CONNECTION SURVIVAL USING POSITION-BASED ROUTING IN MOBILE AD HOC NETWORKS

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Abstract

Connection Survival using Position-Based Routing in Mobile Ad Hoc
Networks

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Mobile ad hoc networks (MANETs) have witnessed a tremendous growth in the recent
years thanks to technological advancements and energy saving techniques that have
made possible the creation of autonomous mobile communicating systems. Still,
MANETs face many challenges in terms of stability, power consumption and quality
of service. Typically, stability is assured through the use of reliable communication
channels protected by failure recovery protocols.

In this thesis, we examine the stability problem by the elaboration of new position-
based routing algorithms that maintain stable connections between nodes in MANETs.
The positions of the nodes are updated by the regular beacon broadcasts. Specifically,
we have extended the backup path mechanism used by Yang et al.'s 2011 Greedy-
Based stable multi-path Routing protocol (GBR), that have been recently used in
MANETs. In terms of stability alone, our algorithms have explored using more
general backup paths; re-establishing broken paths from the last reachable node;
or using a conservative range for neighbor next-hop selection. The latter protocol
(GBR-CNR), using a Conservative Neighborhood Range (CNR), is the most efficient
in simulations.

To be able to accommodate energy constraints typical in MANETs, we study energy efficient variations of these stable position-based routing algorithms. We study the use of Dynamic Transmission Ranges (DTR) or energy-aware neighbor next-hop selection, such as the LEARN algorithm, to assure energy efficiency while preserving connection stability. Out of all the algorithms considered, the combination of CNR and DTR, GBR-CNR-DTR, outperforms the rest in simulation.

Concerning the Quality of Service (QoS), we consider variations of GBR-CNR that improve QoS through the reduction of interference that affect the quality of communications. We develop stable communication protocols that mitigate interference between mobile nodes by minimizing the number of corrupted packets through the use of different techniques such as defining new methods to choose the hereafter hop in a communication process.

Overall, this thesis presents several new stable position-based routing algorithms that improve energy consumption and QoS in MANETs. Several of the introduced algorithms are shown to have better capabilities than previously published algorithms as demonstrated in the simulation results.

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Acronyms

AODV	Ad Hoc On-demand Distance Vector
AODV	Ad Hoc On-demand Distance Vector
CB	Completing Backup
CBR	Constant Bit Rate
CGSR	Cluster-head Gateway Switch Routing Protocol
CNR	Conservative Neighborhood Range
CSI	Channel State Information
CTS	Clear To Send
DSDV	Destination Sequence Distance Vector
DSR	Dynamic Source Routing
DTR	Dynamic Transmission Range
ECG	Electrocardiography
FDMA	Frequency Division Multiple Access
GBR	Greedy-based Backup Routing Protocol
GBR-CTR	GBR with Conservative Transmission Range
GFG	Greedy Face Greedy
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing

IA-CLR	Interference Aware Cross Layer Routing protocol
LBR	LEARN-based Backup Routing
LEARN	Localized Energy Aware Restricted Neighborhood Routing
LET	Link Expiration Time
LS	Location Services
LSEA	Line Stability and Energy Aware
MAC	Media Access Control
MANETs	Mobile Ad hoc Networks
MHSNs	Mobile Healthcare Social Networks
OFDM	Orthogonal Frequency-Division Multiplexing
PDR	Packet Delivery Ratio
PET	Path Expiration Time
QoS	Quality of Service
q-UDG	Quasi Unit Disk Graph
R-DSDV	Randomized Destination Sequence Distance Vector
RF	Radio Frequency
RNA	Restricted Neighborhood Area
RREP	Route Reply Message
RREQ	Route Request Message
RTP	Real-time Transport Protocol
RTS	Request To Send
SINR	Signal-to-Interference-plus-Noise Ratio
TDD	Time Division Duplex
TDM	Time Division Multiplexed

TDMA	Time Division Multiple Access
TS	Time Slots
UDG	Unit Disk Graph
VoIP	Voice over IP
Wi-Fi	Wireless Fidelity
WRP	Wireless Routing Protocol
WSN	Wireless Sensor Network

Chapter 1

Introduction

Wireless networks are formed by interconnected devices communicating wirelessly within a relatively limited area. Mobile Ad hoc NETworks (MANETs) are a type of wireless network where mobile devices are themselves responsible for communication with each other without the presence of a centralized infrastructure. Moreover, each device in a MANET is not only responsible for network traffic related to itself but also has to forward unrelated traffic as an intermediary. Nodes in MANETs can typically move in any direction they want and therefore links between them and other devices may frequently change.

In MANETs with highly mobile nodes, there is a high probability that a link between two neighbors in a path will eventually break. To increase the stability of routing in MANETs and provide a reliable end-to-end route, one approach would be for each node to choose the most stable route from its options. In other words, to improve the stability along the path in the presence of expiring links, another approach is to maintain a backup path to the primary path along the connection. In

particular, a reliable connection could be achieved by protecting the links between each pair of nodes participating in the primary path by maintaining local backup paths in parallel with each link in the path to be used when that link expires. In this thesis, we will study in particular, the latter approach using backup paths.

By focusing on link stability in MANETs, link failures leading to a connection break that will cause the traffic flow to be interrupted until a new route is formed. This leads to packet delivery gaps that are unacceptable for real-time applications such as mobile wireless telemedicine. In fact, a major drawback of the link protection technique occurs when a node in the primary path fails or becomes unresponsive. This makes the connection completely broken. So, we will also address the issue of protecting the intermediate nodes instead of just protecting the link between two neighboring nodes within the same path. Such a protection shall lead to the improvement of the path lifetime, achieving a better routing stability in MANETs environments.

Indeed, MANETs devices are typically powered by batteries with limited computing capability, so that the battery capacity constraint is one of the most important limitations in developing applications and services for mobile devices [31]. As MANET systems become more widely deployed, it is important to maintain stable connections while taking in consideration the energy consumption that is required to communicate over these connections that consumes a large part of the available energy resources of the mobile devices.

In MANETs, all nodes that have messages (packets) to exchange must transmit their packets concurrently if there is no interference that can affect their communication. In other words, to achieve high network efficiency in MANETs, parallel transmissions on more than one link must be considered by routing and scheduling

protocols. Interference in MANETs is a result of concurrent transmissions taking place in the neighborhood (asynchronous). It is also associated with collisions (which produce corrupted data) arising from nodes, outside the range of each other, transmitting to a common receiver at the same time (synchronous) that will affect the quality of communications.

Many routing protocols have been proposed to improve the routing efficiency in MANETs. Those protocols can be broadly categorized into two approaches: 1) Topology-based routing and 2) Position-based routing. In ad hoc routing, position-based routing protocols makes forwarding decisions using its own position, the destination's position to choose the next hop node, and the position of its one-hop neighbors in order to forward packets to it [54]. Since it is not necessary to maintain explicit routes, position-based routing scales well even if the network is highly dynamic. For MANETs, most recent work on routing that is stability-oriented has been for topology-based routing with exception of the position-based Greedy-based Backup Routing Protocol (GBR) [90] using backup paths to maintain link stable paths. For position-based routing to the best of our knowledge on mobile ad hoc networks, no previous work has studied stable routing in combination with energy efficiency.

1.1 Research Focus

To achieve the greatest realism in MANETs, routing is done using reactive on-demand philosophy where routes are established only when required. Also, mobile nodes communicate with each other using multi-hop wireless links that build depend on the location of the nodes; therefore, we study route stability in MANETs by using

a position-based routing protocol. Previously proposed geographic routing protocols commonly employ a maximum-distance greedy forwarding technique that works well in ideal conditions.

1.1.1 Connection with Survivability

Since nodes in MANETs systems can move freely and randomly in any direction, routes often get disconnected. However, the major challenge for MANETs is to implement stable connections that must respond to changes in the network topology in order to maintain and reconstruct the routes in a timely manner as well as to establish stable routes. Therefore, finding and maintaining stable routes is a significant issue on the communication stability in MANETs.

1.1.2 Energy Consumption

As we have discussed, nodes are also acting as intermediate nodes to forward other nodes data. For this reason, those intermediate nodes have large burden that leads to higher energy consumption. Mobile nodes have limited amounts of energy that is consumed in different ways depending on it's transmission range and other energy consuming factors. The energy concentrate on nodes in MANETs operate on limited batteries, so it is a very important issue to use energy efficiently and reduce power consumption. In this research, many routing protocols have been introduce an adaptive routing protocol that is intended to provide a reliable and efficient routing with low energy consumption in MANETs.

1.1.3 Communication Interference

In MANETs, during the route construction process, the neighborhood nodes exchange messages in the contention mode, due to the communication being done wirelessly. This leads to heavy control message overhead and communication interference [28]. As a matter of fact, interference affects the throughput of communication in MANETs by corrupting some of the packets that are exchanged among the mobile devices. Therefore, it is important to study the interference schemes that improve the throughput at the receivers in the MANETs environment.

1.2 Case Study: Application of Reliable Communication in Healthcare System

Our research in the field of MANETs focuses on the path stability; thus many systems can benefit from it. For example, in healthcare systems, where path stability can be a major challenge because it can be affected by many factors. Following is some insight into the motivation and challenges involving healthcare systems and wireless networks. Wireless devices have gained a lot of interest in the field of medicine with a wide range of capabilities and stabilities [29]. In most developed countries, wireless devices are being used to monitor critical illnesses such as cancer, cardiovascular diseases, asthma, and diabetes. Wireless sensor networks have enabled medical doctors to monitor patients remotely and give them timely feedback and support; potentially increasing the reach of healthcare by making it easily accessible by supervisors, anytime and anywhere as illustrated in Figure 1.1. In order to achieve that goal, our study was

about the improvement of the path stability on wireless devices by improving the reliability of the network connection and the energy consumption of the wireless devices.
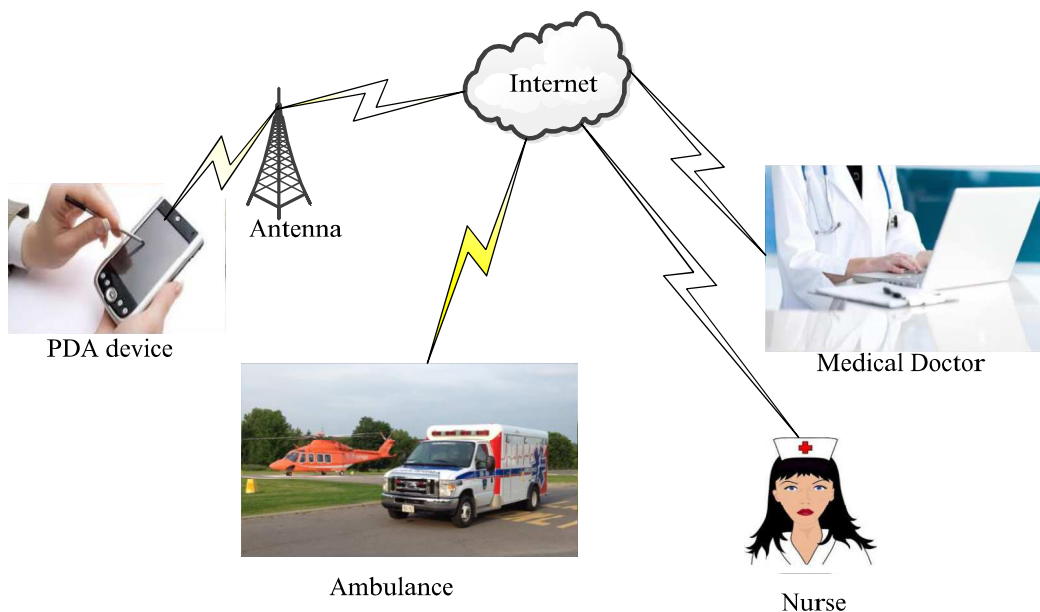
Figure 1.1: Architecture of mobile community platform for healthcare

1.2.1 Motivation of Mobile Healthcare Social Networks

Social networks are beginning to be adopted by healthcare professionals as a means to manage institutional knowledge, disseminate peer-to-peer knowledge, and to highlight individual physicians and institutions [4, 56]. A new trend is emerging where social networks are used to help its members with various ailments - either physical or mental. While building a reliable mobile healthcare system, some of the major challenges to improve Mobile Healthcare Social Networks (MHSNs) are Wireless Body Area Network subsystems [7, 75, 80]. Monitoring applications would be desirable to

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address security, privacy, confidentiality, authentication and reliability of communication, and its categories such as activities of daily living, fall and movement detection, location tracking, medication intake monitoring, and medical status.

1.2.2   Mobile Healthcare Social Networks Challenges

MHSNs serve as mobile community platforms for healthcare purposes. A MHSN topology could be built as a centralized healthcare system or a decentralized healthcare system. The response system increases patient safety by building the topology as a decentralized technique and reducing the healthcare cost in order to provide pre-hospital acute medical treatment [62, 71]. In [88], a MHSN serving as a promising platform for an eHealthcare system, had attracted considerable interest. Profile matching is an effective method for medical users to find possible helpers in the mobile healthcare social networks while preserving personal health information privacy. Also, Yang *et al.* [89] presented a distributed data storage architecture that facilitates secure and efficient data replay in eHelathcare information system.

In a survey done by Alemdar *et al.* [4], the authors evaluated state-of-the-art research activities and present issues that needed to be addressed to enhance the quality of life for the elderly, children, and chronically ill people. With the increasing demand in providing high quality healthcare services to individuals, healthcare applications are gaining a lot of popularity in society. By providing a reliable connection between medical practitioners and doctors, in the case of a medical emergency, we can ensure pre-hospital acute medical treatment.

One such research work was carried out in North Carolina [61]. Pre-hospital care is given to the patients suffering from cardiac arrest by transmitting, wirelessly, the

electrocardiography (ECG) of the patient. The transmission could be sent on-site or from an ambulance to the cardiologist so that hospital staff are prepared to treat the patient accordingly when the patient arrives at the hospital. Also, in case of an emergency involving several people, the system should be able to establish and maintain contact with everyone in life threatening situations such as heart attack, cardiac arrest, and so on. For example, if a person suffers a heart attack on the ground floor of a building, the system should be reliable enough to handle early and specialized pre-hospital patient management.

