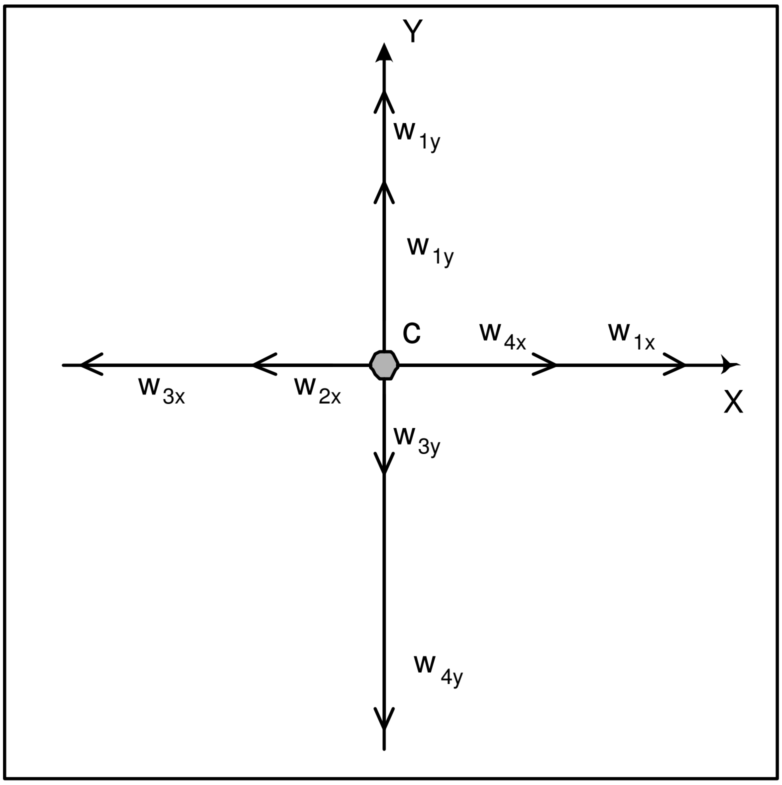


Figure 7.3 Resultant horizontal and vertical components.

The procedure to find the the direction as well as the magnitude of resultant force is illustrated by the following algorithm, which need to be executed by all cooperative nodes *c* that are part of one or more connections to be optimized. The notation used by the algorithm illustrated through the scenario depicted in figure 7.4.

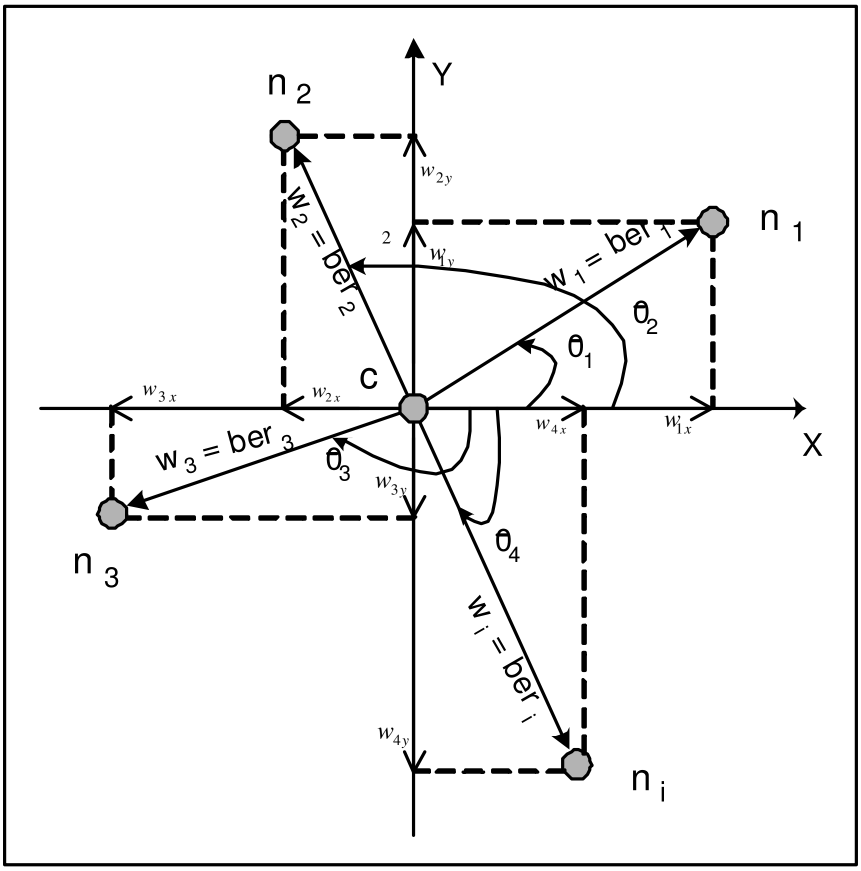


Figure 7.4 Resultant approach illustration.

7.3 Resultant Protocol Description

In this section, we describe the resultant protocol we propose in order to move the cooperative nodes to new locations leading to a better connection quality in terms of end-to-end BER.

The proposed protocol assumes that a wireless ad-hoc network composed of a set of co-operative and non-cooperative nodes are generated and that the links between neighboring

```
begin
    foreach force from node $c$ to node $n_i$ do
        (1) Compute its magnitude $w_i$ such that $w_i = ber_i(c, n_i)$
        (2) Compute its direction with respect to $X$ axis defined by $\theta_i$ such that: $\theta_i = tan^{-1}\left(\frac{y_c - y_{n_i}}{x_c - x_{n_i}}\right)$
        (3) Compute its horizontal component $w_{i_x}$ such that $w_{i_x} = w_i.cos(\theta_i)$
        (4) Compute its vertical component $w_{i_y}$ such that $w_{i_y} = w_i.sin(\theta_i)$
    endforeach
    Find the Resultant force as follows:
    (1) Horizontal component: $Resultant_{x_c} = \sum_{i=1}^{|N|} w_{i_x}$
    (2) Vertical component: $Resultant_{y_c} = \sum_{i=1}^{|N|} w_{i_y}$
    (3) Resultant direction defined by $\theta$ such that $\theta = tan^{-1}\left(\frac{resultant_{x_c}}{resultant_{y_c}}\right)$
    (4) Resultant magnitude defined by: $\sqrt{Resultant_{x_c}^2 + Resultant_{y_c}^2}$
end
```

Algorithm 7.1 Concurrent resultant force algorithm.

nodes are established and has a computable bit error rate, which represents the probability of the occurrence of an error during the data transfer over that link. We also assume that the set of connections that need to be maintained and improved in terms of their end-to-end BER are also generated (this is usually done by the central command node referred to as the movement planner) then diffused or distributed to all cooperative nodes. These set of actions are performed by the network simulator component of the *CoopSim* framework.

The resultant protocol proposed is designed in a distributed fashion. It runs as follows. Upon the reception of the connection set specifications which include the intermediate nodes, each cooperative node searches for the best location that would improve the adjacent wireless channels that are parts of any connection. This requires each cooperative node to execute the following set of actions:

```
begin
    foreach cooperative nodes $c$ that is part of any connection do
        (1) Find $\mathcal{N}$ = the set of neighboring nodes for node c
        (2) Find the movement direction of node $c$ by applying the resultant force method
    endforeach
end
```

Algorithm 7.2 Resultant algorithm.

After finding the resultant direction and based on the available movement budget as well as the movement step size, each cooperative node decides or not to move to a new locations then reports its new locations to the central command, which makes the decision whether further optimization need to me made. Figure 7.5 depicts the flowchart of this protocol.

7.3.1 Protocol Complexity

In this section, we study the complexity of the resultant protocol in terms of the number of messages exchanged between nodes that are part of the connection set. The number of messages exchanged depends on a various number of parameters, including the following:

- b: Movement budget available per cooperative node
- s: Movement step size
- c: The average number of cooperative nodes in the connection set
- n: The average number of neighboring nodes for each cooperative node

Considering this notation, an estimate of the complexity of the resultant protocol is the following. $c \times n \times b/s$. This represents the total number of messages exchanged between all cooperative nodes, their neighboring nodes and the central command.

In the next section we give some experimental results to illustrate the types of investigations which we conducted using the CoopSim platform. We will be answering the following set of questions: What is the impact of using the cooperative mobility scheme based on resultant forces technique in enhancing the end-to-end connections QoS in terms of BER? How is this impact affected by (a) the mobility budgets, and (b) the number of cooperative nodes.

7.4 Experimental Results

The first experiment investigates the effects of increasing the total mobility budget while keeping the number of cooperative nodes fixed. The simulation setup for the top graph of Figure 7.6 consists of 15 autonomous nodes moving according to a Gauss-Markov process, and 8 cooperative nodes with mobility cost equal to one unit per meter; all nodes reside inside a one square kilometer grid. Node transmit power and receiver sensitivities are set so that wireless channels arise whenever two nodes are at distance less than 100m. Command and Control establishes 7 random connections and sets their target Quality of Service to be 60% of their initial BER value of the connection. The top graph shows that having higher mobility budgets permits the routing and optimization layer to achieve lower connection BER over time. The bottom chart of Figure 7.6 depicts this effect in greater detail by considering the same experimental scenario but with varying mobility budget. The graph shows that a mobility budget of 50 units permits the routing and optimization layer to lower average connection BER by almost 8%, and that increasing the mobility budget to 250 units enables BER reduction of almost 40%. The results indicate that connection BER can be improved almost linearly as the mobility budget increases, even under constant numbers of cooperative nodes.

The second experiment investigates the effects of increasing the number of cooperative nodes while keeping the total mobility budget fixed. The simulation setup for the graph in Figure 7.7 consists of 15 autonomous nodes moving according to a Gauss-Markov process, and 0, 3 or 8 cooperative nodes with mobility cost equal to one unit per meter; all nodes reside inside a one square kilometer grid. The mobility budget is fixed at 250 units. Node transmit power and receiver sensitivities are set so that wireless channels arise whenever two nodes are at distance less than 100m. Command and Control establishes 7 random connections and sets their target Quality of Service to be 60% of their initial BER value of the connection. The top graph shows that having more cooperative nodes permits the routing and optimization layer to lower BER more effectively over time, even when the mobility budget is not increased. The bottom chart of Figure 7.7 depicts this effect in greater detail by considering the same experimental scenario but with varying numbers of cooperative nodes. The graph shows that with 4 cooperative nodes, the routing and optimization layer can lower average connection BER by almost 8%, and that increasing the number of cooperative units to 12 enables BER reduction of almost 40%. The results indicate that connection BER can be improved almost linearly as the number of cooperative nodes increases, even under constant total mobility budgets.

7.5 Summary

In this chapter, we define our second proposed approach that uses the cooperative mobility concept to improve the quality of communication channels in mobile ad-hoc network (MANETs). This approach suggests a natural analogy between finding the cooperative node movement direction and the problem of computing resultant forces.

Simulation experiments indicate conclusively that the resulting approach is scalable and succeeds at efficiently moving cooperative nodes in a manner which optimizes connection bit error rates.

We propose combining the cooperative model based on the resultant approach with the cooperative model based on the cognitive radio concept in order to achieve better performance in terms of connection set QoS. This is presented in the next chapter.