In many daily life situations, it is important to protect the path between pairs of nodes. For instance, making communication reliable while providing healthcare services is one of the important issues that should be studied further. Many researchers have evaluated many kinds of backup recovery mechanisms and presented issues that need to be addressed in order to enhance the quality of life for patients [17,51,65,71].

1.3   Thesis Contribution

This research will motivate the need for adaptive mobile ad hoc networks management to best support wireless path protection and dynamic mobile devices movement. It will discuss some current research such as interference and energy efficient protocols and algorithms. The objective of our study focuses on the issues of mobile communication stability, in general, in order to improve network throughput in MANETs. Furthering the work presented in [90], we propose to improve the efficiency (in terms of network throughput) and overall routing communication stability by using ideas such as protecting the nodes in the paths instead of protecting a link between the

nodes. Also, we propose creating more general backup paths for link protection, rediscovering a path from the last reachable node instead of from the source node when a connection fails, use of the conservative neighborhood range technique, minimizing message overhead, minimizing the energy consumption, and minimizing the communication interference.

Extensively, we studied the benefits of conservative neighborhood range protocol in terms of energy efficiency, less message overheads, and less communication interference. We studied those problems by using a position-based routing protocol which is covered in Section 2.3.2. This was based on the combination of link stable routing with dynamic transmission ranges, and stable path without the backup path, in order to minimize messages exchange. The dynamic transmission ranges establish energy efficiency while maintaining the high connection throughput enabled by stable connections. In this thesis, we introduce a backup-path routing protocol that aims to handle both link expiration and nodes that become unresponsive in MANETs.

Our protocols deal with mobility, break-down of wireless links and also the disappearances and reappearances of nodes. By adapting previous work for link protection, we introduced a node protection scheme for the route survival in MANETs that can also be considered effective for link protection. In [92], as discussed in detail later in Chapter 3, we studied the idea of using a Conservative Neighborhood Range (CNR) such that there was no need to establish backup paths. We expected that this would have had reduced the message overhead better than previously studied protocols, such as GBR, that maintain path stability by applying a backup path mechanism. We focus on developing protocols to decrease the number of messages exchanged during

path establishment and to determine a better interval time that will improve communication stability in MANETs. We will use, in particular, an approach based on GBR [90] to ensure link stability.

In MANETs, the interference is a result of concurrent transmissions taking place in the neighborhood (asynchronous). This can be caused by multiple path sharing nodes, for example. Simultaneously, the non-interference links can transmit data to minimize problems at the receiver side such as data collisions, which causes data corruption. Chapter 4 gives a brief study about minimizing the interference that will improve the system performance and to maximize utilization of network bandwidth that lead to higher throughput.

1.4   Plan of Thesis

The rest of this thesis is organized as follows. In Chapter 2, we review specifically related work, give details of the stable routing protocols that we studied, give a brief description about different approaches to calculate the energy in MANETs, give some details of the impact of HELLO interval duration, and describe the effect of communication interference in MANETs. In Chapter 3, we propose our developments to improve connection survival, and the impact of both the effect of varying node velocity and HELLO message interval duration in MANETs networks. We propose different energy efficient routing protocols based on stable routing protocols in Chapter 4. Also, in Chapter 5, we studied the impact of minimizing the interference that will improve the system performance and maximize utilization of network bandwidth. Finally, concluding remarks and future work are discussed in Chapter 6.

Chapter 2

Background and Literature Review

As mentioned in the introduction, in MANETs there are two types of wireless architectures used to build a wireless topology: centralized and distributed architectures. A centralized system is one in which communications are routed through one or more major Base Stations (BS), such as seen in Figure 2.1. Therefore, a source S request has to go through the base station to reach destination D, even if S and D are physically within transmission range of each other. The advantages of a centralized system are: a centralized station will control the entire system and keep the related packets together, so the design of the system will be less complicated. Also, the centralized system will take all the responsibility to manage the network traffic, reduce packet duplication at the receiver side, easily control the privacy and security, and provide uniform service to all users.

There are some disadvantages of a centralized system, which are: even if the destination is within the transmission range of the source, the request will go through the centralized system, and this will increase the number of hops between them.
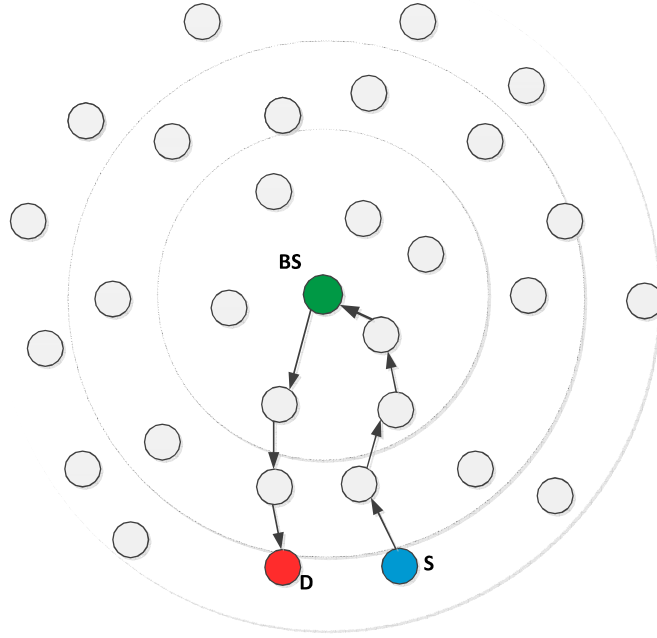
Figure 2.1: Centralized Architecture

Also, when a new node wants to join the network, it needs to get permission from the centralized station. Other drawbacks of the centralized system are lack of scalability and reliability because a node needs permission to join the network. Furthermore, nodes nearest to the central station are heavily used, so their failure will have a disproportionate effect. Moreover, if a centralized system station malfunctions for any reason, the entire system will be severely affected.

In a decentralized architecture, as illustrated in Figure 2.2, there is no single centralized node that makes decisions (e.g. join a network, network routing, shortest path, scheduling, queuing, priority, and fairness) for the wireless nodes. Therefore, if a node wants to send a message to another node, it has the responsibility to manage the traffic. Now, S can communicate directly with D, as shown in Figure 2.2 (a). If D is within the transmission range of S, without having to go through a base

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station. However, if the destination is outside the source's transmission range, the communication will be established through multihops as shown in Figure 2.2 (b).

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(a) Direct Connection   **(b)** Indirect Connection
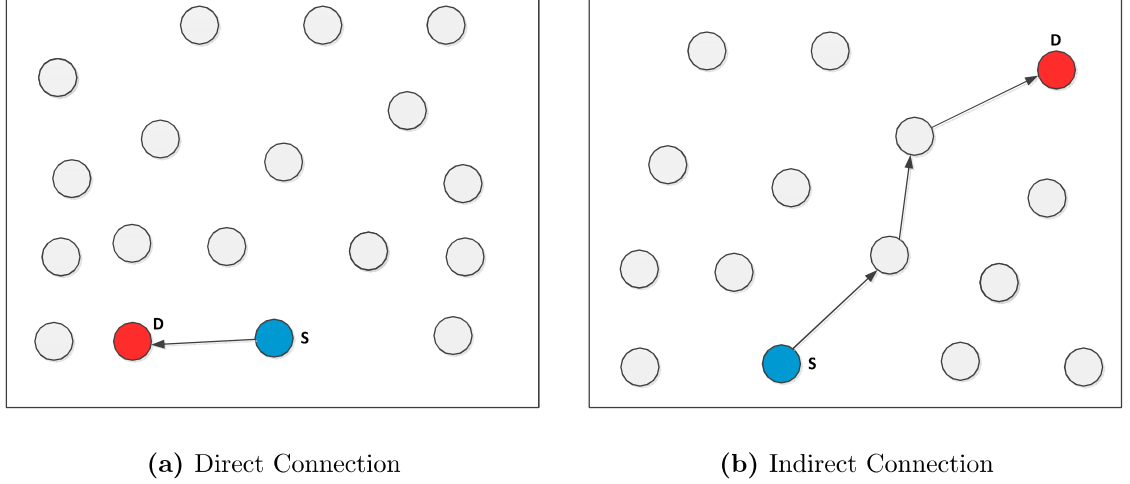
Figure 2.2: Decentralized Architecture

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The advantages of a decentralized are that: a decentralized system results from the incremental growth of the network topology, so the system is scalable, is more reliable since if any node crashes, the system as a whole can still operate. Also, it can more easily accommodate node movement. However, there are disadvantages of the decentralized system. Designing decentralized can be a very complex task for overall system objectives. Therefore, as with a centralized system, controlling the overall system is also very complicated. During the communication in a decentralized system, it is not easy to reduce message duplication at the receiver side of the sensor networking nor does it provide a uniform service to all users. Furthermore, all nodes have equal responsibility to make a decision that will make issues like security and privacy that are more difficult to control during communication.

2.1   Mobile Ad Hoc Networks

At any time t MANETs use a decentralized system architecture in order to achieve less delay and an efficient utilization of network resources such as bandwidth, concurrent transmission,...etc. Also, in MANETs, all the nodes in the network act similar to a router, which will forward messages for other nodes. However, in order to achieve improved performance for a wireless network, one of the major functions of MANETs that, we studied, is the stability of the path between a pair of mobile nodes interested in communicating.

Also, routing in a MANET depends on many factors including network topology, the type of information available during routing, and specific underlying network characteristics that could serve as a heuristic while finding a path quickly and efficiently. However, to define how connections between communicating nodes are established in MANETs, we first need to define our network model of a MANET and discuss how routes are determined in this "model".

2.1.1   Network Model of MANETs

MANETs can be modeled using a graph $G = (V, E)$, where V represents the set of nodes/vertices, and E represents the set of links/edges. Each edge represents a link between two nodes currently within the transmission range which, for this work, we will assume to be the same for all nodes [46] (the resulting graph is termed a Unit Disk Graph (UDG). We will denote the set of neighbors of a node v_i by $N(v_i)$. A path of length n between a source node S and a destination node D is denoted by $(S = v_0, v_1, v_2, \ldots, v_n = D)$, where $v_i \in V$ and $v_i \in N(v_{i-1})$. A path which is used as the first choice while transmitting from source to destination is called a

primary path, denoted as P_p. An alternative path which is used when the primary path has difficulties, no longer exists, or is broken is called a backup path, denoted as $P_b = (S = v_0' = v_0, v_1', v_2', \ldots, D = v_{n'}' = v_n)$ where $v_i' \in V$, $v_i' \in N(v_{i-1}')$ and n may different from n'. Each node in the MANET will have a unique identifier and know its geographic position.

In the real world, we will assume that the location of the nodes in a MANET will be tracked using Global Positioning System (GPS) and/or Location Services (LS) [8,90]. We will assume the nodes are arranged in a two dimensional $2D$ Euclidean space such that G is a geometric graph. We will also assume that all nodes will broadcast at regular intervals their positions to their neighbors using HELLO messages. Each edge in G represents a link between two neighboring nodes within the transmission range.

The protocol that we used for exchanging messages is a bidirectional link between nodes. Different techniques can be employed to share the bandwidth in order to use the available bandwidth efficiently. These include Frequency Division Multiple Access (FDMA) [58], as illustrated in Figure 2.3, Orthogonal Frequency Division Multiplexing (OFDM), and its variation Time Division Multiple Access (TDMA) [58], as illustrated in Figure 2.4.

FDMA and OFDM divide the bandwidth into multiple frequency bands or channels; whereas, OFDM is based on spreading the data to be transmitted over multiple carriers. Both FDMA and OFDM are modulated at a low rate. However, they require a device to have the capability of simultaneously receiving and transmitting signals, which leads to increased equipment cost. Since TDMA shares the available bandwidth in the time domain, a TDMA frame consists of periodically repeating time slots, allowing several users to share the same time slot. Therefore, the device can
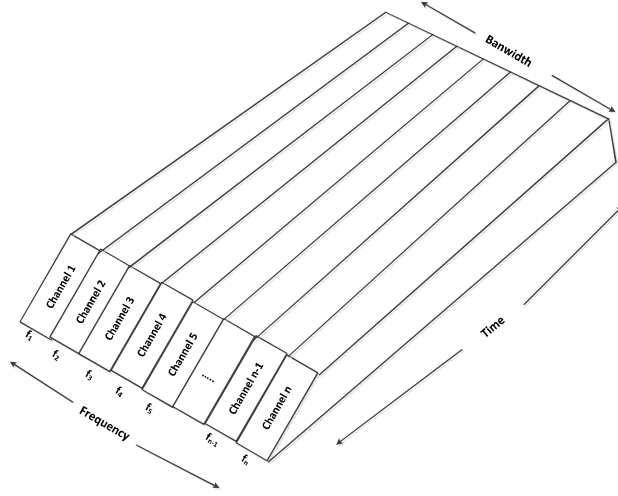
Figure 2.3: Orthogonal frequency-division multiplexing

switch between slots and hence use the same bandwidth for receiving. Also, the cost of using the TDMA's equipment is less expensive than that required in OFDM. In our network models, we used TDMA.

2.1.2   Two Dimensional Network Models

The following provides brief descriptions of some types of two-dimensional (2D) network models for MANETs.

A Unit Disk Graph (UDG): is a type of geometric graph, as illustrated in Figure 2.5, where an edge exists between two vertices if and only if the Euclidean distance between them is less than or equal to one unit. In a MANET, the vertices in the UDG represent nodes, where an edge exists between two nodes if the Euclidean distance between the two nodes is less than or equal to the transmission range of the nodes, which is the same for all nodes [46].