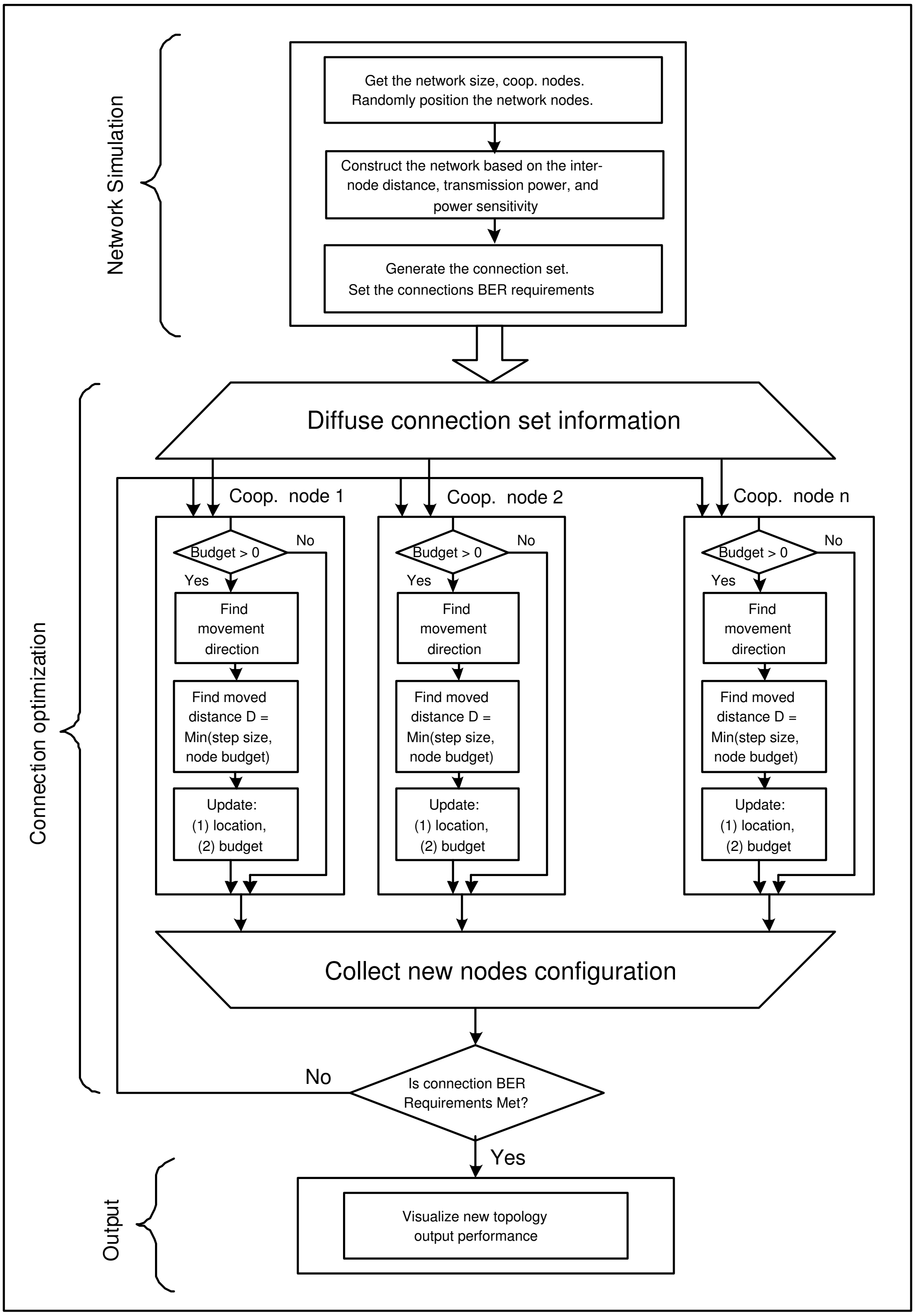


Figure 7.5 Resultant protocol flowchart.

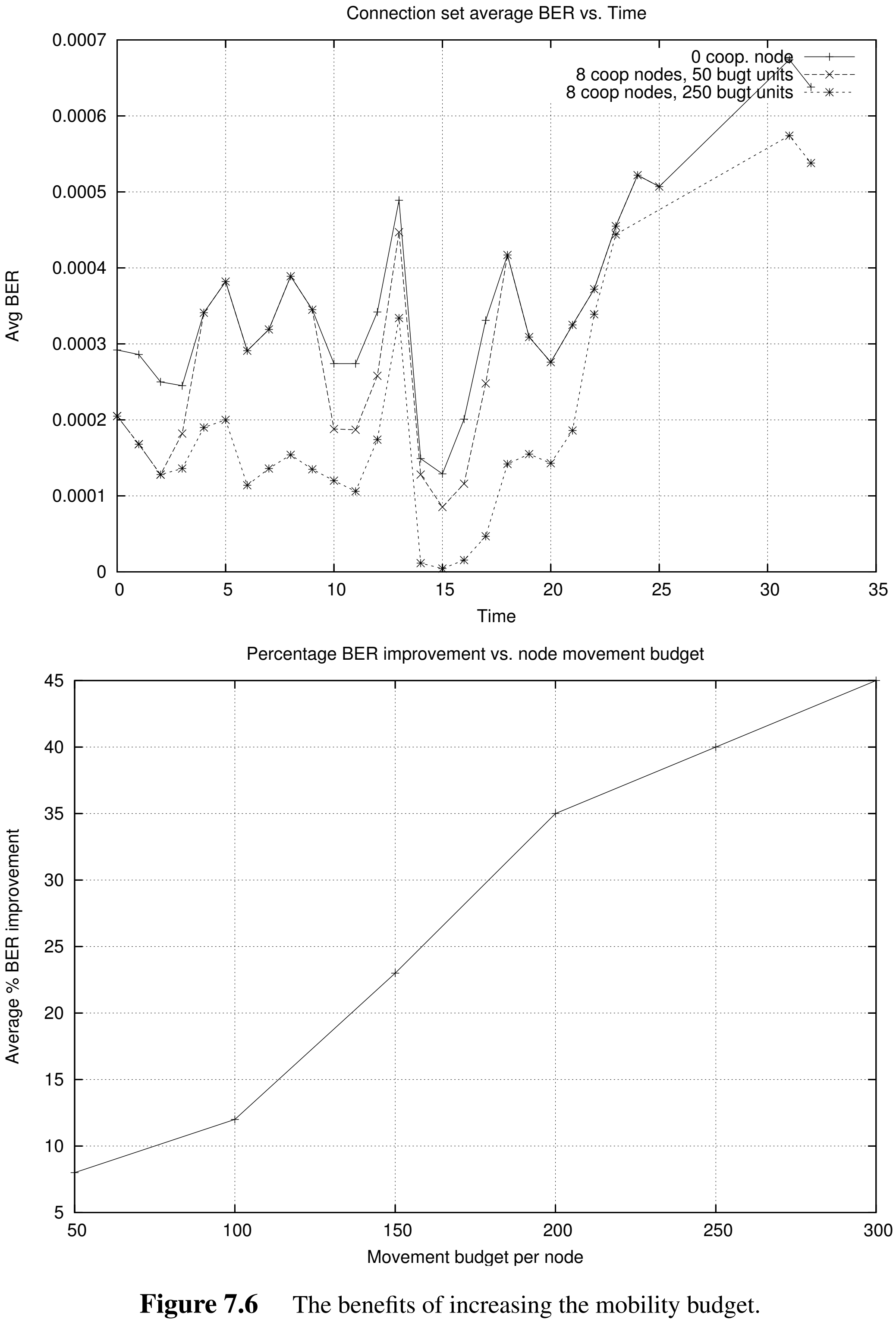
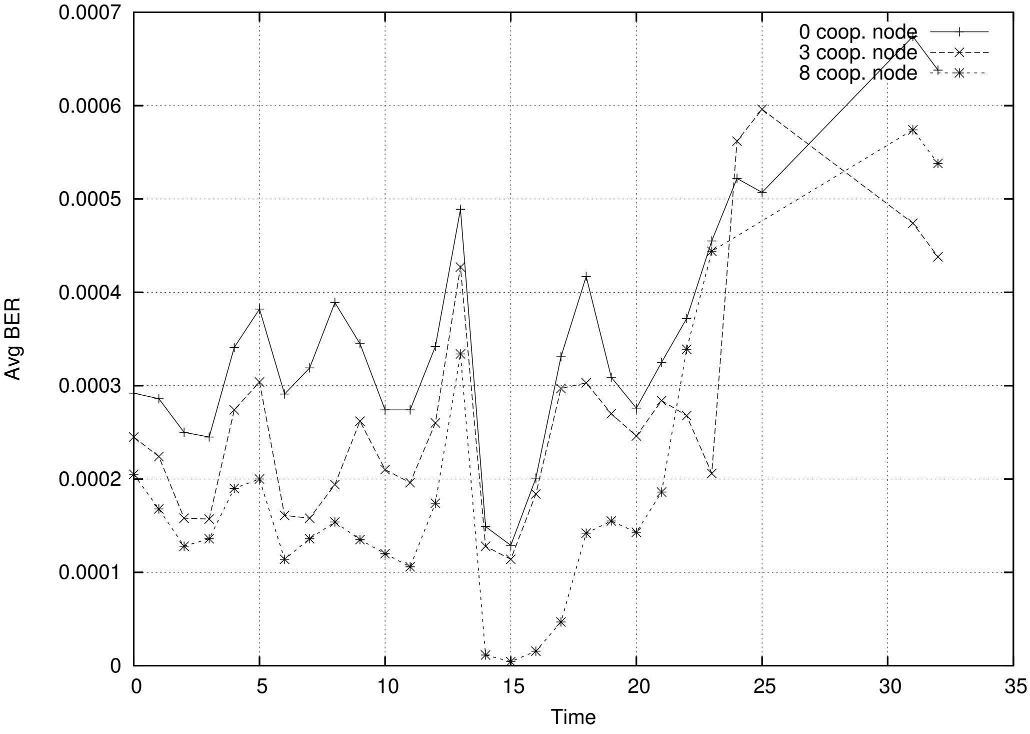


Figure 7.6 The benefits of increasing the mobility budget.



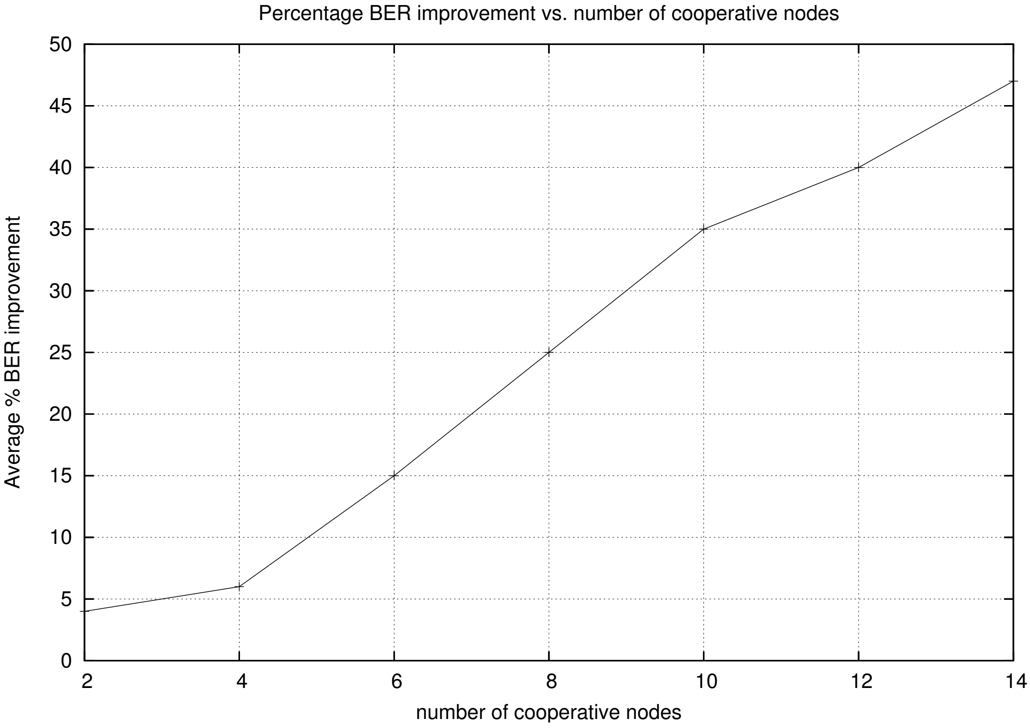


Figure 7.7 The benefits of increasing the number of cooperative nodes.

CHAPTER 8

OPTIMAL MOVEMENT PLANNING: CR BASED APPROACHES

8.1 Introduction

Contrarily to all previous techniques where we proposed improving the communication channels based on moving the cooperative nodes to different location, in this chapter, we proposed our second cooperative model which is based on the cognitive radio concept. In this model, we assume that we are operating in a cognitive radio type of network, where cooperative nodes can switch to different radio frequency channel during data transfer. As we will show later in this chapter, this technique tremendously enhances the quality of wireless channel. We will also be proposing a hybrid approach where both cooperative models based on movement and cognitive radio are combined to provide better QoS.

This chapter is organized as follows. In section 8.2, we provide a brief overview about the cognitive radio network, which offers new mechanism for flexible usage of radio spectrum. Estimating the traffic over the wireless channels is one of the most challenging tasks when operating in cognitive radio network. Therefore, in this work, we propose using Fuzzy logic for the wireless channel estimation purpose. We will start first by giving a brief overview about Fuzzy Logice in section 8.2. In section 8.3, we present our new cooperative model, which is based on the cognitive radio concept. We will be comparing this model to the cooperative model based on the node mobility described in chapter 3. In section 8.4, we describe our proposed wireless channel estimation algorithm, which is based on flip-flop filter, wavelet transform, and fuzzy logic. Our next cooperative model is a combination of the cooperative mobility and cognitive radio based cooperative models. This will be introduced in section 8.5. We will be discussing both schemes: the cognitive radio scheme with minimum channel selection, and the cognitive radio scheme with minimum mobility budget. In section 8.6, we describe the extensions performed to the current CoopSim toolkit in order to support cognitive radio network. In section 8.7, we present our simulation setup as well as discuss our experimental results. Finally, in section 8.8, we draw some conclusions about the proposed approach

8.2 Background

In this section, we present a brief overview about the cognitive radio type of networks and fuzzy logic, which will be used during the wireless channel estimation techniques.

8.2.1 Cognitive Radio Network

It is commonly believed that there is an impending crisis of spectrum availability at frequencies that can be economically used for wireless communications. This misconception is bolstered by the FCC frequency allocation chart [1] which shows multiple allocations over all of the frequency bands. As a result, there is fierce competition for the use of spectra, especially in the bands below 3 GHz. Actual measurements taken in an urban settings, however, reveal an altogether different reality: typical utilization in the 3-4 GHz frequency band is around 0.5% [1]. The utilization drops to 0.3% in the 4-5 GHz band. Thus, we actually have spectrum abundance, and the spectrum shortage is partially an artifact of the regulatory and licensing process.

The under-utilization of the pre-assigned frequency bands, has motivated the development of cognitive radio [1]: a new class of radios that can reliably sense the spectral environment over a wide bandwidth, detect the presence/absence of legacy users (primary users) and use the spectrum only if the communication does not interfere with primary users. Cognitive radio systems offer the opportunity to improve spectrum utilization by detecting unoccupied bands and adapting their transmission to those bands while avoiding the interference to primary users. This novel approach to spectrum access introduces unique functions at the physical layer: reliable detection of primary users and adaptive transmission over a wide bandwidth. In order to achieve a better performance, CR-capable nodes adapt their behavior to changing network conditions.

To adapt, CR-capable nodes must first accurately estimate network traffic. Producing quality estimates is challenging because network observations in MANETs are especially noisy and become stale rapidly. Current systems depend on simple, exponentially-weighted moving average (EWMA) filters such as those described in [35]. These parametric filters are either able to detect true changes quickly or to mask observed noise and transients, but can not do both. In [35], the authors designed new filtering techniques to overcome some of the shortcomings of EWMA based filters. Here we extend and improve these filtering techniques for estimating the traffic parameters on the primary channels of cognitive radio enabled nodes. Our first approach uses a *flip-flop* filter based on the technique proposed in [35]. The second approach relies on the wavelet transform to remove the noise from raw traffic measurements. Both approaches serve to provide more accurate estimates (compared to raw measurements) for later use by our fuzzy-based channel selection module.

8.2.2 Fuzzy Logic Overview

The idea of fuzzy logic was introduces by Prof. Lotfi Zadeh [74, 75, 76] and it continues to evolve till this day. Fuzzy logic is a generalization of standard logic. While standard logic applies only to concepts that are completely true or completely false, fuzzy logic applies to concepts that possess a *degree of truth* anywhere between 0 and 1. Fuzzy logic is supposed to be used for reasoning about inherently vague concepts, such as “tallness”. In standard logic, one might say that people taller than 6 feet are tall, while people shorter than six feet are short. But, what about a person with hight 5 feet 11 inches? We can not consider such a person to be short. In fuzzy logic, one might define overlapping regions to define whether a person is tall or short.

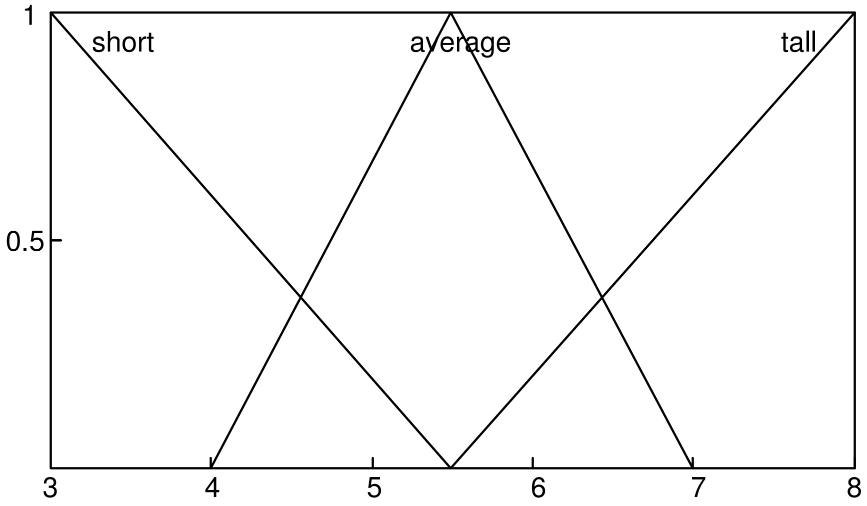


Figure 8.1 Three membership functions defining the relative “tallness” of people.

In figure 8.1, three triangular membership functions are defined to represent the hight of a person. The x-axis is the person’s hight. The membership functions can be one of many shape (trapezoidal, gaussian, bell, etc.). The membership functions can be explained as follows:

1. Less than 4 feet, the person is “short”.
2. Between 4 feet and 4.5 feet, the person is “short” with a *high* degree and “’average” with a *low* degree.
3. Between 4.5 feet and 5.5 feet, the person is “short” with a *low* degree and “average” with a *high* degree.
4. Between 5.5 feet and 6.5 feet, the person is “average” with a *high* degree and “tall” with a *low* degree.
5. Between 6.5 feet and 7 feet, the person is “average” with a *low* degree and “tall” with a *high* degree.
6. More than 7 feet, the person is “tall”.

Figure 8.2 shows the steps that the fuzzy logic controller executes before making a decision about the system under study. The steps can be summarized as follows: (1) Receiving of one or more input values representing the measurements of the parameters to be analyzed or aggregated. (2) Subjecting the input values to fuzzy “*If-Then*” rules. The rules can be expressed in plain language words, for example, “If a person is tall, Then back-pain is high”. (3) Averaging and weighting the resulting outputs from all the individual rules into one single output decision. (4) *Defuzzification* of the output to get a “crisp” value between 0 and 1.

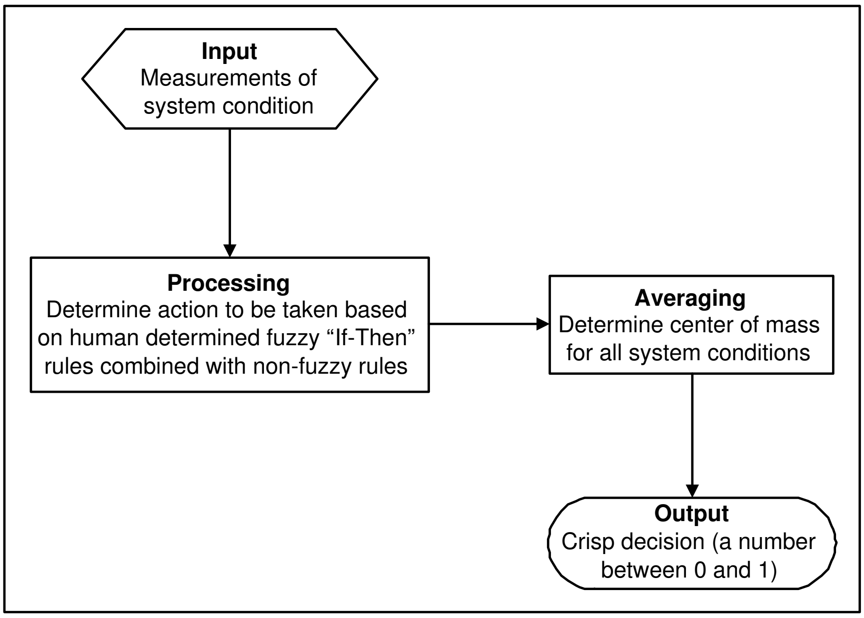


Figure 8.2 Components of the fuzzy logic controller.

In general, two major components are needed to develop the fuzzy logic controller: (1) define membership functions for each input/output parameter and (2) design the fuzzy rules. The membership function is a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs, define functional overlap between inputs, and determines an output response. The fuzzy logic rules use the input membership values as weighting factors to determine their influence on the output sets. The membership functions, discussed in this chapter, were designed to satisfy the following two conditions: (1) Each membership function overlaps only with the closest neighboring membership function; (2) for any possible input data, its membership values in all the relevant fuzzy sets should sum to 1 (or nearly so).

In the next section, we present our opportunistic cognitive radio based cooperative model.

8.3 The Opportunistic Cognitive Radio Model

In contrast to the Cooperative Mobility Model, in which cooperative nodes are willing to move to a different location with the goal of improving the end-to-end communication channels bit error rates, the opportunistic cognitive radio model aims to opportunistically benefit from the abundant spectrum that is not fully utilized by primary users, while seeking to enhance the QoS provided on all communication channels, vis-a-vis bit error rate (BER). The model assumes that all nodes operate in a cognitive radio network, and each node is able to scan the radio spectrum and determine the set of channels to be used by the primary and secondary users. Techniques for scanning and identifying the set of these channels are beyond the scope of this work.

We present a new wireless channel estimation technique based on the wavelet transform and flip-flop filter techniques. Each node estimates the utilization of each of the primary channels then decides whether exchanging traffic over unused primary channels is feasible and will enhance the quality of the communications*. First, we present our techniques for estimating the status and utilization of the wireless channels,.

8.4 The Wireless Channel Estimation Algorithm

In cognitive radio networks, in order to reduce the overhead caused by switching the traffic back and forth between secondary channels, estimation techniques can help predict the metrics of these channels. Estimation techniques provide a mechanism to filter out the

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*It is important to mention here that under our scheme, traffic opportunistically sent over the primary channel is preempted when a traffic generated by a primary user arrives—this is done by switching opportunistic traffic back to the secondary channel.

noise from raw measurements in order to produce quality estimates.

The originality of this work stems from the process through which we are able to apply a combination of EWMA filters, the wavelet transform, fuzzy logic, and time series prediction techniques to perform channel estimation in cognitive radio enabled cooperative networks.

As mentioned earlier, in a cognitive radio enabled network, the traffic flows between two neighboring nodes over either the secondary or any of the unutilized primary channels, based on a decision protocol. Over a period of time, these channels can either be carrying traffic or idle. In the rest of the paper we refer to the period of time during which the channel is idle by T_{off} and to the period of time during which the channel is occupied by T_{on}. Figure 8.3 depicts this convention; the example shows three primary channels between nodes m and n (traffic can be sent using one of three different frequencies). It is important to note that each of these sub-channels has different sequences of T_{on} and T_{off}.

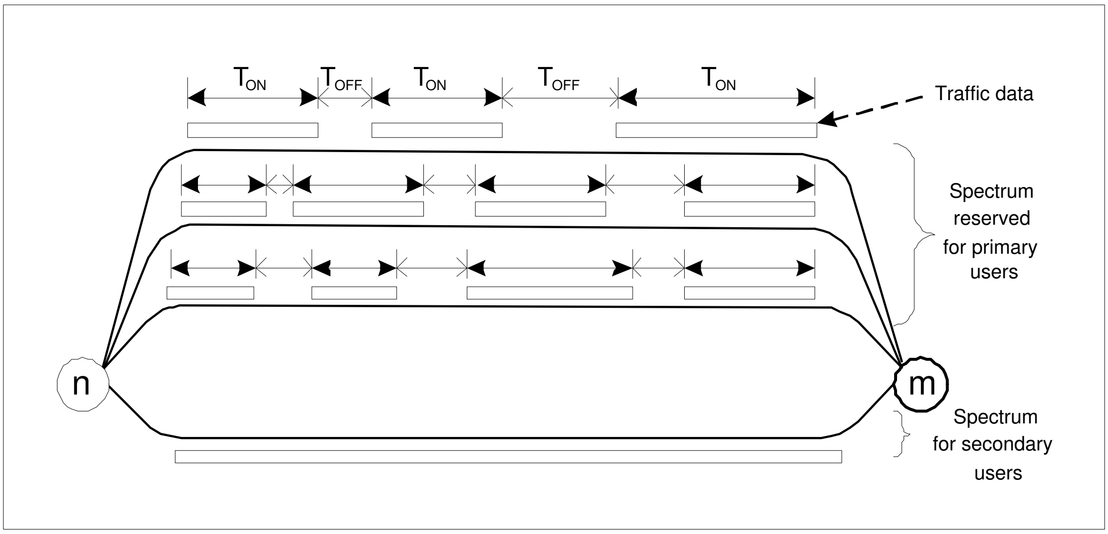


Figure 8.3 Wireless channel structure in cognitive radio enabled network.