While modeling a MANET as a unit disk graph, it is reasonable to assume that

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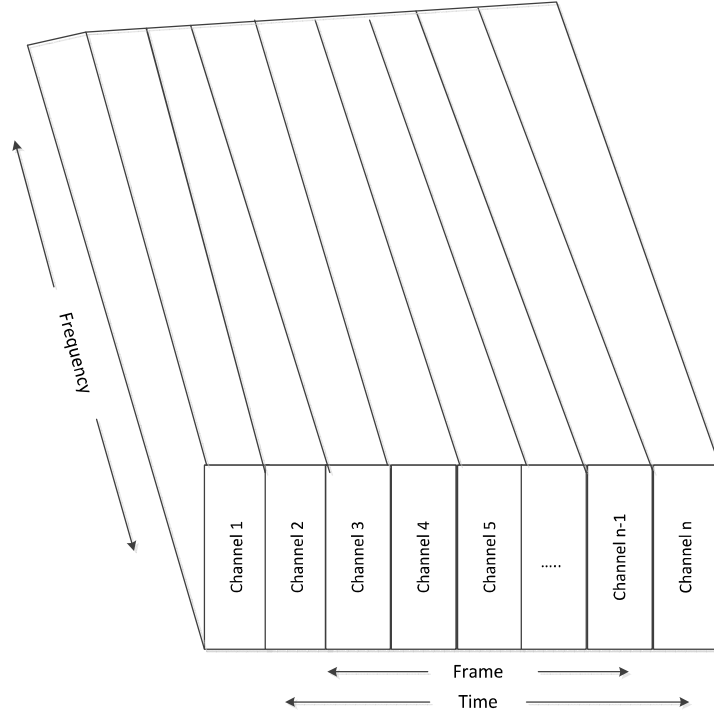
Figure 2.4: Time division multiple access

the connection information between all vertices of the network graph contains enough information so that correct coordinate information can be obtained. This information is very handy for fulfilling a number of needs of ad hoc sensor networks [47]. In general [39], the unit disk graph model was used to model a very reliable communication range between two nodes to the extent that any communication beyond that was discarded or simply assumed to be non-existent.

A Quasi Unit Disk Graph (q-UDG): is a type of UDG [13, 60] in which two nodes are connected by an edge if their distance is less than or equal to d, where d is a parameter between (0 and 1) as illustrated in Figure 2.6. Furthermore, if the distance between two nodes is greater than one, this implies that there is no edge between those nodes. In the range between (d and 1), there may, or may not,

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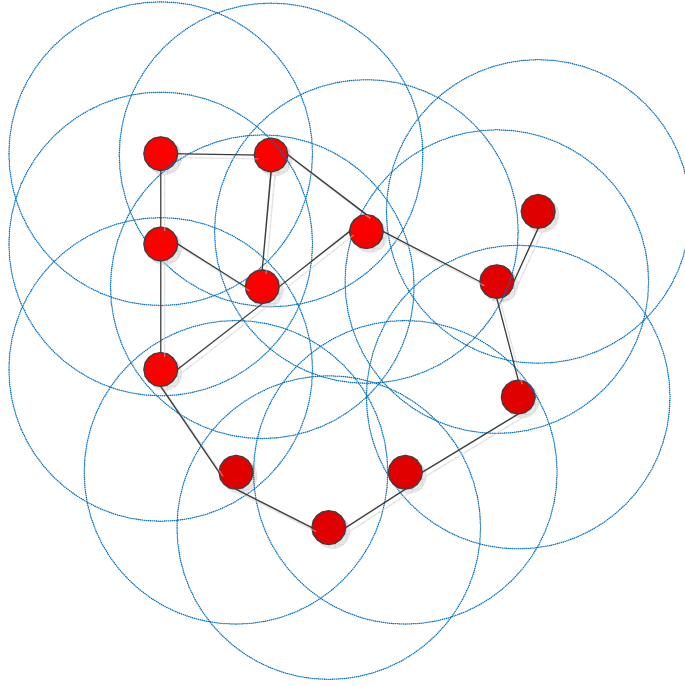
Figure 2.5: A unit disk graph

be an edge between the nodes as seen in Figure 2.6 where edges to the neighbors of v are shown. A more general network model, the q-UDG model, captures the characteristics of wireless networks much better. However, the understanding of the properties of general q-UDGs has been very limited, which impedes the design of key network protocols and algorithms.

Wireless Sensor Networks (WSN): consists of spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, humidity, motion or pollutants. They must cooperatively pass their data through the network to a main location, as illustrated in Figure 2.7. A WSN can range from a small network, consisting of few sensors, to a large network consisting of hundreds or thousands of sensors. Also, the location parameters of
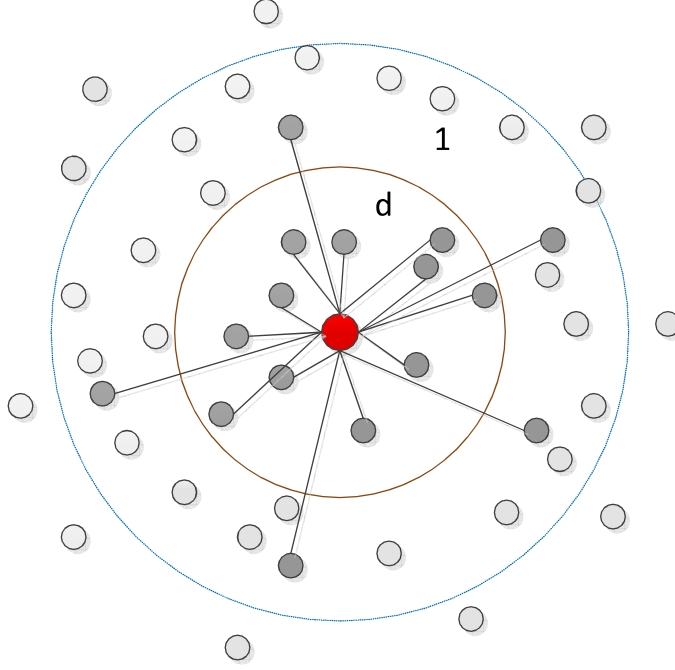
Figure 2.6: A quasi unit disk graph

nodes interested in communication in wireless sensor networks can be obtained by using services like GPS [5, 81]. Each sensor network node typically has several parts: a radio transceiver with an internal antenna or connection to an external antenna, a microcontroller, an electronic circuit for interfacing with the sensors, and an energy source, usually a battery or an embedded form of energy harvesting.

2.2 Mobility Models in Wireless Topologies

Mobility models are the most practical representations of the real world MANETs [23]. Mobility networks model mobile users, and how their location, velocity, and acceleration change over time. In MANETs, in order to achieve the highest realism,
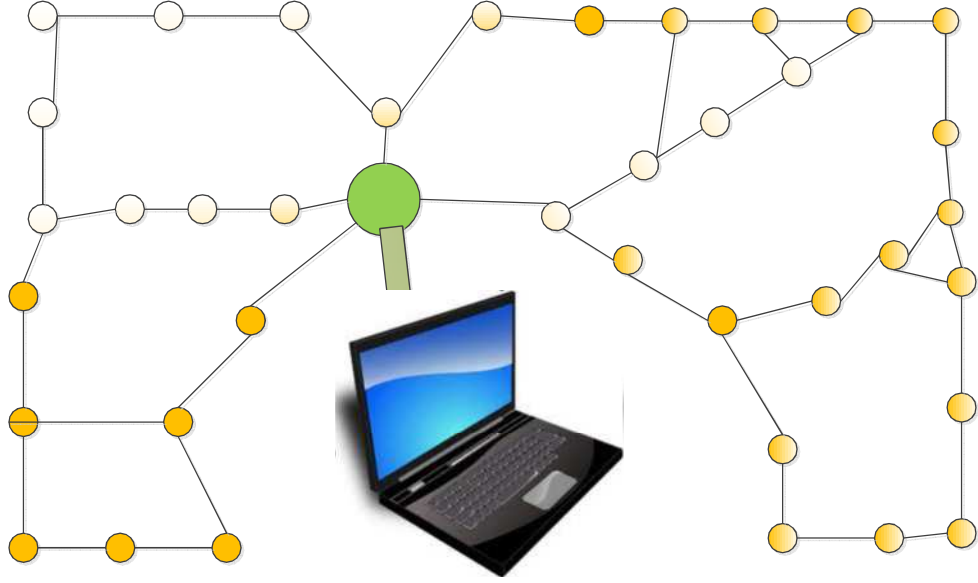
Figure 2.7: A topology of wireless sensor networks

mobility modeling must take this into account.

The mobility model is designed to describe the movement patterns of mobile users, and how their location, velocity, and acceleration change over time. Since mobility patterns may play a significant role in determining the protocol performance, it is desirable for mobility models to emulate the movement pattern of targeted real life applications in a reasonable way. Otherwise, the observations made and the conclusions drawn from the simulation studies may be misleading. Thus, when evaluating MANET protocols, it is necessary to choose the proper underlying mobility model. For example, the nodes in the random waypoint model behave quite differently as compared to nodes moving in groups. It is not appropriate to evaluate the applications where nodes tend to move together using the random waypoint model. Therefore, there is a real need for developing a deeper understanding of mobility models and their impact on protocol performance.

One intuitive method to create realistic mobility patterns would be to construct trace-based mobility models, in which accurate information about the mobility traces of users could be provided. However, since MANETs have not been implemented and deployed on a wide scale, obtaining real mobility traces becomes a major challenge. Therefore, various researchers proposed different kinds of mobility models, attempting to capture various characteristics of mobility and represent mobility in a somewhat 'realistic' fashion.

2.2.1 Most Commonly Employed Mobility Models

There are many mobility models illustrated in [66], which attempt to simulate mobile user movements. We describe some of these models in the following paragraphs.

Random Walk: The random walk model Figure 2.8 is the simplest of all mobility models. In this model, a node is placed into a random location and is then free to move into any random direction $[0, 2\pi]$ and at a random speed [min speed, max speed].

Random Walk with Wrapping and Reflection: Random walk does not handle scenarios when a node reaches the boundary of the network. Two modifications of this random walk model, which address this problem, are random walk with wrapping and random walk with reflection. In the random walk with wrapping, a node, upon reaching a boundary, will wrap around the opposite edge and continues with the same speed and direction. For the random walk with reflection, when a node reaches the boundary, it will reflect by changing its angle $\alpha + \pi/2$ and maintains a constant velocity, as illustrated in Figure 2.9.

Random Waypoint: In the random waypoint model, a node is placed into a random
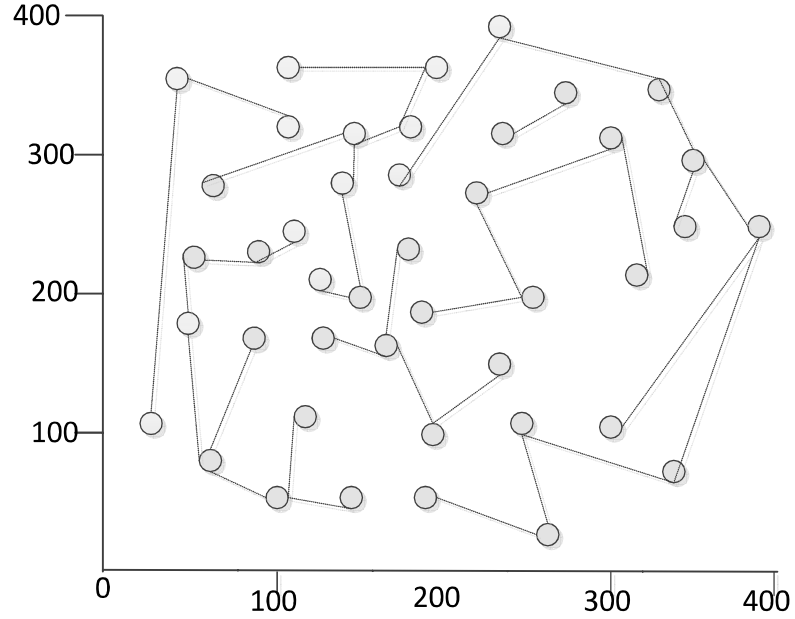
Figure 2.8: A Random walk approach in wireless sensor networks

location and a random destination within the simulation area. The node moves towards the destination with a random speed. Once it reaches the destination, it pauses for a small amount of time, and then the process is repeated. Note that in this type of model, since the selected destination node is within the area of simulation, a node cannot go out of bounds, as illustrated in Figure 2.10.

Random Direction: In random direction, each node is assigned a random direction between $[0, 2\pi]$, and continues in that direction from the center of the simulation area as illustrated in Figure 2.11. When it reaches the boundary, it selects another direction between $[0, \pi]$ and after pausing for a constant time, it continues in the new direction.

Swiss Flag: This is also a modification of random waypoint model. In this model, the simulation area is considered as a combination of connected areas resulting in
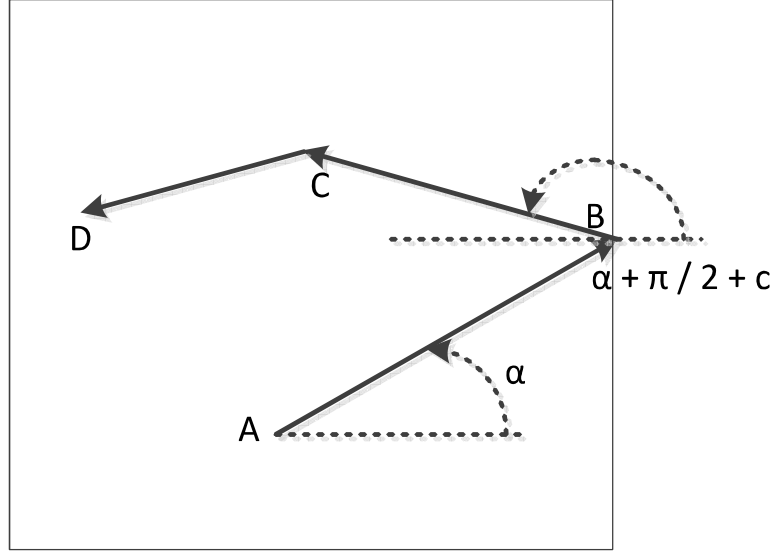
Figure 2.9: A Reflection approach in wireless sensor networks

a shape that resembles the Swiss flag, as illustrated in Figure 2.12. However, each mobile node starts its movement from a random location and travels to a random destination through the shortest path between two points. Note that sometimes these routes can result in an actual path with two segments.