The estimation procedure is depicted in Figure 8.4. The first step of this procedure consists of passive monitoring of the channel usage profile. This process produces two distinct time series T_{on} and T_{off}. In the next step, these time series are input to the flip-flop and wavelet filtering modules in order to produce quality estimates of the average and auto-correlation metrics, respectively. These quantities are then given to the Fuzzy logic module which selects the best primary channel to use based on the average and auto-correlation estimates. In the following, we give more details about these three modules.

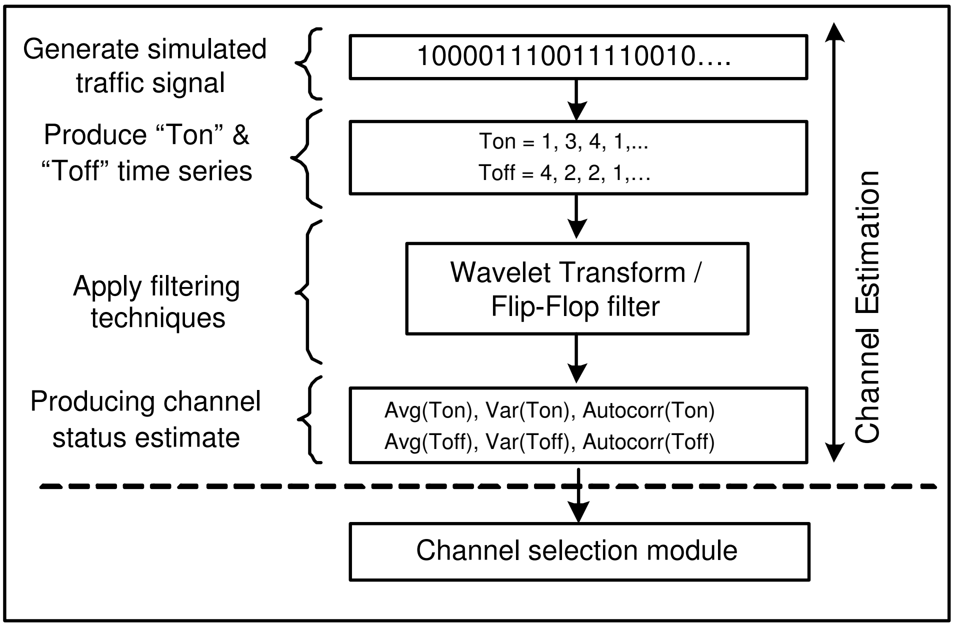


Figure 8.4 Wireless channel estimation procedure.

8.4.1 Flip-Flop Filter Module

The flip-flop filter consists of two EWMA filters: one agile and the other stable [21]. A controller selects between the two. The underlying principle of the controller is to employ the agile filter when possible, but falls back to the stable filter when observations are unusually noisy. The switching decision is made based on a control chart defined by upper and lower control limits (UCL and LCL respectively). These bounds are based on the 3-sigma rule [21] and are defined as follows:

$$UCL = E_t + 3\frac{|O_t - O_{t-1}|}{d_2} \tag{8.1}$$

$$LCL = E_t - 3\frac{|O_t - O_{t-1}|}{d_2} \tag{8.2}$$

where, d_2 estimates the standard deviation using the moving range, approximately 1.128 [52].

In this work, we utilize the flip-flop filter to estimate the average of the T_{on} and T_{off} parameters. This enables us to utilize the rich literature of process control (e.g., six sigma) to produce stable estimates of the traffic parameters when the raw observations are within the control limits (i.e., UCL and LCL) but switch quickly to the agile mode when *actual* changes are introduced to the traffic parameters. Thus, the flip-flop filter serves to distinguish between actual and transient parameter changes.

8.4.2 Wavelet Transform Module

The wavelet transform is analogous to the Fourier transform which represents a signal as a sum of sinusoids. But while the Fourier transform is localized in the frequency domain, the wavelet transform is localized in the frequency and time domains. The Short Time Fourier Transform (STFT) allows for frequency and time domain localizations but the wavelet transform allows a better resolution through multi-resolution analysis. The wavelet transform is employed in a variety of engineering applications ranging from signal and image processing to digital communication.

The detail coefficients reflect the change in the time series at various resolutions. In our case, for T_{on} and T_{off} samples of size n each (where n is a power of 2) the following steps are followed in order to find the wavelet transform of the samples.

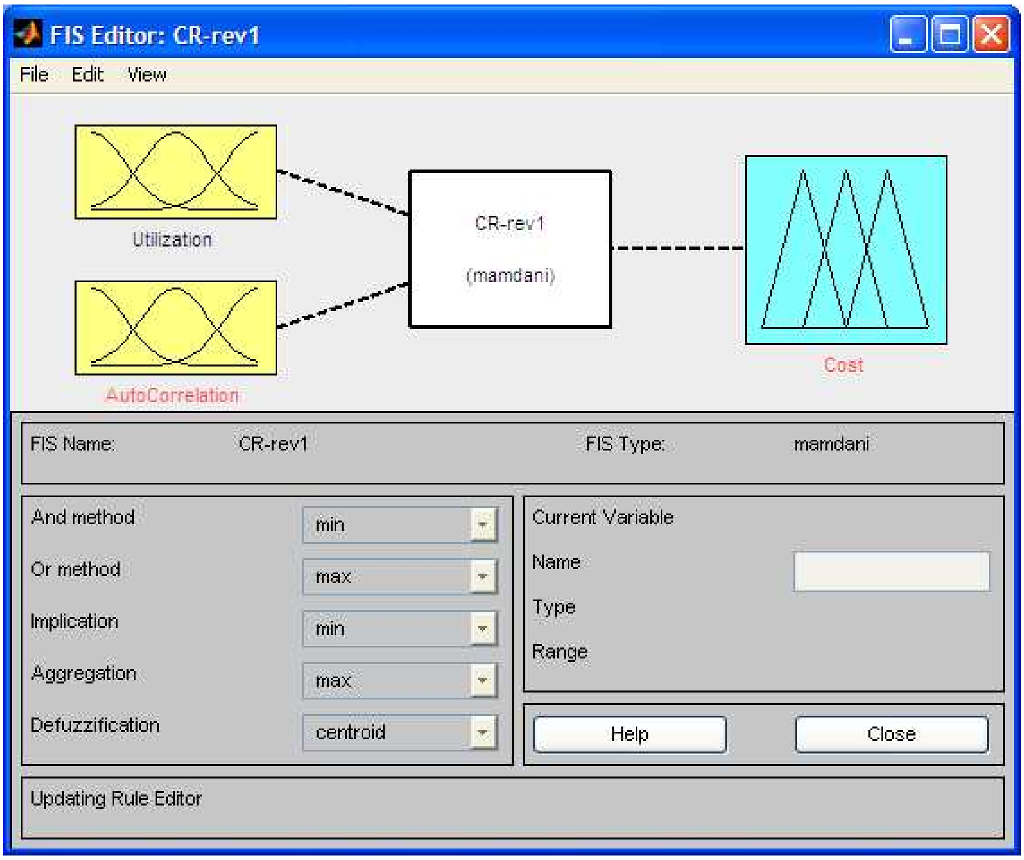
```
begin
    (1) Find the average of each pair of samples (n/2 low-freq. coefficients)
    (2) Find the difference between each pair of samples (n/2 high-freq. detail coefficients)
    (3) Fill the first half of the array with low-freq. coefficients
    (4) Fill the second half of the array with high-freq. coefficients
    (5) Repeat the process for $\log n$ times
    (6) Calculate the mean and standard deviation of the detail coefficients at stage $\log n$
    (7) Filter out all detail coefficients with values less than 3*sigma
    (8) Calculate the auto-correlation metric based on the filtered series
end
```

Algorithm 8.1 Wavelet transform procedure.

We utilize the wavelet transform to get an estimate of the traffic auto-correlation. This is achieved by applying the wavelet transform to the raw T_{on} and T_{off} samples to obtain the series detail coefficients. The standard deviation (sigma) of the detail coefficients is then computed, and detail coefficients that are 3*sigma units lower than the mean of the coefficients are filtered out. Then, the inverse wavelet transform is used to re-create the series in the time domain. We believe that this process reduces the noise in the raw T_{on} and T_{off} measurements, allowing for better estimation of the traffic auto-correlation metric.

8.4.3 Fuzzy Logic Module

Since the traffic conditions on the primary cognitive radio channels change frequently, a smart strategy that selects a primary cognitive channel based on the estimated traffic parameters is needed. Our fuzzy-based channel selection policy is based on the channel utilization and the degree of auto-correlation. These are depicted in figure 8.5. Therefore, we propose five simple rules as shown in Figure 8.6. Rules 2, 3, and 5 cause the overall fuzzy cost of a given channel to be proportional to the utilization estimate that is determined by the flip-flop filtering module as explained previously. Rules 1 and 4 cause the overall fuzzy cost of channels with higher degree of auto-correlation to be lower when compared to channels with the same utilization and a lower degree of auto-correlation.



FIS Name: CR-rev1

FIS Type: mamdani

And method: min

Or method: max

Implication: min

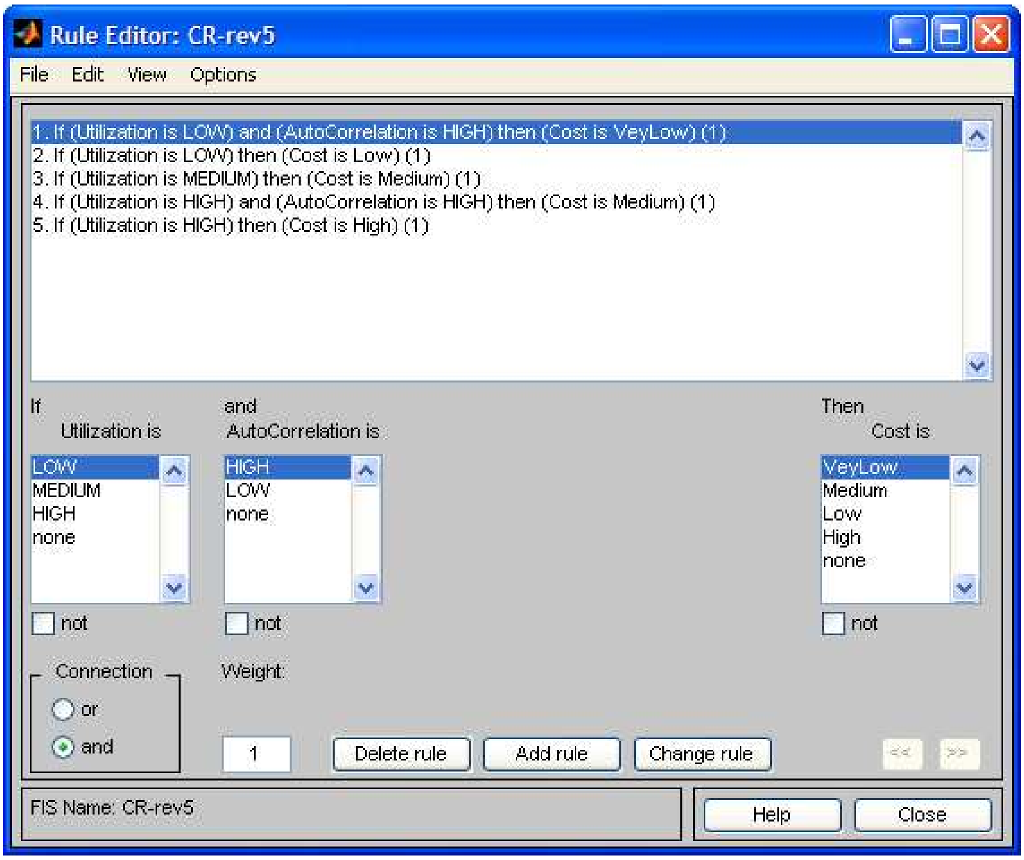
Aggregation: max

Defuzzification: centroid

Updating Rule Editor

Figure 8.5 Fuzzy rules.

The rationale behind these rules is straight-forward. Channels with lower utilization should be preferred over ones with higher utilization, as these yield better QoS and lower blocking probabilities. Channels with higher degree of auto-correlation should be preferred



Rule Editor: CR-rev5

1. If (Utilization is LOW) and (AutoCorrelation is HIGH) then (Cost is VeyLow) (1)
2. If (Utilization is LOW) then (Cost is Low) (1)
3. If (Utilization is MEDIUM) then (Cost is Medium) (1)
4. If (Utilization is HIGH) and (AutoCorrelation is HIGH) then (Cost is Medium) (1)
5. If (Utilization is HIGH) then (Cost is High) (1)

If Utilization is: LOW

and AutoCorrelation is: HIGH

Then Cost is: VeyLow

Connection: ○ or ● and

Weight: 1

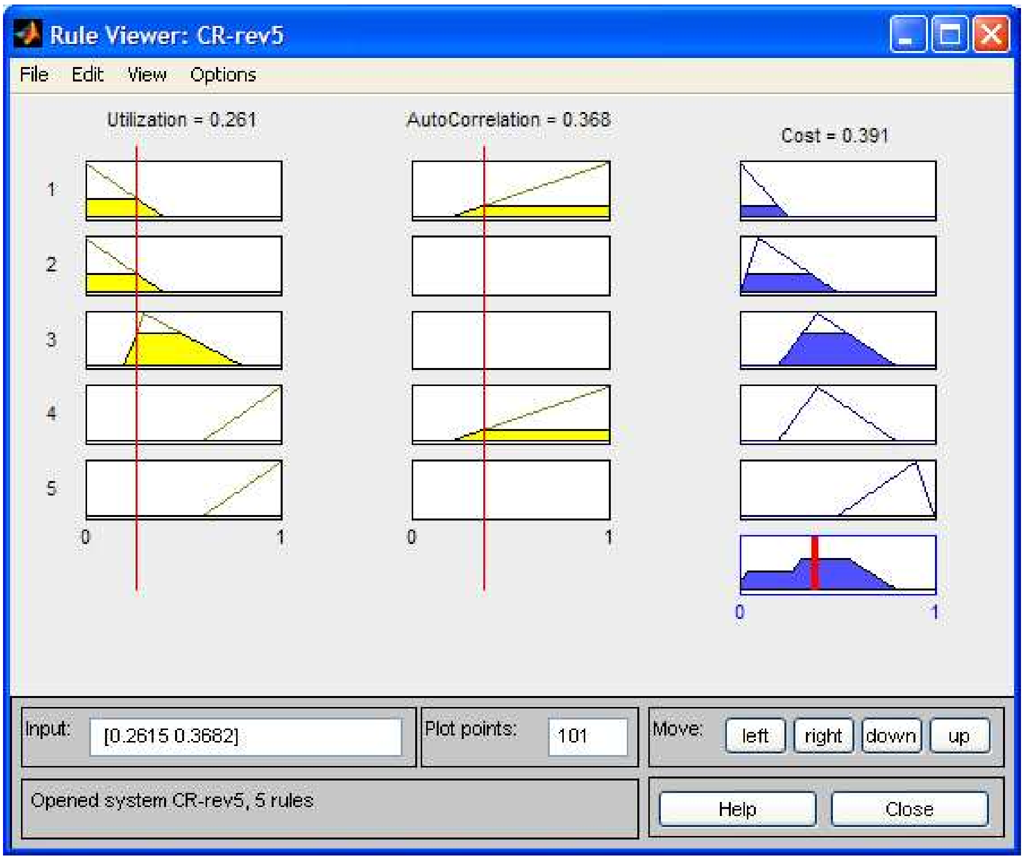
FIS Name: CR-rev5

Figure 8.6 Fuzzy rules.

as that indicates that the primary users traffic parameters are repeating. When the auto-correlation is high, this indicates that our estimates are expected to be repeated in the future, and so we assign channels with higher degree of auto-correlation a lower overall fuzzy cost.

Figure 8.6 provides an example that illustrates the computation of the overall fuzzy cost based on the fuzzy rule base. The recommended rules try to determine the overall fuzzy cost based on the estimated channel utilization and auto-correlation metrics. Higher utilizations result in higher overall fuzzy costs and higher degrees of auto-correlation results in lower overall fuzzy costs. The fuzzy cost increases gradually as the estimated utilization increases. Figure 8.7 illustrates an example where the estimated utilization level is 0.261

(using the flip-flop filter) and the estimated auto-correlation is 0.368 (using the wavelet transform). After applying the five fuzzy rules, the overall fuzzy cost is 0.391. This overall cost is used to select the primary cognitive radio channel with the lowest overall fuzzy cost. We remark that our channel selection policy utilizes the *min, max, min, max*, and *centroid* methods for the fuzzy *and, or, implication, aggregation* and *defuzzification* operators, respectively.



Utilization = 0.261

AutoCorrelation = 0.368

Cost = 0.391

Input: [0.2615 0.3682]

Plot points: 101

Opened system CR-rev5, 5 rules

Figure 8.7 Fuzzy cost.

After the selection of a channel with lower cost, a bit error rate estimate is computed as follows:

$$BER_{\text{estimate}} = \frac{BER_s \times C_s + BER_p \times C_p \times U_{\text{estimate}}}{C_s + C_p}, \tag{8.3}$$

where BER_s represents the bit error rate of the secondary channel, BER_p represents the bit error rate of the primary channel, C_s represents the maximum capacity of the secondary channel, C_p represents the maximum capacity of the primary channels, and $U_{\text{estimate}} = \frac{T_{\text{on}}}{T_{\text{on}}+T_{\text{off}}}$ (T_{on} and T_{off} are the estimated average calculated using the flip-flop filter).

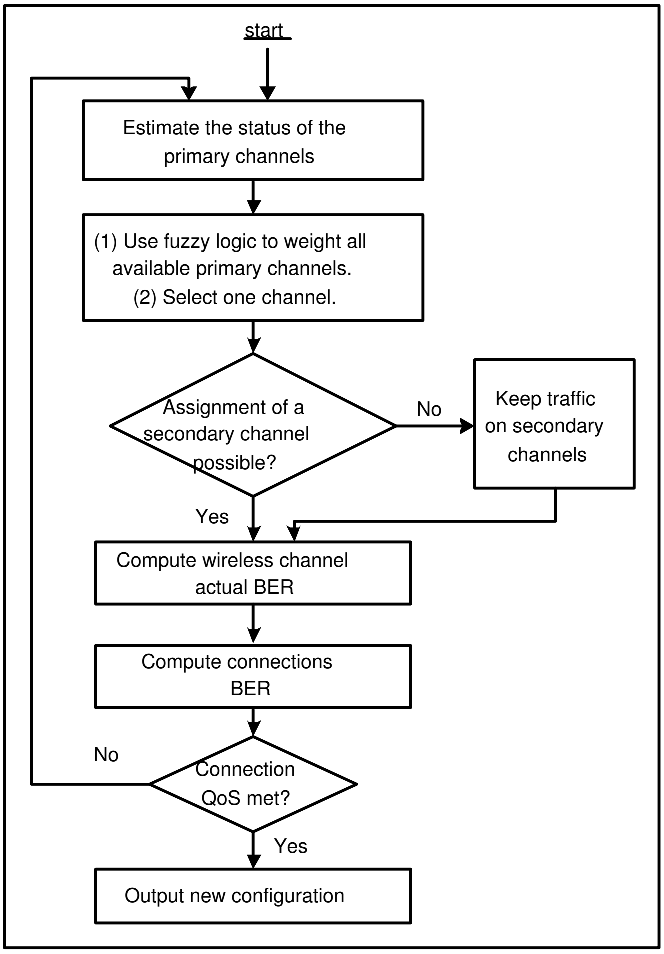


Figure 8.8 Primary channel selection algorithm.

8.5 Cooperative Hybrid Approaches

The cooperative mobility schemes and opportunistic cognitive radio schemes can be combined and applied simultaneously to achieve superior QoS. We consider using the following two **policies**: (1) Cognitive Radio Scheme with Minimum Channel Selection, and (2) Cognitive Radio Scheme with Minimum Mobility Budget. This will be based on the resultant approach presented in chapter 7

8.5.1 Cognitive Radio Scheme With Minimum Channel Selection

This policy tries to minimize the frequency of switching between the primary channels, while meeting the targeted QoS. This is achieved by first having all nodes that are part of the connection set engage in the cooperative mobility scheme, and then applying the opportunistic channel selection for only those nodes involved in connections whose QoS is still unsatisfied.

8.5.2 Cognitive Radio Scheme With Minimum Mobility Budget

This policy tries to minimize the mobility budget used, while meeting the targeted QoS. This is achieved by first having all nodes that are part of the connection set engage in the opportunistic channel selection scheme, and then using the cooperative mobility scheme for only those nodes involved in connections whose QoS is still unsatisfied.

This model is illustrated through the flowchart of Figure 8.9.

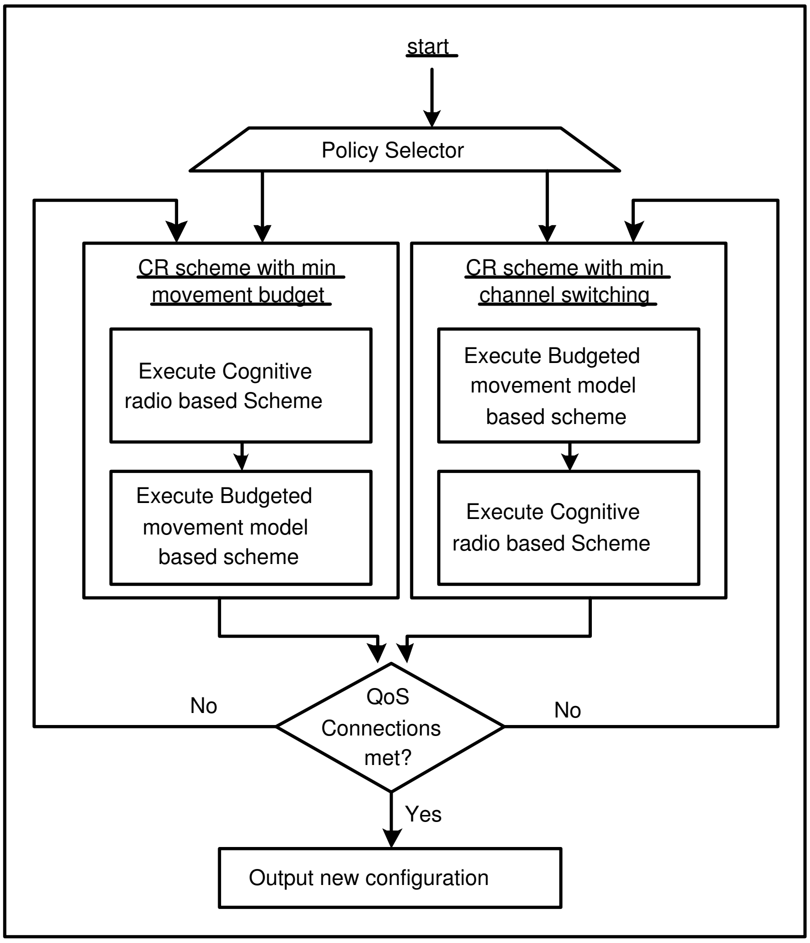


Figure 8.9 Hybrid approach.

8.6 CoopSim Extension in Support of Cognitive Radio Concept

As we already mentioned in chapter 4, we have developed a simulation platform to investigate how parameter, policy and algorithm choices influence the efficacy of systems based on the proposed Cooperative Mobility Model.

The previous design of the CoopSim has been extended to support nodes with cognitive radio capability. The CoopSim platform is implemented as a modular discrete event simulator that is naturally organized in layers. Figure 8.10 presents a modular schematic diagram.