2.2.2 Comparison of Mobility Models

To achieve the greatest realism, mobility modeling must take into consideration three essential factors. These are, spatial environments, user travel decisions, and user movement dynamics. Moreover, a mobility model must address both the regular and random components of a user's movement. Failing to consider each aspect of movement, in a balanced manner, results in unrealistic modeling. Additionally, for an accurate evaluation of the performance of a protocol, the mobility model must
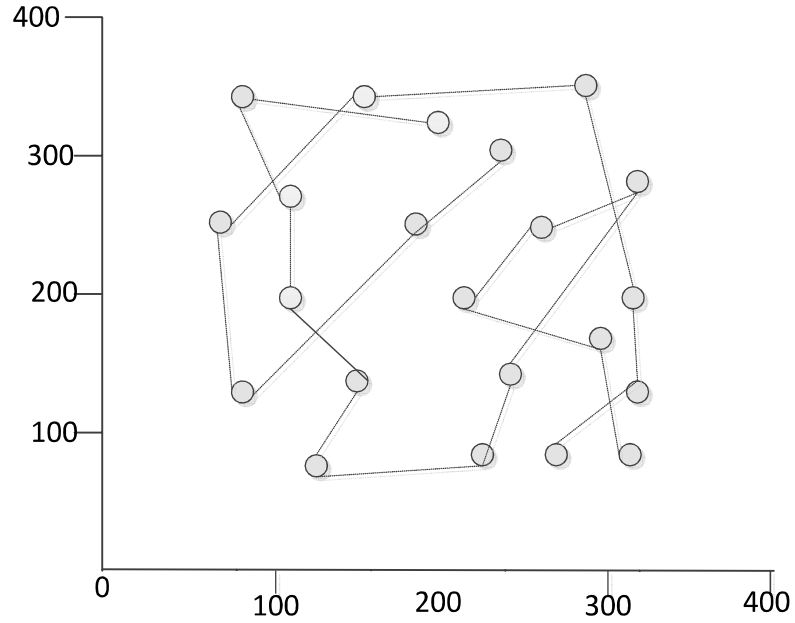
Figure 2.10: A random waypoint approach in wireless sensor networks

supply a stable movement pattern during the simulation time and attain its steady state for most of the simulation time. The discussed mobility models have different characteristics leading to varying degrees of acceptance.

2.3   Routing Protocols

Routing is the process of path selection on which network traffic is sent. In MANETs routing protocols can be broadly categorized into two approaches, topology-based routing and position-based routing [54].
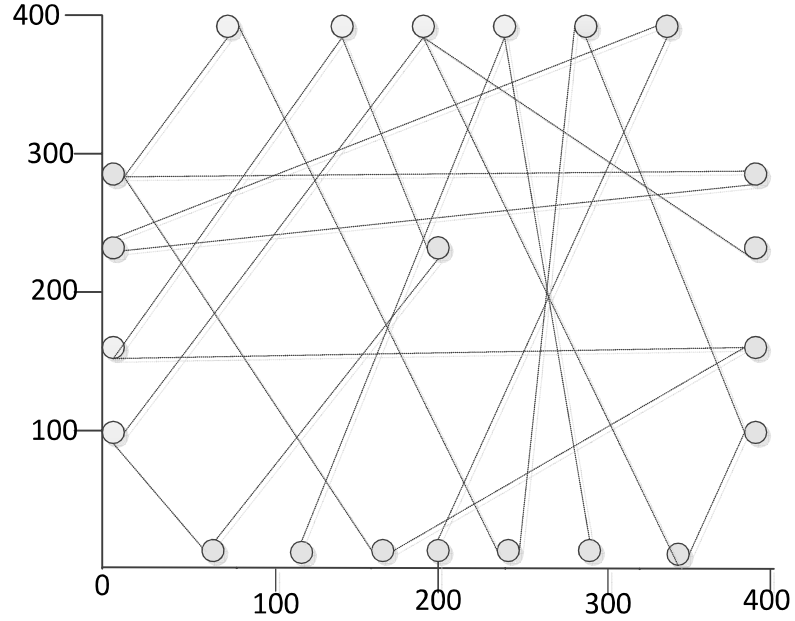
Figure 2.11: A random direction approach in wireless sensor networks

2.3.1 Topology-Based Routing

The most recent work on routing, that is stability-oriented, has been for topology-based routing [10, 32, 33, 35, 49], with the exception of the position-based, Greedy-based Backup Routing Protocol (GBR) [90], which uses backup-paths to maintain link stable paths. Topology-based routing protocols use link information available from the network to determine a route between the nodes. These protocols are mainly classified into three categories: proactive, reactive, and hybrid routing protocols [36]. **Proactive Routing:** In proactive routing protocols, the whole network information must be known to all nodes. Effectively, each node has the complete understanding of the network topology. The main advantage of these type of protocols is that each node can figure out the path to a destination almost immediately from the

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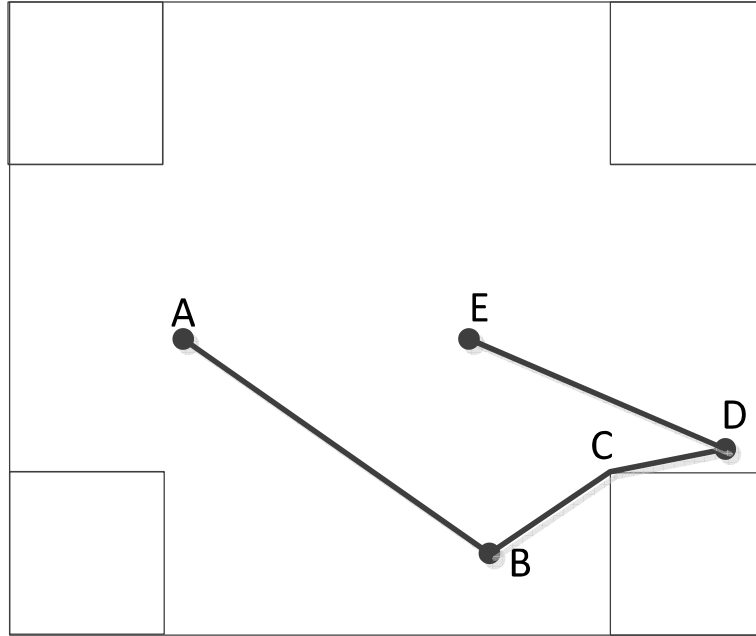
Figure 2.12: Swiss flag approach in wireless sensor networks

information it already has. The Destination Sequence Distance Vector (DSDV) [68] routing protocol, the Wireless Routing Protocol (WRP) [59], and the Cluster-head Gateway Switch Routing Protocol (CGSR) [14], are all types of proactive routing protocols. However, proactive algorithms generate a large amount of control packets on the network in order to distribute network topology information, which results in significant overhead.

Reactive Routing: Reactive protocols discover and set up routes when they are needed. That is if a node wants to communicate with another node, for which it does not have the path, it will send out control messages to establish the route. Since reactive protocols maintain only the routes that are currently in use, they therefore, typically use less bandwidth. However in order to discover routes, control packets are

flooded through the network which can consume a lot of bandwidth. The dynamic Source Routing Protocol (DSR) [9, 37], and the Ad hoc on Demand Distance Vector routing protocol (AODV) [67] are some examples of reactive routing protocols.

Hybrid Routing: As the name suggests, hybrid routing protocols use the local proactive routing and global reactive routing [54], in order to achieve a higher level of efficiency and scalability. However, they still require maintenance of the paths. Distribution efficiency of the information about the state of the network topology changes is limited, due to the border between local region and global region.

2.3.2   Position-Based Routing

Position-based routing uses one or a combination of two types of geometric based routing, which are greedy and face based routing [41, 45]. In geometric based routing, each network node is informed about itself, its neighbors' positions, the source of a message, and the position of its destination. Position-based routing algorithms forward packets in the direction of the destination using the positional information from the nodes [1, 40, 52]. Essentially, a node, willing to communicate, makes a decision of packet forwarding by considering the position of the node itself, the position of the destination, and the position of the nodes which are directly connected to it. We chose to study position-based routing in order to make wireless ad hoc networks more usable and efficient. Recent research in position-based routing usually addresses such routing algorithms in two-dimensional $2D$ networks [8, 48, 54, 73].

Greedy Based Routing: In greedy based routing, each node makes local optimum choice while selecting its next hop. One such type of a greedy based algorithm simply forwards a message to the neighbor that is geographically closest to the destination

[21]. In other words, each node only considers the closest node to the destination within its transmission range as its next hop while constructing a path. Geographic routing is routing which relies on the geographic location or position information for it to work. Main uses of this type of routing are in wireless networks where a source sends a message to the geographic location of the destination instead of using the network address.

Face Based Routing: To guarantee the delivery of the packets, position information can be used to extract a planar subgraph so that routing can be performed on the faces of this subgraph, known as Face routing or perimeter routing [11, 42]. The advantage of this approach is that the delivery of packets can always be guaranteed. The original Face routing algorithm was called Compass Routing *II* in [44]. When, face routing starts, it will traverse by using the right-hand rule [22], as shown in Figure 2.13.
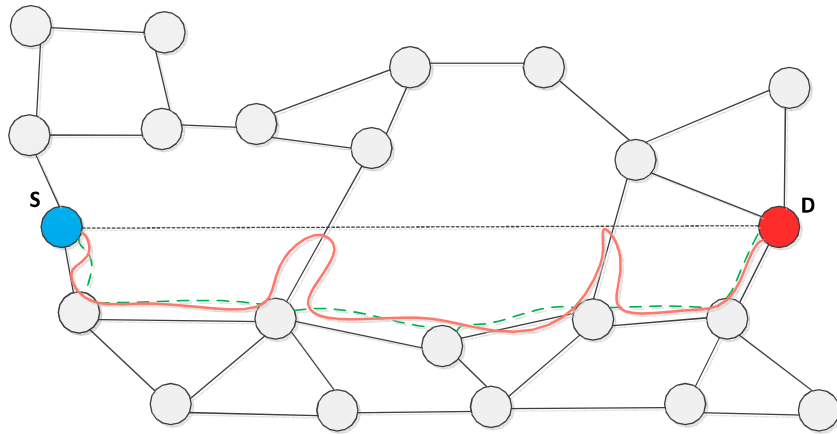
Figure 2.13: Face Based Routing

Hybrid Based Routing: Face based routing helps to obtain the alternate node(s) when greedy based routing fails to find closer node(s) leading to the destination. Face

algorithm uses the righthand rule in order to recover from a failure. Then the greedy algorithm can return, once a closer node is found, and continue discovering the path. This routing technique is called Greedy Face Greedy (GFG) [11]. There is a similar hybrid based routing algorithm that is called Greedy Perimeter Stateless Routing (GPSR) [42].

The difference between GFG and GPSR is that after crossing variant requires changing between the left and right hand rules each time a message decides to select the next face. On the other hand, it seems that before crossing variant requires strict application of one of these rules. An implementation of the before crossing variant in this form can be found in the GPSR face recovery part [22]. Position hybrid-based routing use the greedy based routing and face based routing to achieve a higher level of network efficiency and scalability.

2.3.3   Multi-path Route Discovery Protocol

The basic multi-path route discovery protocol for MANETs we describe in this section is originally presented by Yang *et al.* [90]. The protocol presented by Yang *et al.* is called the Greedy-based Backup Routing Protocol (GBR). To discover a route from a source node S to a destination node D, GPSR is used. The path discovered is termed the primary path. We also need to determine the backup paths that provide link protection for the links belonging to the primary path. Since these backup paths have to survive after the link expires, we need to know the lifetimes of both individual links and the paths as a whole. Following [90], we denote these lifetimes, respectively, as Link Expiration Time $LET(v_i, v_{i+1})$ for the link $v_i v_{i+1}$, and Path Expiration Time $PET(P)$ for a path P. $LET(v_{i-1}, v_i)$ is defined as in Equation 2.2.

Let $p = \tau_{i-1} \sin\theta_{i-1} - \tau_i \sin\theta_i$, $q = \tau_{i-1} \cos\theta_i - \tau_i \cos\theta_i$, $l = X_{i-1} - X_i$, $d = Y_{i-1} - Y_i$, where (X_i, Y_i) are the node coordinates, τ_{i-1} and τ_i are the node velocities, θ_{i-1} and θ_i are the direction angles, and R is the transmission range, as in Figure 2.14. Then

$$LET(v_{i-1}, v_i) = \frac{-(pl + qd) + \sqrt{(p^2 + q^2)R^2 - (pd - lq)^2}}{p^2 + q^2} \qquad (2.1)$$
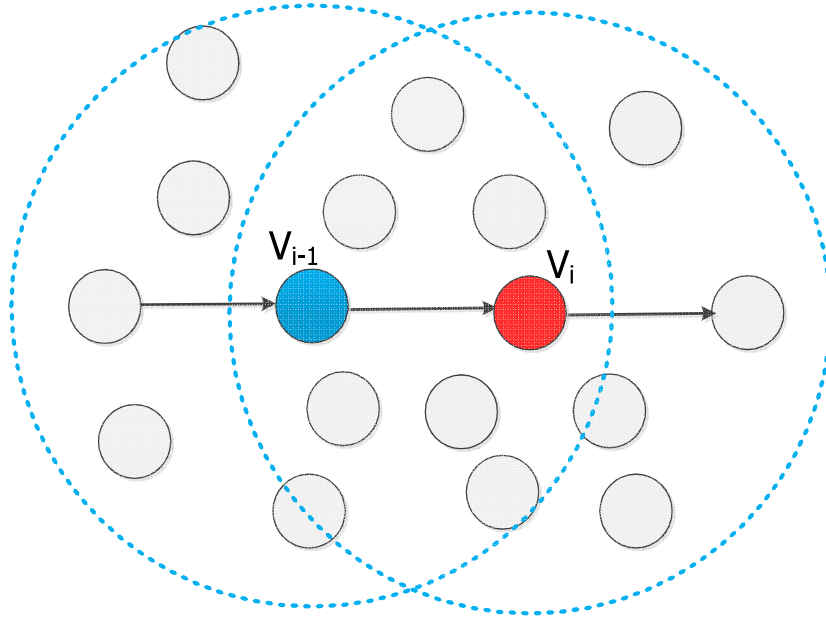
Figure 2.14: Primary path's link

All nodes maintain a neighbor table, which stores the ID and position of each neighbor. Additionally stored are, a primary path table, which stores primary path information for a destination node, a backup path table, which stores local-backup path information for the links in the primary path, a Route Request (RREQ) table, which stores information about all received RREQs, and a data cache as part of the protocol, at regular intervals, all nodes send HELLO messages containing their ID and position information to their neighbors.