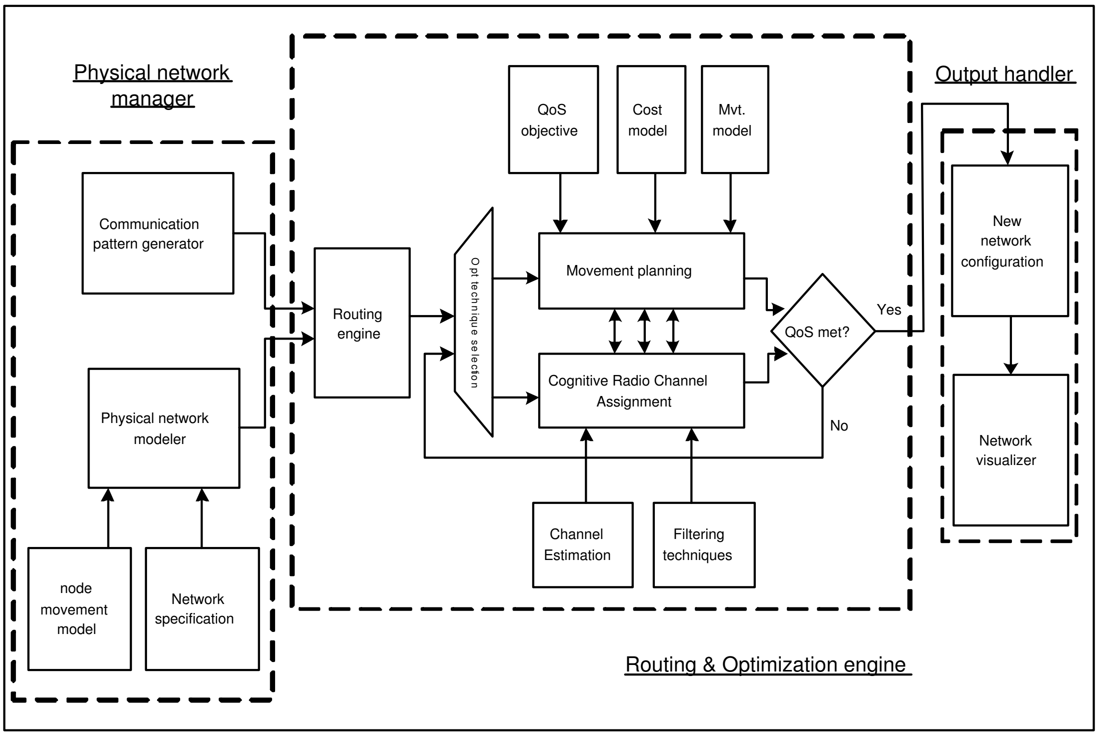


Figure 8.10 CoopSim architecture.

The first module of the CoopSim framework is the **Physical Network Manager**, which consists of a collection of wireless components such as UGVs, manned tanks, etc. Important aspects of this layer include:

Network Discovery. These protocols are used to enable all nodes to discover their neighbors and establish wireless communication channels with them. The design of the network discovery protocol is beyond the scope of this article; a good reference can be found in [56]. For simulation purposes CoopSim assumes that a unidirectional channel connecting a transmitter to a receiver arises whenever the distance separating the two nodes is less than the communication range of the transmitter. A wireless channel forms between two battlefield MANET nodes whenever there is unidirectional channel in both directions.

Channel Characteristics. Suppose we have a pair of nodes at distance D communicating using transmission signal power P over a wireless channel L with noise power P_{noise} through a medium with propagation constant α. The relationship between wireless channel bit error rate (BER) and the received power P_{rcv} is a function of the modulation scheme employed. CoopSim considers non-coherent Binary orthogonal Phase Shift Keying (BPSK) modulation scheme, so $P_{rcv} = P/D^{\alpha}$, and the instantaneous channel bit error rate is [40, 48, 55]:

$$BER(L) = \frac{1}{2}\, e^{-\left(\frac{P}{D^{\alpha}}\right)\frac{1}{P_{noise}}}.$$

Under the new current scheme, the channels now support the two types of sub-channels. The first type consists of channels with radio frequency reserved to primary network users. However, the second type consists of frequencies reserved to secondary network users.

The **Routing and Optimization Engine** is the central layer of CoopSim. This layer has also been extended to support modules for wireless channel estimation based on flip-flop filters, wavelet transform, and fuzzy logic. This layer is responsible for routing the set of connections that need to be maintained and repositioning the cooperative nodes in order to better provide the required QoS. Important aspects of this layer include:

Routing. Connections are routed along shortest paths in the graph using Dijkstra's algorithm, where the weight of link L is taken to be $w_L = -\log(1 - BER(L))$. It is easy to verify that shortest paths in this graph metric yield connections with minimal end-to-end BER.

QoS Requirements. In this exposition, we consider QoS requirements to be defined in terms of maximum acceptable end-to-end BER, but we note that CoopSim can incorporate any computable definition of QoS. The end-to-end BER of a connection C which traverses links L_1, L_2, ... L_k can then be computed as $BER(C) = 1 - \prod_{i=1}^{k} 1 - BER(L_i)$.

Filtering technique. The T_{on} and T_{off} sample sets over the wireless channels are filtered out using flip-flop filter and wavelet transform in order to produce quality estimates of the average and autocorrelation metrics, respectively.

Channel estimation and selection. The cognitive radio channel estimation module utilizes a combination of flip-flop and wavelet-based filters. On the other hand, the channel selection module employs a fuzzy rule-based scheme to determine the overall cost of the cognitive radio channel based on its utilization and auto-correlation metrics.

Mobility budget. This is the amount of credit available within each node, for funding the movement of cooperative MANET nodes. The mobility budget is replenished periodically, every T_m time units. In the current simulation, mobility budgets do not accumulate across time intervals.

In the next section, we present our simulation setup then discuss our experimental results.

8.7 Experiments

In this section, we describe our simulation setup, then we will address the type of experiments we will be carrying in order to study the performance of the proposed approaches.

8.7.1 Simulation Setup

Topologies. In our simulations, network topologies were randomly generated by placing nodes uniformly on a $100m$ x $100m$ square and moving them according to the Gauss-

Markov mobility model. Two nodes are connected if the received signal power at at the two nodes exceeds a technology dependent power sensitivity parameter P_{min}.

Node capabilities. In experiments involving *CR-capable* nodes, each node supports 8 secondary channels, each with capacity of 150 kbps. In experiments involving *cooperative mobility*, each cooperative node is given a constant initial mobility budget between 50 to 300 units (depending on the experiment). A cooperative node is assumed to charge 1 unit to move a distance of 1 meter. The number of cooperative nodes is taken to be 20% and 60% of the total network size, for networks with small and large degrees of cooperativeness, respectively.

Traffic. We assume the traffic arrival over the primary channels to follow the Poisson process in which the inter-arrival and holding times are exponentially distributed. In our experiments, the T_{off} and T_{on} time series are exponentially distributed based on the parameters of the simulated primary channel.

Connections. We study the routing decision by considering connection requests between random source-destination pairs. Connections are routed using a simple version of the weighted shortest path algorithm based on the link BERs. We consider connection sets ranging from 10 to 20, with the target Quality of Service of each connection is set to be 60% of its initial BER value.

We use the current simulation setup to answer the following set of questions:

Q1. What is the impact of (a) using flip-flop and wavelet-based filtering techniques on enhancing the end-to-end connections' QoS in terms of BER, and (b) how do these schemes perform when applied as part of an opportunistic cognitive radio scheme?

Q2. How do the two schemes interact? (a) Can the opportunistic cognitive radio scheme benefit from using cooperative mobility, in terms of minimizing the amount of channel switching required to meet the QoS requirements? (b) Can the cooperative mobility scheme benefit from using opportunistic cognitive radio, in terms of minimizing the mobility budget required to meet the QoS requirements? (c) How do hybrid schemes based on the proposed policies (minimize channel switching, minimize mobility budget) perform, and (d) do they scale to high-load settings?

The graphs in the next section answer these questions by depicting the mean values collected from 1000 trial runs of corresponding appropriately designed experimental scenarios.

8.7.2 Experimental Results

Q1-a. In the next experiment, we investigate the benefit of using filtering techniques in our cognitive radio based cooperative scheme to predict the traffic on the primary channels. We run this experiment of Figure 8.11 for a network of size 20 nodes and a connection set size equals 15. The charts show that using estimation techniques based on wavelet transform and flip-flop filtering techniques to predict the status of the primary channels, yields a lower average connection set BER compared to the scheme where we consider raw (non-filtered) data.

Q1-b. The next result illustrates the benefit of using the cooperative model based on the cognitive radio concept. This experiment was conducted for a network of size 25 nodes,

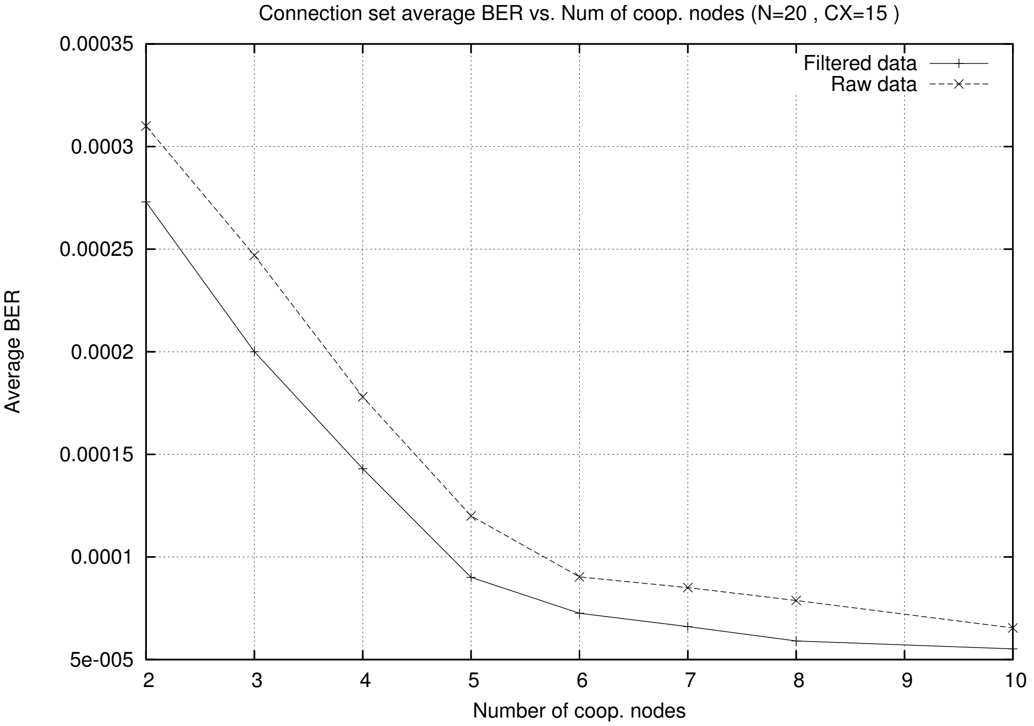


Figure 8.11 Using filtered data to reduce wireless channel BER.

connection set size equals to 15, and while using filtering techniques based on wavelet transform and flip-flop filters to estimate the traffic over the primary channels. Figure 8.12 shows that, over time, we achieve an improvement in the average connection set BER of about 40% when benefitting from the primary channels compared to that of a non cognitive radio capable network.

Q2-a & b. In the next experiments, we investigate the performance in terms of channels switching and mobility budgets of the proposed policies. This experiment was conducted for a network of size 25 nodes, connection set size equals to 15, and while using filtering techniques based on wavelet transform and flip-flop filters to estimate the traffic over the primary channels. The top graph of Figure 8.13 shows that the targeted QoS can be achieved while having an average of 20 fewer switches between primary channels of the

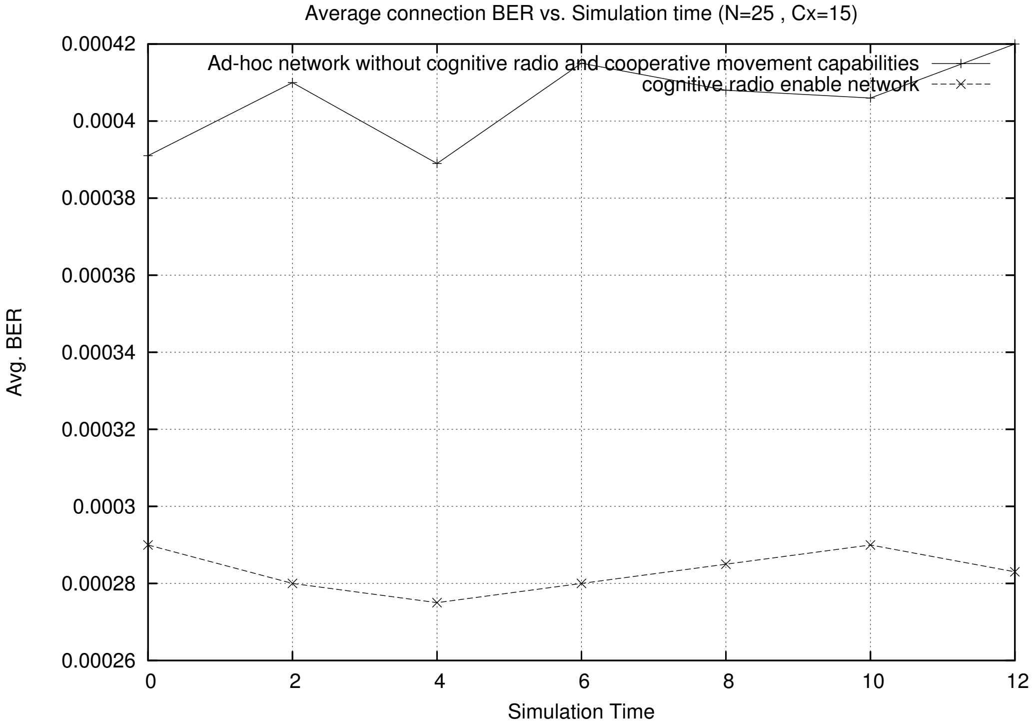


Figure 8.12 Using opportunistic cognitive radio to reduce average BER.

cognitive radio channel, when using the cognitive radio scheme with minimum channel switching policy. However, if the goal is to reach the target QoS with minimum mobility budget used, the cognitive radio scheme with minimum mobility budget policy would result in an average of 75 fewer units. This could be seen from the bottom graph of Figure 8.13.