During the primary route discovery, each node v_i in the discovered route, $P_p = (S = v_0, v_1, v_2, \ldots, v_n = D)$, unicasts a RREQ to D, and sends a message to its neighbors, starting from S. The RREQ contains the IDs and positions of v_i and D, the velocity of v_i, and $LET(v_{i-1}, v_i)$. Each node v in $N(v_i)$ adds the RREQ to its RREQ table, and each v except v_{i-1} and v_{i+1} begins a back-up path determination and then discards the RREQ. The neighbor v_{i+1} calculates $LET(v_i, v_{i+1})$ and adds the reverse path to its primary path table. If v_{i+1} is not the destination, it adds the $LET(v_i, v_{i+1})$ and its velocity and position information to the RREQ message, where upon it continues the primary route discovery by unicasting the RREQ. When the RREQ is received by the destination, it will send back the Route Reply Message (RREP) back through the reverse route in the RREQ. When a neighborhood node m_j, not on the primary path, saves the RREQ, it starts calculation for the backup path for a link using the calculation for PET given in Equation 2.2.

$$PET(v_i, m_j, v_{i+1}) = \min(LET(v_i, m_j), LET(m_j, v_{i+1})) \qquad (2.2)$$

where m_j is a neighboring node for both v_i and v_{i+1}. We denote this set of common neighboring nodes as $C(v_i, v_{i+1})$, as seen in Figure 2.15.

To determine the backup path, Yang *et al.* [90] use a contention-based scheme where a node m_j broadcasts a Completing Backup (CB) packet (with m_j's ID and *PET* value) after waiting a heuristic delay amount of time, $\beta/PET(v_i, m_j, v_{i+1}) + \delta$, where β and δ are predefined parameters. If m_j hears another CB packet during its delay time, it does not broadcast its own, such that the m_j with the largest *PET* completes the backup path, as illustrated in Figure 2.15.

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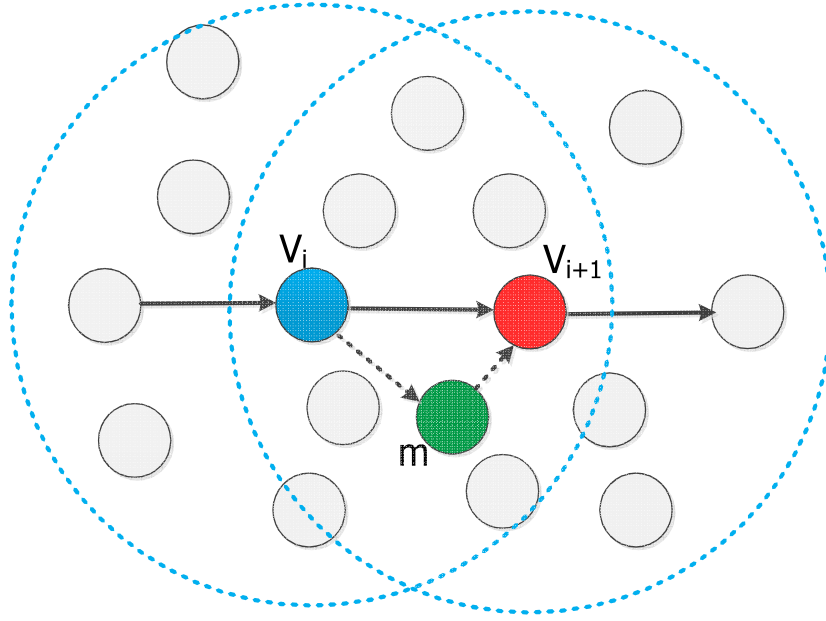
Figure 2.15: One hop backup link

2.3.4   Measures of Efficiency in Routing

Routing in a MANET depends on many factors including topology, selection type
of routers, location of request initiator, and specific underlying characteristics that
could serve as a heuristic in finding the path quickly and efficiently. One of the
major challenges in designing a routing protocol for MANETs is the availability of
various connections between a pair of wireless nodes interested in communicating
and deciding which one to use. In MANETs, the possible paths could be decided
by many factors [82], such as energy consumption, end-to-end data throughput and
delay, limited privacy and security, link capacity and expiration time, hop count,
error count, and path stability. However, in our research, we consider link and route
weights measured by one or more of the following four factors:

Hop Count: In MANETs, a hop count refers to the number of intermediate nodes

through which a message must pass, between a pair of wireless nodes interested in communicating.

Error Count: In MANETs, the error count is used to indicate the number of failures occurring while constructing the route between two wireless nodes interested in communicating. Link failures are caused by nodes becoming unreachable due to several reasons such as lack of energy, node failure, or unresponsive node.

Energy Consumption: In MANETs, exchanging messages comes at a cost of energy lost by the node during route discovery and actual communication. Such a stability-energy consumption is a tradeoff within the domain of stability routing protocols [55]. Energy sensor nodes in sensor networks have limited battery life; therefore, using energy efficient sensors is of critical importance in order to reduce power consumption [79].

Link Expiration Time: LET can be obtained by the principle that two neighbors in motion will be able to predict future disconnection time. However, LET depends on node transmission range and the node density in MANETs [16]. In MANETs, one of the major reasons for route breakages is node movements; therefore, many approaches have been developed to predict the quality of connections and the LET [70].

When nodes move, there is a high probability that a node participating in a path may become unreachable. Therefore, one approach is to maintain multiple paths to counter these situations. By keeping multiple paths we prolong the lifetime and reliability of the network connection. Therefore, our research also focuses on the problems of using this approach to improve communication stability.

2.3.5 Stable Routing and Energy Efficient Routing

For MANETs, the most recent work on routing that is stability-oriented (occasionally combined with energy efficiency), has been for reactive topology-based routing, specifically for DSR [2,84] and AODV [76,87]. Hamad *et al.* [27] presented a routing protocol called Line Stability and Energy Aware (LSEA), which was a modified version of AODV. For protocols based on multicasting, Zhang *et al.* [95] use multicast trees and a stability evaluation metric to propose a stability-based multicast routing protocol. Mohamamdzadeh *et al.* [57] used multicast trees to create an energy-aware, stable routing protocol.

For static ad hoc networks, energy-efficient routing has been extensively studied [12,20,48,72–74,83]. For position-based routing for static ad hoc networks, Seada *et al.* [72] used an analytical link loss model to strike a balance between shorter, high-quality links, with longer lossy links. Wang *et al.* [83] based their choice of neighbors for routing on a critical transmission radius, for energy efficiency, combined with dynamic transmission ranges, in order to define their Energy-Efficient protocol Localized Energy Aware Restricted Neighborhood Routing for Ad Hoc Networks (LEARN).

For position-based routing for mobile ad hoc networks, using the position information of the nodes, we can evaluate links in terms of Euclidean distance and LET between two neighborhood nodes participating in the path. To increase the stability of routing in MANETs, and to provide a reliable end-to-end route, one approach would be for each node to choose the most stable route from its options [53]. Alternatively, to improve the stability along the path in the presence of expiring links, another approach is to maintain multiple paths along the connection. In particular, with GBR, Yang *et al.* [90] achieved a reliable connection by protecting the links

between each pair of nodes participating in the primary path. This was achieved by maintaining local backup paths, in parallel with each link in the path, to be used when a particular link expires. In Sub-Section 3.1.1, we will introduce a variation of the GBR by using only neighbors during routing from a conservative neighborhood range. This method maintained path stability without the need to determine backup paths. Additionally, in the Sub-Section 3.1.2 we will introduce a variation of GBR that improved path stability in the presence of both node and link failure.

2.4 Quality of Service and Minimizing Interference

In [30], the research was focused on Quality of Service (QoS) metrics, Packet Delivery Ratio (PDR), and latency, in conjunction with Network Coding protocols in MANETs. To support diverse traffic over a MANET channel, the notion of QoS of a connection was beneficial in MANET nodes, where a particular node cannot transmit and receive at the same time. This corresponds to the situation where a node is transmitting to a closer neighbor node by using the exact sufficient power such that the farther neighbor nodes will not receive the interfering signal.

2.4.1 Quality of Service Management

Setting up a connection involves negotiation along a path from source to destination in order to reserve the required resources in order to fulfill the QoS needed in the MANETs communications. Due to the dynamic nature of MANETs channels, and the movement of the mobile nodes, the approved QoS level in one or more contracts

generally cannot be continued for a longer period of time. These situations are not errors, but are the modus operandi for mobile nodes in MANETs. Therefore, we handled these situations by applying different interval times in order to reestablish the paths when it was needed, and when QoS frequently occurred.

Developing QoS aware routing protocols for MANETs has been an active research area over the years. Most of the QoS aware routing schemes lack in addressing the feature of energy conservation [6]. Also, most researchers have argued that every QoS provisioning scheme for MANETs should be energy or power aware. Therefore, part of this thesis considered energy efficiency in MANETs, which is fundamentally influenced by the trade-off between energy consumption and achievable high QoS.

2.4.2 Minimizing Interference

During data transmission, a node may receive two or more identical packets, resulting in interference and redundancy. For a certain node in the network, only the neighbors that send or forward packets (i.e. the active neighbors) will interfere with it. So, other neighborhood nodes will not affect it. The interference index of a path is the sum of interference index values of the constituent links. Therefore, in a single channel Time Division Duplex (TDD) network in MANETs, any broadcast transmission follows the principle that there must be only one node which can transmit among the neighbors of a receiver. Also, each mobile device can not act as a sender and receiver at the same time.

2.5 Impact of Simulation Parameters Choices

One of the limiting factors in MANETs using traditional messages exchange is the inability to transmit and receive at the same time slot or frequency simultaneously. Therefore, a proper interval time is required to decrease the number of corrupted packets that is occurring while constructing a new route between two wireless nodes interested in communicating. Also, stable paths provide communication reliability, eliminate the void problem substantially, and provide more robust routes. To keep messages exchange limited nodes out of the route, also the decision to transmit should includes Quality of Service (QoS) parameters.

2.5.1 Impact of HELLO Messages Interval Duration

In wireless communication, the message overhead generated by route rediscovery in single path mechanisms are much less than the message overhead generated by route rediscovery in backup path mechanisms, in order to maintain overall communication [77]. During the route construction process, the neighborhood nodes exchange messages in the contention mode. Consequently, in MANETs, due to the communication being done wirelessly, this will lead to heavy control message overhead and communication interference [28].

In [92], which will be discussed in Sub-Section 3.1.1, we studied the idea of using a Conservative Neighborhood Range (CNR) such that there is no need to establish backup paths. We expected this would reduce the message overhead better than previously studied protocols, such as GBR, that maintain path stability by applying multi-paths or a backup path mechanism. Our study focused on developing protocols to decrease the number of messages exchanged during the process of establishing

a path. Also, we aimed to determine the better interval time that would improve communication stability in MANETs.

Kim and Eom [43] presented a novel reprogramming scheme that uses dynamic transmission power control, in order to deal with the energy consumption of each wireless sensor node and the network load distribution. Also, Wu and Dai [85] proposed the distributed solution based on reducing energy consumption and density of the virtual backbone network by using an adjustable transmission range combined with clustering. In our work, we use adjustable transmission power, which is dynamically dependent on the location of next hop node, so as to improve both link stability and energy efficiency for MANETs.

2.5.2 Effect of Varying Node Velocity

In MANETs, in order to achieve the greatest realism, mobility modeling must be taken into consideration. Mobility networks model mobile users, and how their location, transmission range, velocity and acceleration change over time that will provide important information in MANETs systems [18]. This group evaluated the adaptability of GBR, GBR-CNR, and LEARN to a dynamic topology. Hence, the maximum node velocity Vmax varied from 5 to 25 m/s to reflect the frequency of the topology changes. In this thesis, we consider the impact of node velocity in terms of network throughput.

2.6 Background Summary

The routing infrastructure of MANETs has important attributes which must be considered when constructing the path between source and destination. Also, in MANETs, efficient routing protocols have to deal with several performance criteria in order to improve the network efficiency. However, due to the dynamic nature of the network topology in MANETs, a major reason for a connection to break down is when an intermediate node or destination node becomes unreachable. The node can become unreachable due to several reasons such as running out of energy, node failure, moving out of transmission range, or when a node becomes unresponsive. As a matter of fact, different applications require maximization of different performance indicators, thus a protocol, aiming to be applicable to a wide range of situations, has to meet different performance requirements. The following chapter describes a multi-path routing protocol that aims to prolong the lifetime and reliability of the network connection in MANETs.

Chapter 3

Stability Oriented Connections and Survivability Assurance

Mobility networks are the most practical representations of real world MANETs [23], as they model mobile users, and how their location, velocity and acceleration change over time. Topology and route maintenance include a significant overhead message control in MANETs where the topology can quickly change. Therefore, in order to model such networks better, mobility should be taken into account.

Indeed, our research protocols deal with issues such as mobility, break-down of wireless links, and the disappearances and reappearances of mobile nodes. Our main idea resides in the fact that we should protect the primary route in such a way that the stability of the paths is improved and the control traffic and the packets forfeiture are reduced. As the main purpose of our work is to model a mobile MANETs environment, we also consider the problems of link expiration time and communication stability routing. In this chapter, we propose several algorithms to insure the stability

and survivability in MANETs.

3.1   Connection Survival Protocols

Since MANETs topology do not have a stable connections between active nodes, the conventional network functions such as the routing are difficult to realize. The router nodes and the links between them are not stable, which causes links between nodes to appear and disappear randomly; thus, resulting in an unstable MANET network. Therefore, typical routing algorithms cannot be used to manage the traffic successfully. Many special reactive, proactive and hybrid routing algorithms have been proposed to solve the data communication in multi-hop nodes [9, 10, 33, 36, 37, 67, 68]. In MANETs, finding more stable routes is an important goal in dynamic multi-hop nodes. In this section, we discuss the issues of link expiration time, node protection, message overhead, and the effects of HELLO interval duration and variable node velocity. We also propose several improved stable routing protocols that ameliorate the communication stability in MANETs.

3.1.1   Connection Survival Schemes Based on Link Protection

We extend the work in [90], and we propose to improve the efficiency (in terms of network throughput) and overall communication stability of the routing. We achieve this by using ideas such as: creating more general backup paths for link protection, rediscovering a path from the last reachable node instead of from the source node when a connection fails, and by using the conservative neighborhood range technique. In

the following, we give a brief overview on the used algorithms.

GBR: Greedy-based Backup Routing Protocol

The stable routing protocol GBR, as proposed by Yang *et al.* [90], uses the static transmission range R. GBR was introduced in detail in Section 2.3.3. The rest of the protocols will be compared primarily to this protocol, which represents the best known position-based stable routing for MANETs.

GBR-MBP: One Hop or Two Hop Backup Paths

For this variation of GBR, rather than employing the contention-based scheme used by Yang *et al.* [90] for GBR to determine the backup path, we propose to do the following in order to determine a backup path that will protect the primary path link from node v_i to v_{i+1} once $PET(v_i, m_j, v_{i+1})$ has been computed by all the common neighboring nodes m_j in $C(v_i, v_{i+1})$. First, node v_i will try to create a single hop backup path using the node m_1, selected from $C(v_i, v_{i+1})$, such that m_1 is closest to the receiver node v_{i+1} and satisfies the condition that $PET(v_i, m_1, v_{i+1})$ is greater than $LET(v_i, v_{i+1})$. Consequently, we will consider $v_i m_1 v_{i+1}$ as the backup path similar to Figure 2.15. If the neighboring node closest to v_{i+1} does not satisfy the condition, then the second closest node to v_{i+1} is tried, and so on, until a node in $C(v_i, v_{i+1})$ is found which satisfies the condition.

If there is no node in $C(v_i, v_{i+1})$ which satisfies the condition that $PET(v_i, m_1, v_{i+1}) > LET(v_i, v_{i+1})$, then the node v_i will pick the node m_1 in $C(v_i, v_{i+1})$ that is closest to v_{i+1} where $LET(v_i, m_1) > LET(v_i, v_{i+1})$. Node m_1 will then look at its subset of neighbors in $C(v_i, v_{i+1})$ and pick the node m_2 with the largest $PET(m_1, m_2, v_{i+1})$ which is greater than $LET(v_i, v_{i+1})$. Then, we will protect the link from node v_i to v_{i+1} using $v_i m_1 m_2 v_{i+1}$ as the backup path as illustrated in Figure
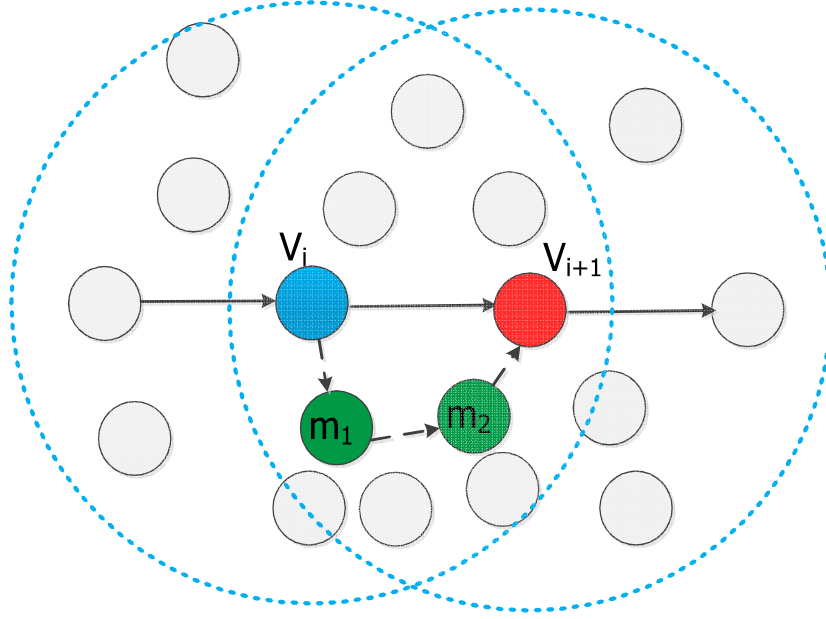
Figure 3.1: Two hops backup link

3.1.

If there is no such common neighborhood nodes that can protect the link from node v_i to v_{i+1} and satisfy the condition, then the link has no local-backup path. We will call this protocol GBR-MBP which is again based on GBR but uses path rediscovery in order to try to find multiple backup paths rather than a single one-hop backup path as done with GBR.

GBR-RPLRN: Rediscover a Path From Last Reachable Node

The main threat to the backup path approach to path stability in a MANET is when nodes move out of transmission range; thus, breaking the primary path link as well as a link in the backup path protecting the primary path link, as shown in Figure 3.2.
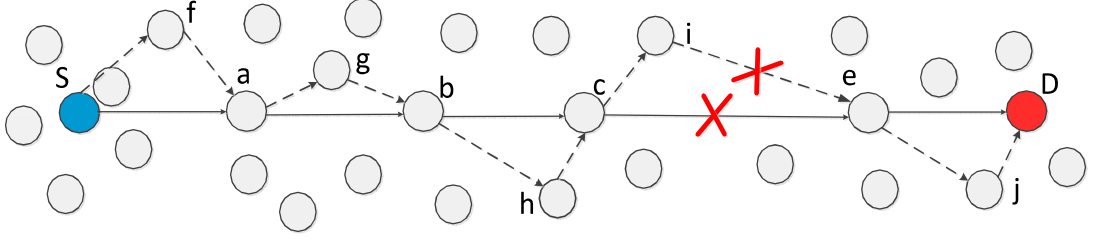
Figure 3.2: Broken both primary and backup paths

When both the primary path link and backup path links break, GBR [90] recalculates the primary path and backup paths from the source to destination. This can cause significant interruption, which is highly undesirable in critical systems. Also, the time spent on rediscovering a new path from the source to the destination may be unacceptably long for critical applications. However, when a path is completely broken between a wireless pair, it is most likely due to one of intermediate nodes that participated in the path becoming unreachable. However, the rest of the path is still connected (possibly through the use of the backup paths) from the source S to the failed node. The resulting delay and decrease in throughput can be mitigated by recalculating the path from the last reachable node in the primary path until the destination D in order to achieve a higher route throughput.

Moreover, by rediscovering the path from last reachable node will significantly reduce the chance of lost packets that are in the buffers of the intermediate nodes. This is so because by recalculating the path from source node, the path may not include most of the nodes which had participated on the previous path. We will call this protocol GBR-RPLRN, which is a variation of GBR that does path rediscovery from the last reachable node rather than the source node, as done by GBR.

GBR-CNR: Conservative Neighborhood Range

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Sun *et al.* [76] presented a link stability based routing protocol based on AODV, by utilizing the idea of a stable zone and a caution zone around nodes, so as to initiate re-routing when a routing neighbor enters the caution zone. In [92], we proposed a similar approach for position-based routing, which we review here. Since the nodes that are constantly moving with different speeds and directions, a node positioned within the transmission range of another neighboring node at a certain moment in time, might be out of range in at a later time. In GBR, to construct the primary path, each node considers the closest node to the destination within its transmission range as its next hop. Therefore, a node which at one moment is within the transmission range of another node might not be in the range after a certain time interval, that is, before the next HELLO beacon will broadcast. Thus, there is a high probability that the nodes, which are picked as the next hops, will no longer be within the transmission range during the interval and before the next HELLO beacon broadcast, which results in no transmissions during that time.

With the CNR we take into account the possibility of nodes that can go out of the range during the interval and subsequently avoid including them in the path as illustrated in Figure 3.3. That will lead to a significant reduction in the number of lost packets, as well as increasing the reliability of communication. The CNR depends on the interval between HELLO message broadcasts and its value is R_c, as illustrated in Equation 3.1.

$$R_c = R - (v_{max} * t) \tag{3.1}$$

where, R_c is the conservative neighborhood range, R is the actual transmission range,
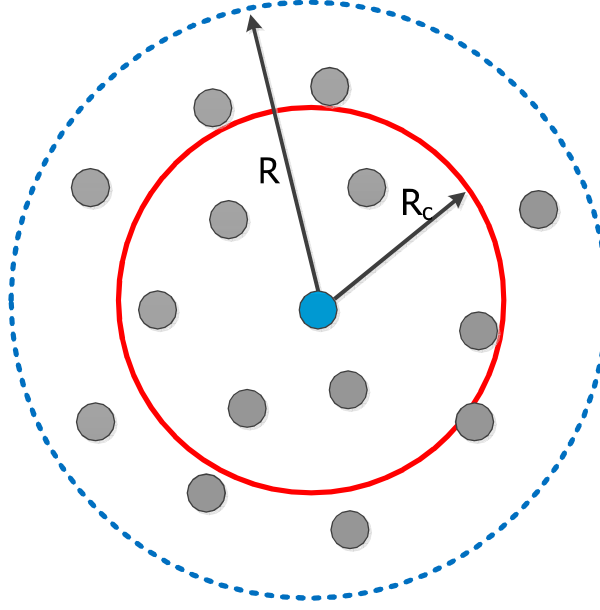
Figure 3.3: Considering Transmission Range R_c

v_{max} is the maximum node velocity, and t is the time interval between HELLO message broadcasts. If the next hop neighbor v_{i+1} is chosen within this conservative neighborhood range from v_i then v_{i+1}, then it will not go out of transmission range of v_i during this interval, and thus no links in the primary path will break before the next HELLO beacon will broadcast.

We call this protocol GBR-CNR which is GBR but with the next-hop neighbors restricted to be chosen from the CNR; thus, eliminating the need for backup paths for link protection. In addition, this removes the need to establish backup paths. We expect that GBR-CNR will reduce the message overhead better than previously studied protocols, such as GBR that maintain path stability by applying multi-paths or a backup path mechanism.

3.1.2   Connection Survival Scheme Based on Node Protection

Our protocol copes with mobility, break-down of wireless links, and also the disappearances and reappearances of nodes. By adapting previous work for link protection, we introduced a node protection scheme for the route survival in MANETs which can be considered effective for link protection. Furthering the work in [86,90], we propose to improve the efficiency (in terms of network throughput) and overall communication stability of the routing by protecting the intermediate nodes of the path instead of just the link between two neighboring nodes, this work is published in [91]. Most previous research have considered both route length and/or link lifetime to achieve a high route stability by protecting the links between each pair during the communication [24]. However, the problem with this approach is when a node in the primary path fails or becomes unresponsive it will cause both primary and backup paths to break, as seen in Figure 3.4. This will result in the recalculation of the entire path from the source to the destination, causing significant interruption, which is highly undesirable in critical systems. By contrast, with a backup path node protection ap-
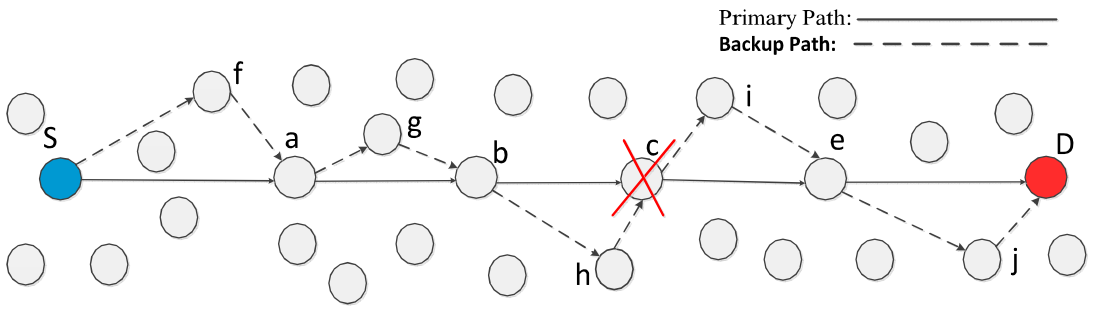
Figure 3.4: Node failure in link protection mechanism

proach, even if the node on the primary path is unreachable, we will be able to utilize the backup path. Since our research was focused on increasing the communication

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reliability and path stability of MANETs, we studied a backup path approach to node protection, as shown in Figure 3.5, in order to improve ad hoc networks efficiency. This, in turn, will lead to higher throughput. Here, each node in the primary path can be bypassed in the event of failure by a backup path independent of this node between the previous and following nodes on the primary path. Thus, protecting the nodes instead of, or in complement to, protecting the links, the result avoids the need to recalculate the complete path due to node failure during communication.
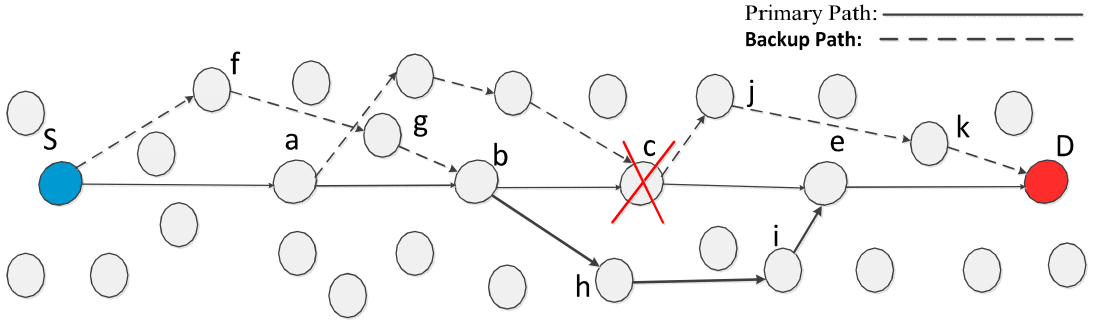
Figure 3.5: Node recovery in node protection mechanism

To determine the backup paths for node protection, we do the following. First, the primary path is determined as described above for GBR. During the transmission of the RREP back to S, when an intermediary node v_i, or S, receives this RREP, it computes a node protection backup path P_b for v_{i+1} from v_i to v_{i+2} using only links between nodes in P_b with LET greater than $PET(v_i, v_{i+1}, v_{i+2})$ while ignoring the node v_{i+1}.

We will consider that the node v_{i+1} has no node protection backup path if we cannot find a path P_b from v_i to v_{i+2} which satisfies the condition: $PET(P_b) > PET(v_i, v_{i+1}, v_{i+2})$. We will call this protocol GBR-NP, that is based on GBR but using node protection (GBR-NP), rather than link protection (as done with GBR).