Q2-c. In the next experiment, we investigate the effect of increasing the number of cooperative nodes on the performance of the proposed schemes. The simulation setup consists of a network size of 25 nodes, a connection set size of 15, mobility budget per node equals to 300 units, and considering the wavelet transform and flip-flop filtering techniques to estimate the traffic over the primary channels of the cognitive radio channel. The graphs in Figure 8.14 show that both proposed policies achieve comparable performance

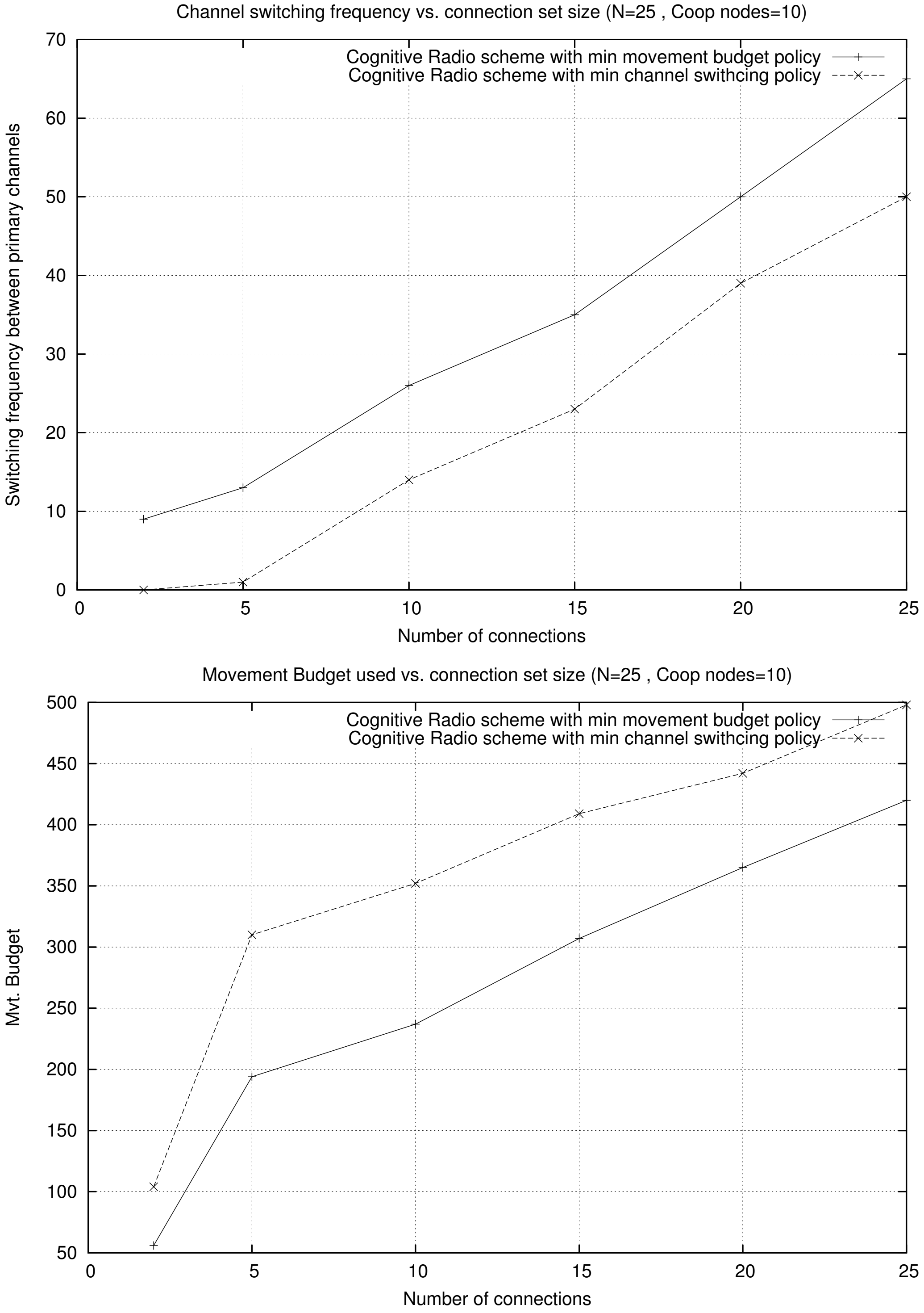


Figure 8.13 Opportunistic cognitive radio and cooperative mobility.

in terms of (i) average connection set BER, (ii) percentage of connections that did not meet the required QoS, and (iii) average improvement percentage. Compared to the cooperative network without cognitive radio, both policies of the cognitive radio based schemes outperform the cooperative mobility model alone. The graph of Figure 8.14 show an improvement of about 50% in the average BER, 25% in the percentage connections that did not meet the required BER, and and average of about 30% in the percentage improvement, which is shown in Figure 8.15.

Q2-d. In the last experiment, we investigate the effect of increasing the size of the connection set on the performance of the proposed schemes. The simulations setup consists of a network size of 25 nodes, a connection set size of 10, mobility budget per node equals to 300 units, and considering the wavelet transform and flip-flop filtering techniques to estimate the traffic over the primary channels of the cognitive radio channel. The graph of Figure 8.16 shows that both proposed policies of the cognitive radio based schemes outperforms the cooperative model without cognitive radio capability. Although the percentage improvement in the number of connections that did not meet the required BER decreases as the connections set size increases, the improvement remains in excess of 30% regardless of connection load.

8.8 Summary

In this chapter, we presented our cooperative model approaches, which were based on both: the node mobility and cognitive radio capability. We proposed new techniques to leverage two optimizations for cognitive radio networks that are specific to such contexts:

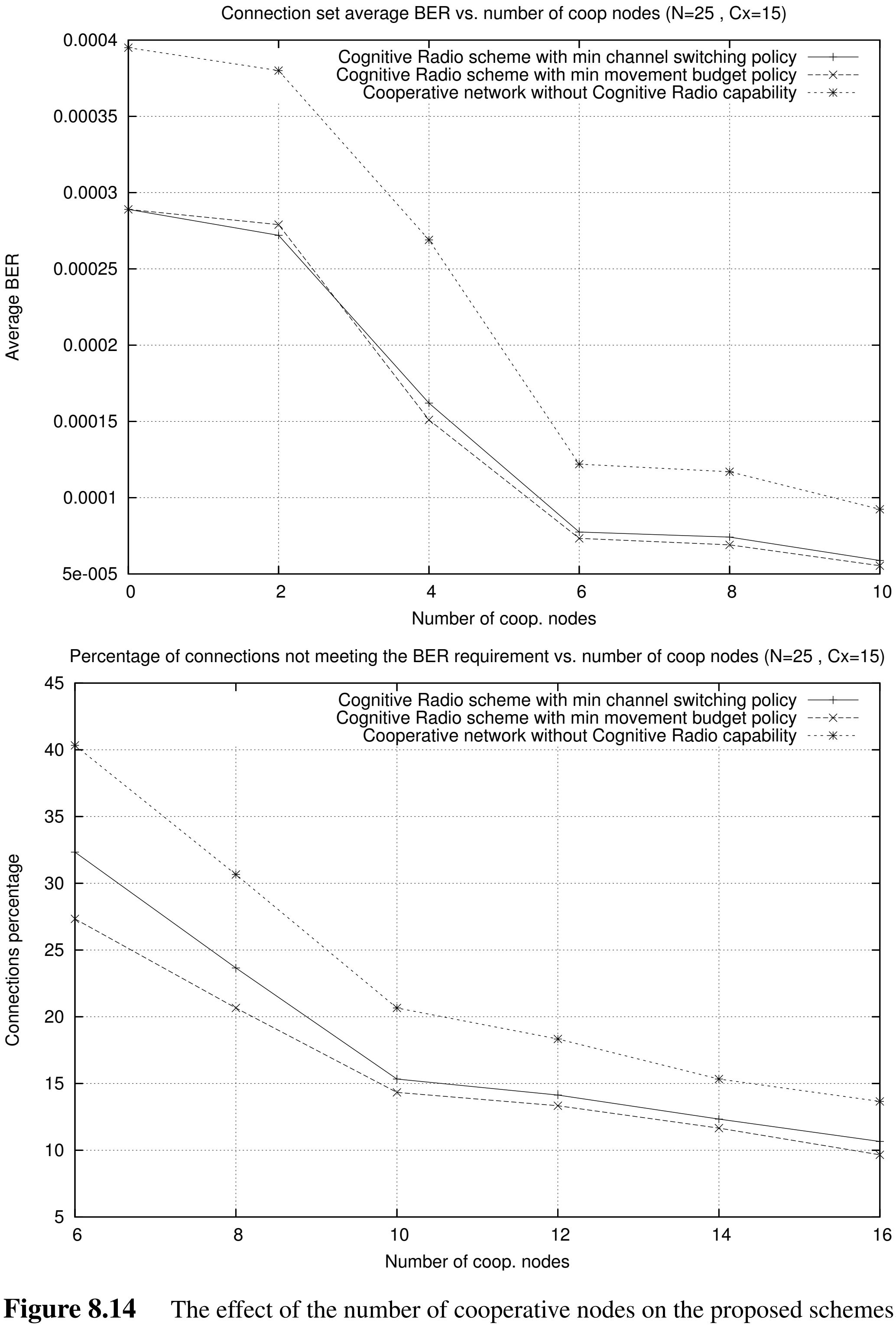


Figure 8.14 The effect of the number of cooperative nodes on the proposed schemes.

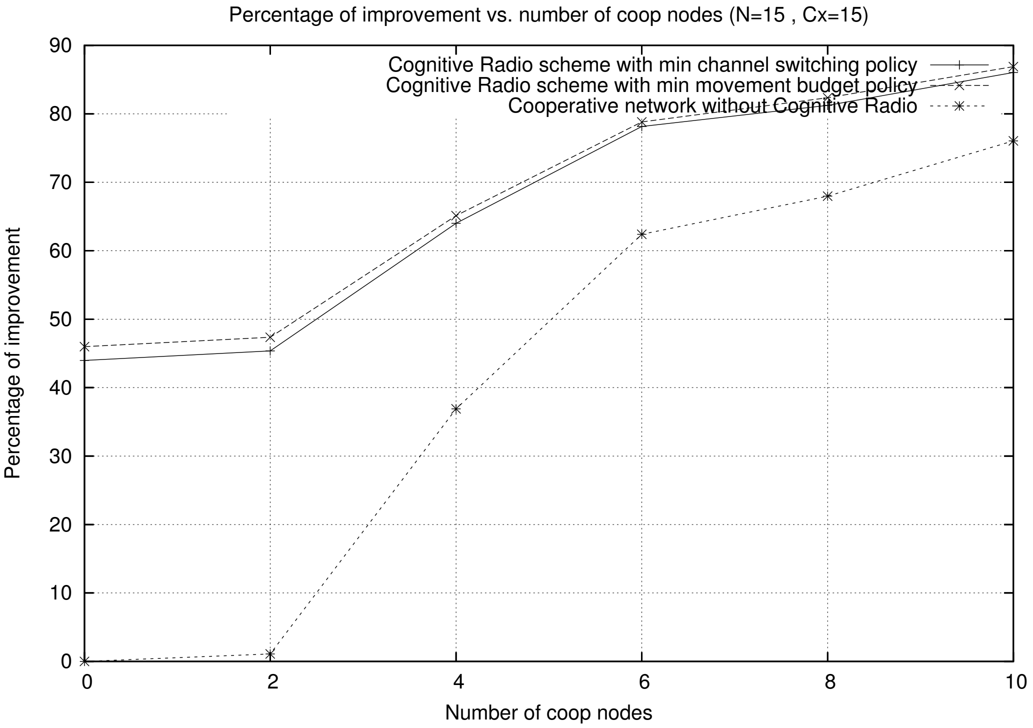


Figure 8.15 The effect of the number of cooperative nodes on the proposed schemes.