Establishing both Primary and Backup Paths Algorithm

In order to create the primary path in both techniques link protection and node protection we follow the steps that illustrated in Algorithm 3.1. However, to protect the links between the nodes, which are participated in the primary paths we follow the steps that illustrated in Algorithm 3.2. To protect participated nodes between the source and the destination within the primary path in case of the node protection technique we follow the steps that illustrated in Algorithm 3.3.

Algorithm 3.1 Establish Primary Path Algorithms' Steps

Input: Parameters in Section 4.3.
Output: Primary Path.

  $N_c = N_s$
  while $||N_c - N_d|| > R$ **do**
    $d_{min} = ||N_c - N_d||$
    for N_i in $\{N_{c_{neighbors}}\}$ **do**
      if $||N_i - N_d|| < d_{min}$ **then**
        $d_{min} = ||N_i - N_d||$
        $N_c = N_i$
      end if
    end for
  end while

Algorithm 3.2 Backup Routing Algorithm Using Link Protection Technique

---

Input: Parameters in Section 4.3.
Output: Backup1 Path.

  for N_k in $\{PrimaryPath\} \setminus \{N_{source}, N_{destination}\}$ **do**
    $N_c = N_{k-1}$
    $N_d = N_{k+1}$
    while $||N_c - N_d|| > R$ **do**
      $d_{min} = ||N_c - N_d||$
      for N_i in $\{N_{c_{neighbors}}\} \setminus \{N_k\}$ **do**
        if $||N_i - N_d|| < d_{min}$ **then**
          $d_{min} = ||N_i - N_d||$
          $N_c = N_i$
        end if
      end for
    end while
  end for

Algorithm 3.3 Backup Routing Algorithm Using Node Protection Technique
___
Input: Parameters in Section 4.3.
Output: Backup2 Path.

    for N_k in $\{PrimaryPath\} \setminus \{N_{source}, N_{destination}\}$ **do**
        $N_c = N_{k-1}$
        $N_d = N_k$
        $d_{min} = ||N_c - N_d||$
        for N_i in $\{N_{c_{neighbors}}\} \setminus \{N_k\}$ **do**
            if $||N_i - N_d|| < d_{min}$ **then**
                $d_{min} = ||N_i - N_d||$
                $N_c = N_i$
            end if
        end for
    end for
___

3.1.3   Impact of HELLO Messages Interval Duration

The links in an MANET network are normally kept alive by the exchange of Hello messages between neighboring nodes. These Hello messages are prone to collisions with traffic from hidden active nodes [19]. Also, mobility in MANETs will cause topology changes that necessitate the exchange of HELLO beacon messages periodically between a node and its one-hop neighbors. This keeps the node aware of its current neighbors as well as inform the node if the next hop node of a path is still within its transmission range. If not, the node will send back a message to inform the source of the connection to start a new route discovery process. Before resending a HELLO message, each node in a MANET is expected to wait for a pre-specified interval of time, generally termed as the back off interval [78]. If the back off interval time expires and the node did not receive a HELLO message from the next hop node, then the link is considered to be broken [63].

As part of our experimental exploration of our proposed protocols in Sub-Section 3.2.3, we will study the effect of the choice of HELLO interval duration. These

experiments were performed on the overall number of messages exchanged during establishing a path, and during message routing in order to determine the interval time that will improve communication stability in MANETs.

3.2 Experiments and Results

The simulation environment for this work is modeled using network parameters [66,90] that are a network area of size $2200m \times 2200m$; a varying number of nodes from $200, 250, 300, \ldots, 600$; and a fixed transmission range of $R = 250m$. The direction in which a node can move is given randomly at the beginning of the simulation. However, when a node reaches the boundary, following the mobility model Random Walk with Wrapping and Reflection, we reflect the node traveling at the angle γ using the formula $\gamma + \frac{\pi}{2} + c$ [66]. For each different node density, we randomly distributed 40 connected graphs that were used as a starting network topology for each run of the simulation for all algorithms. There were 20 pairs of Constant Bit Rate (CBR) data flows in the network layer, and non-identical source and destination flows were randomly selected such that each flow does not change its source and destination throughout the simulations. For the studied algorithms, we constructed the primary path (and the backup path, if it is not a CNR based protocol), as described in Sub-Section 2.3.3, from the sources to the destinations. Each simulation ran for 600 seconds with enough packets assigned for the simulation time, and the presented results are averaged over the 40 graphs. The error bars in each figure represent 95% confidence intervals. Unless indicated otherwise, the velocity was set to be the same for all nodes at $V_{min} = V_{max} = 10m/s$, and the interval between HELLO beacon

broadcasts was set to 2 seconds.

In the following, we study several protocols properties including link and node protection properties, the effect of varying the interval between HELLO broadcasts, and the effect of varying the maximum speed of the nodes.

3.2.1   Node Protection vs. Link Protection: Results and Discussion

In order to compare our proposed approach, namely the node protection technique, with the link protection technique, we propose to evaluate their performance when the stability of paths is weakened. Thus, we propose to randomly select two paths from the set of established paths, and then we randomly switch off a node from the primary paths of the selected paths, during every time interval. In the link protection technique, when a node that is participating in the primary path is switched off, the primary path is broken and the next hop node becomes unreachable. In this case, the backup path becomes broken. Before dying, each node will send a HELLO beacon message to inform its neighbors. Then, a message will be sent back to the source which will recalculate the path again to the destination. On the other hand, when the same scenario happens using the node protection technique, the primary path is broken as well, but still, the last reachable node locally uses the backup path to cover the unreachable node, and the recalculation of the whole path is avoided. In addition, if a link between two nodes in the primary path is broken due to nodes mobility, the node protection technique still can restore the path locally, as shown in Figure 3.5.

We propose to compare our GBR-NP algorithm that assures nodes protection with the original GBR algorithm that establishes links protection. The evaluation of

the two algorithms is established using performance metrics, namely the total number of packets successfully delivered over the simulation and the Packet Delivery Ratio (PDR) such that:

$$PDR = \frac{P_d}{P_s} \qquad (3.2)$$

where P_d is the total number of delivered packets during the simulation, and P_s is the total number of packets sent during the simulation.
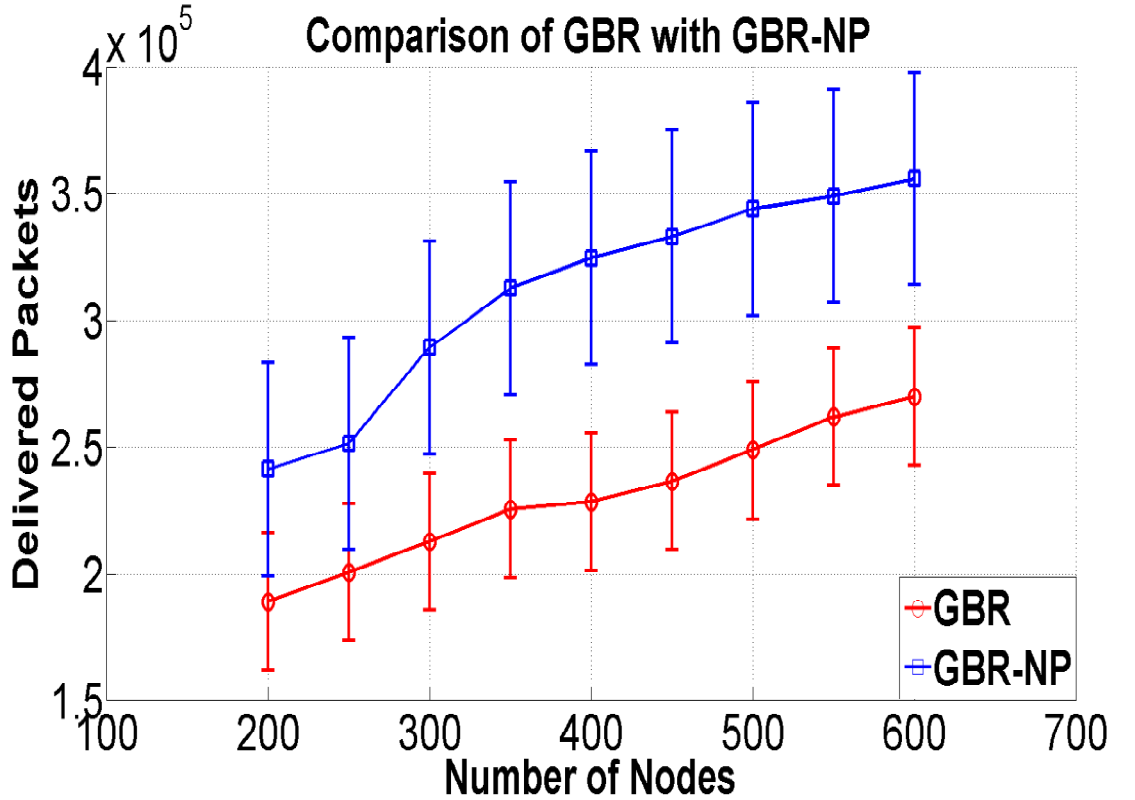
Figure 3.6: Number of Delivered Packets

Figures 3.6 and 3.7 show the performance of the node protection protocol GBR-NP when compared to link protection protocol GBR. GBR-NP was able to successfully deliver a higher number of packets, as shown in Figure 3.6, across a range of node densities. This shows that the node protection strategy performs better than the link
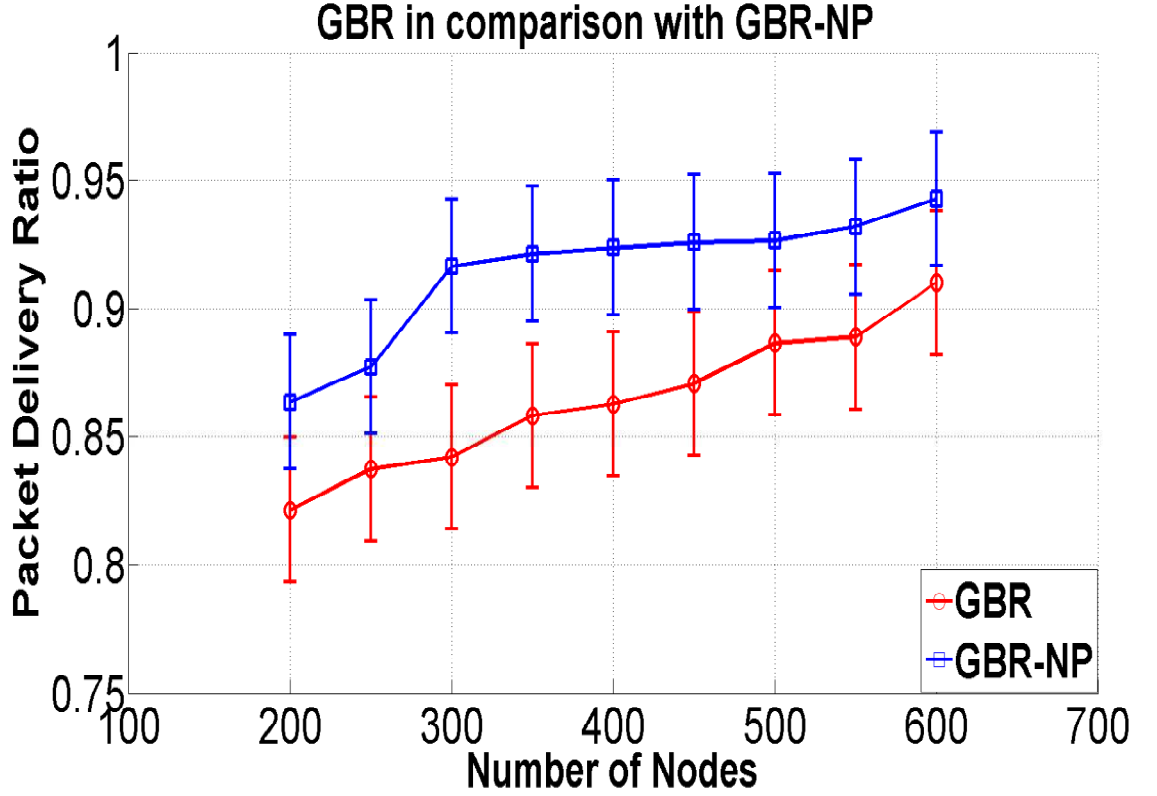
Figure 3.7: Packet Delivery Ratio

protection strategy in terms of bandwidth efficiency. When we consider the PDR, Figure 3.7 shows that the GBR-NP provides a considerably better quality of service than the GBR, under the same network environments, as it achieves a better PDR. We notice that the more the nodes density increases, the better the performance and stability of the MANETs using GBR-NP are.