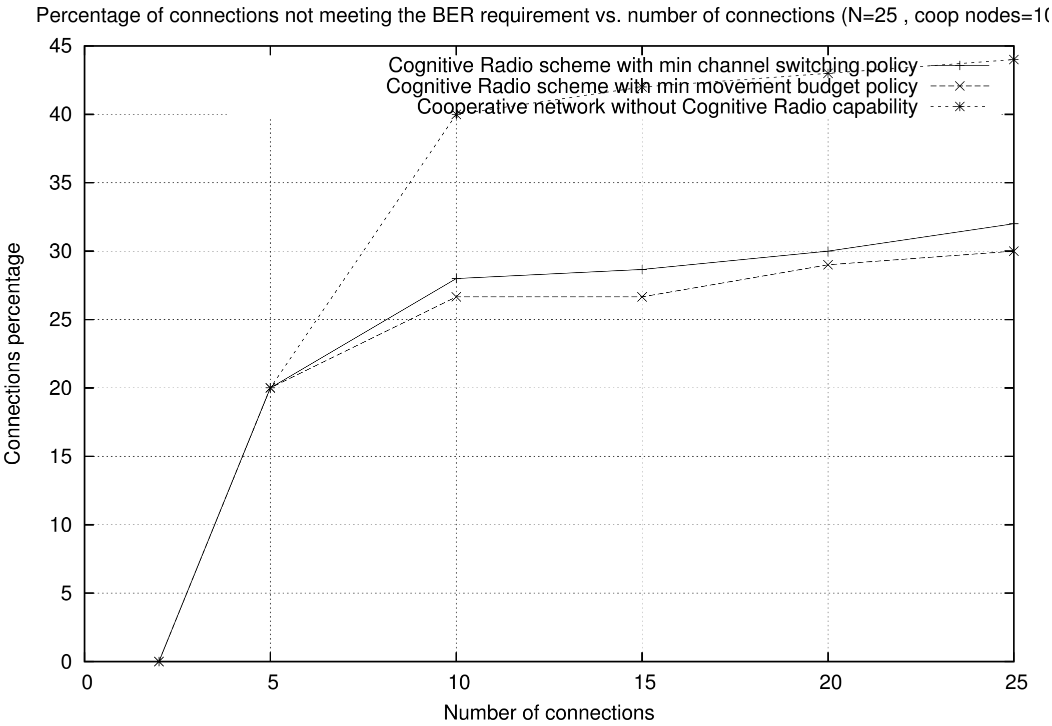


Figure 8.16 The effect of increasing the connection set size on the proposed scheme.

opportunistic channel selection and cooperative mobility. We also presented our effective decentralized algorithm for mobility planning, and new fuzzy techniques for both channel estimation and channel selection.

Our experimental results are compelling and demonstrate that the communications infrastructure—specifically, connection bit error rates—can be significantly improved by leveraging cooperative mobility and opportunistic channel switching using our proposed techniques. The techniques thus have significant impact on practical mission-oriented MANETs, with applications to battlefield communications and response and rescue missions.

The wavelet transform and flip-flop filtering techniques are effective, predict the status of primary channels, enable lower average connection BER especially when coupled with our channel selection scheme. The cooperative mobility and opportunistic channel selection schemes can be hybridized without negative tradeoffs. The schemes scale and continue to provide significant BER reductions (in excess of 30%) even as network load increases.

CHAPTER 9

CONCLUSION AND FUTURE WORK

This work has considered the ways in which cooperation between nodes can improve communications in mobile ad-hoc networks (MANETs). We developed a novel cooperative mobility model that is suited for the kind of communication-reactive mobility control that is feasible in MANETs. The cost benefit framework of this model is able to capture heterogeneous networks in which nodes exhibit a wide range of autonomy needs. This is particularly true in the settings where MANETs are most compelling, i.e. battlefield, response & rescue, and contexts requiring rapid deployment of mobile users. The time-critical nature of the underlying circumstances frequently requires deployment of both manned and un-manned nodes, and a coordination structure which provides prioritized tasking to them. Unlike consumer MANETs, these settings bring with them a common group purpose, making inter-node cooperation plausible. The proposed cooperative mobility model is build based on the assets and the limitations of previous cooperative models.

We started this research work by taxonomizing the models of cooperation that have been manifested in MANET research effort. These models include the following: (1) Relay Cooperation Models, (2) Models of Cooperation using Spatial-Diversity, (3) Cooperation Models for Reputation Management, (4) Cooperation Models for Power-based Topology Control, (5) Cooperation Models for Mobility-based Topology Control, (6) Cooperation Models for Distributed Control, and (7) Cognitive Radio based Cooperation Models.

Our initial model begins with the model of Basu et al. [2], but extends it by postulating that future MANETs will not be homogeneous in terms of node autonomy. While Basu et al. consider networks consisting of robots and non-robots, we contend that the general setting requires us to consider heterogeneous networks comprised of nodes which exhibit the entire spectrum of personalities: from defiant autonomy to self-sacrificial cooperativeness. We capture this viewpoint by adopting a cost model for mobility. Every node is willing to move for the sake of the common good, but for a price. Each node is assigned a movement cost (proportional to distance moved)—this is the price it charges to be moved, say, per meter. Defiant autonomy is exhibited when a node declares this cost to be infinite; self-sacrificial cooperativeness is manifested when this cost is declared to be zero.

In order to evaluate the merits of the proposed cooperative model, we developed the CoopSim, a platform for conducting simulation experiments to evaluate the impact of parameter, policy and algorithm choices on any system based on the proposed Cooperative Mobility Model. The CoopSim platform is implemented as a modular discrete event simulator that is naturally organized in layers including the following: (1) physical network manager, (2) routing and optimization engine, (3) command and control, and (4) output handler.

We propose an MILP formulation that accurately depicts the proposed cooperative model. Our formal description of this model describes both cases: (1) minimizing the movement budget used by all nodes while meeting the end-to-end QoS requirement of all connections, and (2) minimizing the BER of all connections under movement budget constraints. The MILP model was evaluated through simulations and found to be very effective, albeit for small networks. To make the proposed technique scale to large networks we developed a new technique based on divide & conquer principle for converting a large global MILP into a sequence of smaller local MILP optimizations. Simulation experiments using the CoopSim platform indicate conclusively that the resulting approach is scalable and succeeds at efficiently moving cooperative nodes in a manner which optimizes connection bit error rates.

Our next cooperative node movement planning scheme we consider is based on the multigird method. This technique consists of defining a hierarchy of successively finer grids, based on an original "fine" grid. At each phase, all cooperative nodes that are part of any connections requiring optimization successively consider moving to nearby grid locations. Simulation experiments indicate conclusively that the resulting approach is scalable and succeeds at efficiently moving cooperative nodes in a manner which optimizes connection bit error rates.

Our next cooperative node movement planning scheme we consider is based on the resultant method. This approach suggests a natural analogy between finding the cooperative node movement direction and the problem of computing resultant forces. Simulation experiments shows that, indeed this model leads to a better network performance in terms of wireless channel quality. We also show that with this model, increasing mobility budgets increases the potential benefit of cooperation, while increasing the number of cooperative nodes improves the efficiency with which a mobility budget can be leveraged.

In contrast to the Cooperative Mobility Model, our next cooperative model that we developed, consists of opportunistically benefit from the abundant radio frequency spectrum that is not fully utilized by primary users, while seeking to enhance the QoS provided on all communication channels, vis-a-vis bit error rate (BER). The model assumes that all nodes operate in a Radio network, and each node is able to scan the radio spectrum and determine the set of channels to be used by the primary and secondary users. We refer to this model as the opportunistic channel selection Cognitive Radio Model. Along with this model, we present new fuzzy wireless channel estimation techniques based on the wavelet transform and flip-flop filter techniques. Each node estimates the utilization of each of the primary channels then selects over which channel should the traffic be sent.

Our final proposed cooperative model consists of combining the cooperative mobility model and the cognitive radio based cooperative model. These two models were applied simultaneously to achieve better QoS. Two policies were proposed: (1) The cognitive radio scheme with minimum channel selection. This policy tries to minimize the frequency of switching between the primary channels, while meeting the targeted QoS for all connections. This is achieved by first having all nodes that are part of the connection set engage in the cooperative mobility scheme, and then applying the opportunistic channel selection for only those nodes involved in connections whose QoS is still unsatisfied, and (2) The cognitive radio scheme with minimum mobility budget. This policy tries to minimize the mobility budget used, while meeting the targeted QoS. This is achieved by first having all nodes that are part of the connection set engage in the opportunistic channel selection scheme, and then using the cooperative mobility scheme for only those nodes involved in connections whose QoS is still unsatisfied.

Our experimental results are compelling and demonstrate that the communications infrastructure—specifically, connection bit error rates—can be significantly improved by leveraging cooperative mobility and opportunistic channel switching using our proposed techniques. These techniques thus have significant impact on practical mission-oriented MANETs, with applications to battlefield communications and response and rescue missions. The wavelet transform and flip-flop filtering techniques are effective, predict the status of primary channels, enable lower average connection BER especially when coupled with our channel selection scheme. The cooperative mobility and opportunistic channel selection schemes can be hybridized without negative tradeoffs. The schemes scale and continue to provide significant BER reductions (in excess of 30%) even as network load increases.

Several extensions to this work are presently being considered. They include the following:

(a) In the multigird approach, we seek to quantify the impact of the grid refinement schedule on the quality of the solutions derived. In addition, we will design distributed implementations of this scheme, under the presumption of effective clock synchronization protocols.

(b) We propose extending existing routing protocols to make them aware of cognitive-radio capabilities. We will design provably robust distributed algorithms that further leverage cooperative mobility in MANETs. We will evaluate the scalability, tradeoffs and performance of these ideas through both analysis and simulation experiments conducted using our CoopSim platform.

(c) Unfortunately, the current MILP solution formulation for large network size is not suitable for a decentralized implementation of the extended divide and conquer MILP technique. We will design new distributed schemes for mobility planning, and use the MILP formulation as a baseline by which to assess the relative performance. We will also be considering alternate centralized schemes that extend the MILP technique to even larger networks.

(d) We propose designing new distributed algorithms for cooperative movement planning based on genetic and simulated annealing heuristic techniques.

(e) The QoS parameter considered so in this current research is the Bit Error Rate, which accurately captures the quality of the wireless channels. Under this generic model, different QoS parameters can be considered. We plan extending the current model to provide secure/trusted end-to-end routes. This can be achieved by quantifying the degree of security of the wireless channels. This new concept is considered as a combination of the current work and our previous research work about designing a new secure routing protocols in ad-hoc networks: ”TARP”. TARP is a routing protocol that computes secure routes based on the trust level of wireless network nodes. In this model, TARP proposes quantifying the node trust metric based on different properties of the wireless node including: (1) encryption techniques, (2) hardware resources, (3) power level, (4) credit history, (5) exposure to other nodes, (6) organizational hierarchy, etc. The main objectives of the proposed TARP suite are: (a) implement security that is inherently built into the routing protocol, (b) deliver messages that are received with a user defined or best available level of confidence.

(f) In the current research work, the network performance parameter considered is the bit error rate. We will be evaluating our cooperative model by considering different network QoS parameters. These include the delay, network throughput, network lifetime, etc.

(g) In the current research work, the mobility model considered for the regular mobile nodes is the Gauss Markov model. We will be evaluating our cooperative model under different mobility model. These include radom models, models with geographic restrictions, etc.

(h) We propose extending the current cooperative mobility model to add more restrictions to the terrain of operations. In other words, cooperative nodes will be making decision to relocate based on the current budget as well as the type of new locations. This is a very suitable model especially in hostile type of terrains such as battlefield environment.

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