3.2.2 Improved Link Protection Techniques: Results and Discussion

This Sub-Section presents the simulation results for the protocols GBR-MBP, GBR-RPLRN, and GBR-CNR, introduced in Sub-Section 3.1.1, in comparison with the

original GBR. We also analyze their performances using the total number of packet delivery, as shown in Figure 3.8, and the PDR metric, as shown in Figure 3.9.
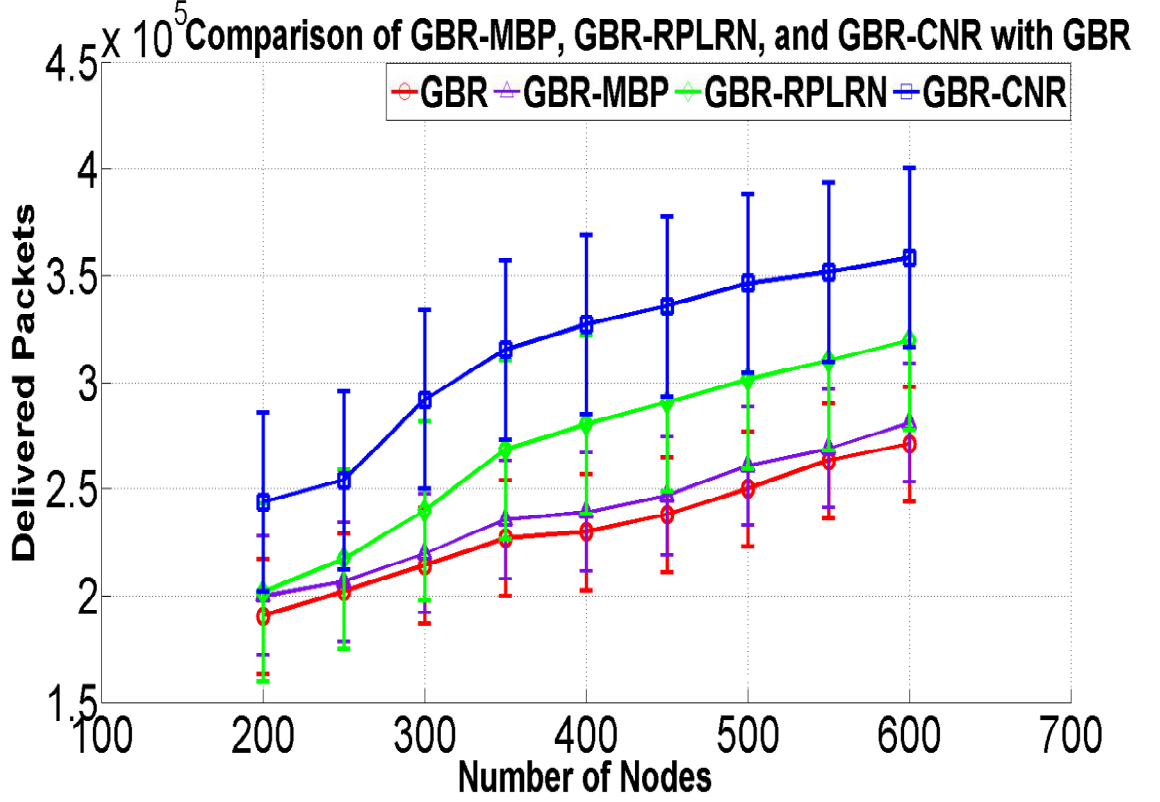
Figure 3.8: Delivered Packets

Both Figures show that the proposed protocols GBR-MBP, GBR-RPLRN, and GBR-CNR outperform the GBR, in terms of the considered metrics. However, overall, GBR-CNR gave the best result among all the considered algorithms. These results are explained by the fact that the GBR-CNR restricts the neighbor selection only to the nodes that will remain in the transmission range during the interval. Such restricted selection outperforms the other algorithms that consider multiple hop backup paths or limiting the recalculation of the communication path from the broken link back to the source node.
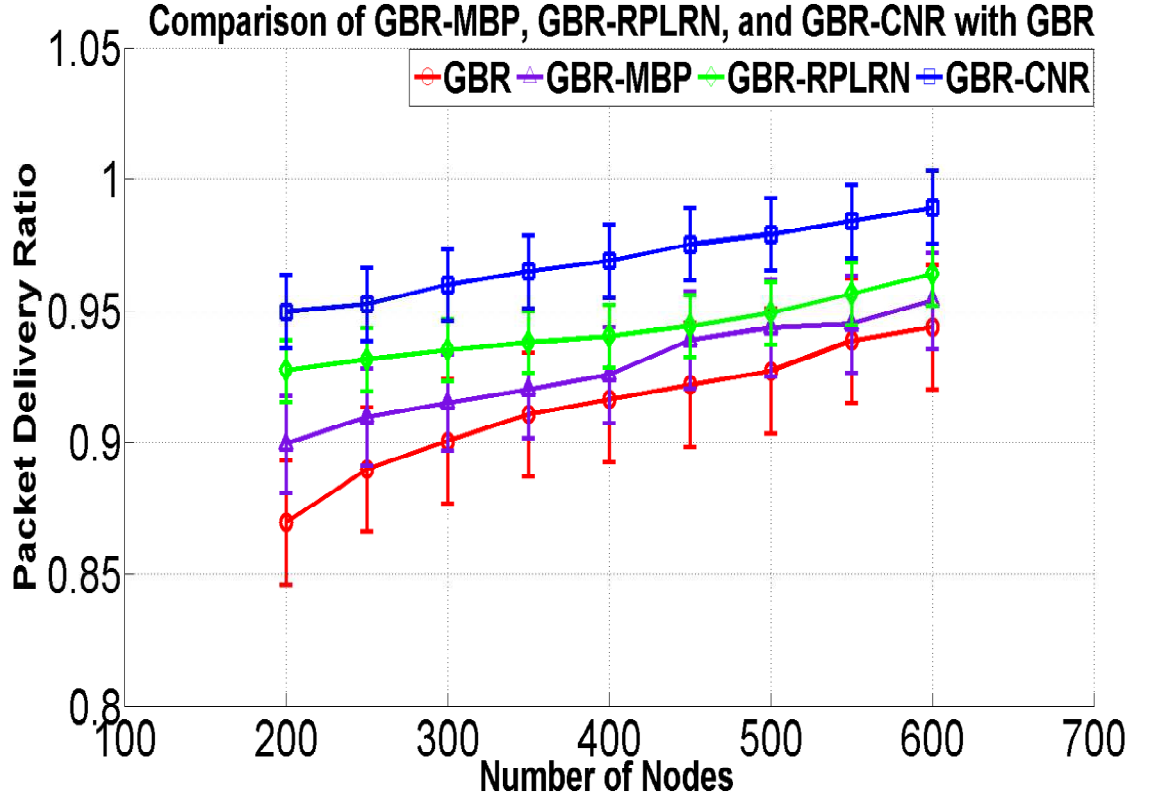
Figure 3.9: Packet Delivery Ratio

3.2.3 Effect of HELLO Interval Duration: Results and Discussion

Since MANET does not have a single centralized system to make decisions (e.g. join a network, network routing, shortest path, scheduling, queuing, priority, and fairness) for the wireless nodes, the number of message exchanges among the wireless nodes to make such decisions is larger than for a centralized system. Reducing the high number of message exchanges in the decentralized system, without sacrificing performance, is one of the important challenges in deploying these systems. Also, exchanging messages in wireless system comes at a cost of energy lost by the node during route discovery and actual communication.

In this part of the thesis, we were particularly concerned with position-based routing in MANETs; where as part of the MANET protocols maintain nodes' lists of current neighbors. At regular intervals, all nodes send HELLO beacon messages containing their ID and current position information to their neighbors. Since the choice of the duration of the HELLO message interval can not be arbitrary, the interval size is one of the significant issues that needs be investigated further to make communication reliable in MANETs. Therefore, we will study the effect of varying the length of the time interval on three contrasting types of greedy-based stable routing protocols for MANETs - two using backup paths, GBR/LBR, and the other using a conservative neighborhood range, GBR-CNR, in terms of the number of control messages exchanged and throughput for the protocols. Also, as previously mentioned, completely breaking a connection during the interval resulted in a loss of time because the source node would have had to be informed. Consequently, it would have to initiate the route discovery process.

While constructing the new route, intermediate nodes in the old path will lose the packets currently in transit. Therefore, building a new path leads to an increased number of overhead messages. This overhead is significant in GBR, with large HELLO interval durations, since GBR will pick the next hop node that is closest to the destination node; so, increasing its probability of becoming unreachable during the interval. Conversely in GBR-CNR, the next-hop was selected taking into account the possibility of nodes that can go out of range during the interval and would subsequently avoid including these exiting nodes in the path. Although GBR-CNR is better in this respect, because it only considers a subset of neighboring nodes during route discovery, it is more likely to fail to construct a path when the number of nodes

is small.

However, LBR chooses the next node during route discovery on the neighboring node with respect to a critical transmission radius r_0, which is the distance d, and where $d/E(d)$ is maximum. In comparison, in GBR-CNR, the next-hop is selected while avoiding nodes. Although GBR-CNR is better in this respect, due to only considering a subset of neighboring nodes during route discovery, it will more likely fail to construct a path when the number of nodes is small.

This section shows the effect of changing the duration of the HELLO interval on the performance of the three schemes, GBR in comparison with LBR and GBR-CNR. The topology and movement of mobile nodes are the key factors in the performance of the routing protocols. Once the nodes are initially placed, the mobility model dictates how each mobile node will move. Subsequently, the mobility of nodes causes a randomness of topology due to the fact that a node can appear and disappear from the transmission range of the other nodes without following any specific pattern, which causes links between nodes to appear and disappear.

The simulation results of GBR, LBR and GBR-CNR are illustrated in Figures 3.10 − 3.13. We observe that the lower number of nodes have higher number of messages exchanges. This is because of more breaking of paths (primary and backup) due to lower neighborhood density. We have simulated different interval times (i.e, 1, 2, 3, 4 seconds) and the result shows that lower interval time has smaller number of message exchanges. This concludes that number of message exchanges increasing due to the fact that the establishment of stable paths becomes harder when the number of nodes decreases and the interval size increases.
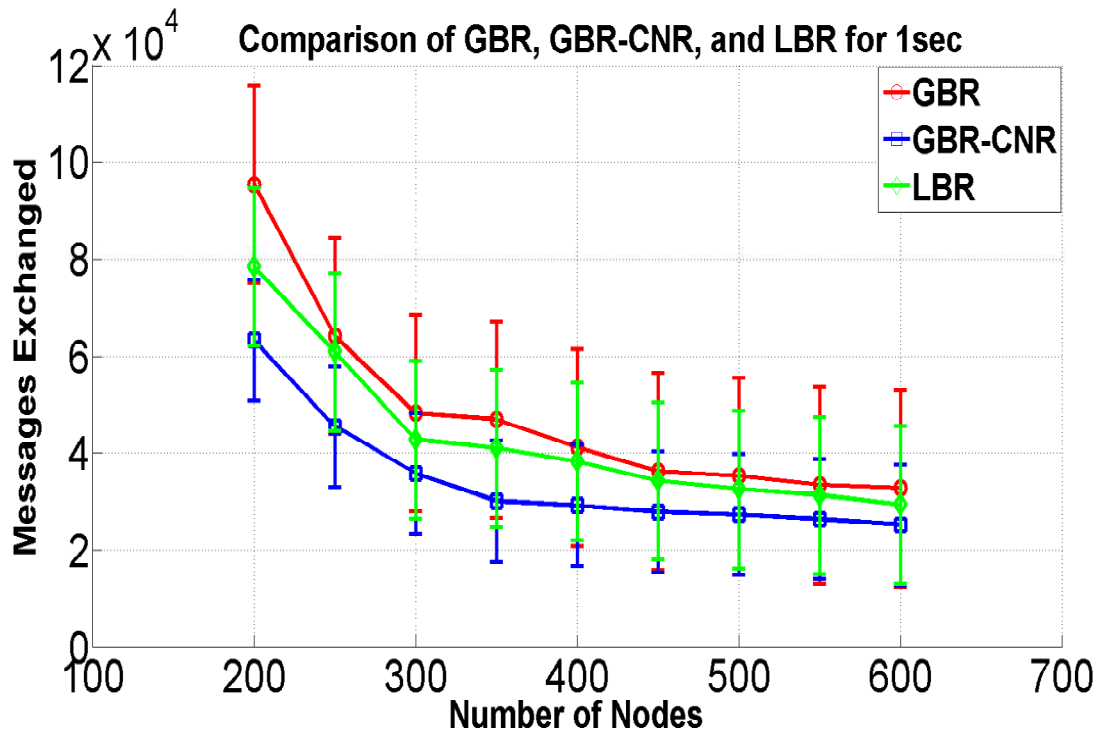
Figure 3.10: Message Exchange vs. Number of Nodes in One seconds
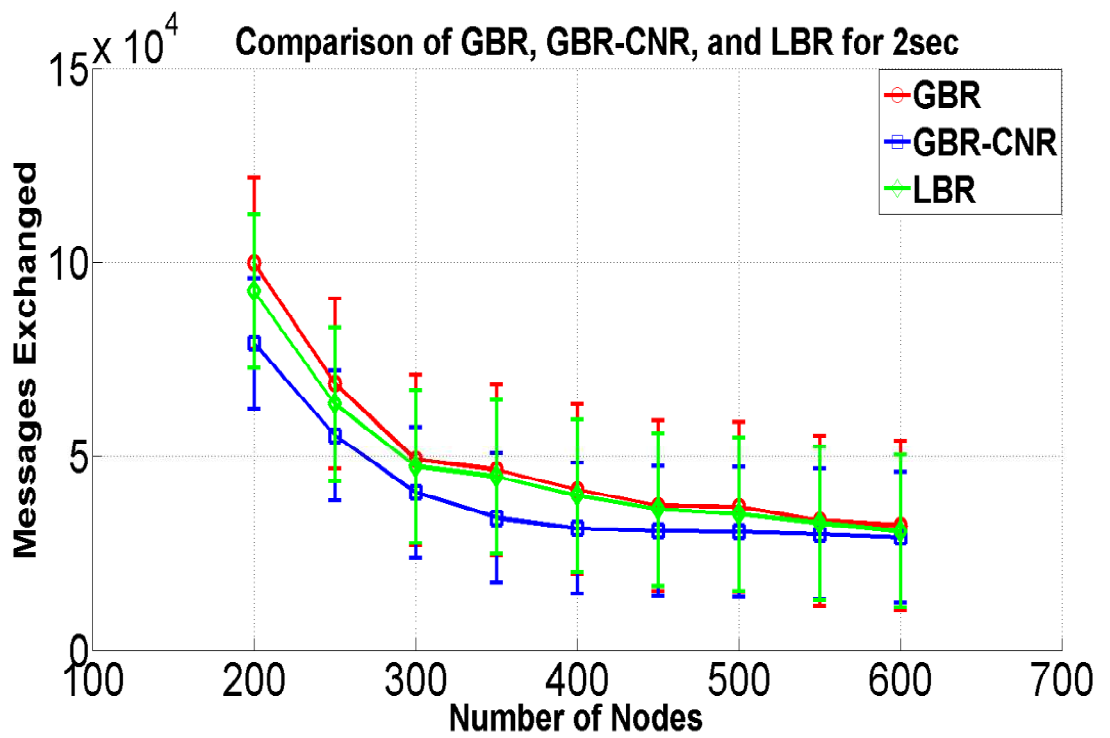
Figure 3.11: Message Exchange vs. Number of Nodes in Two seconds

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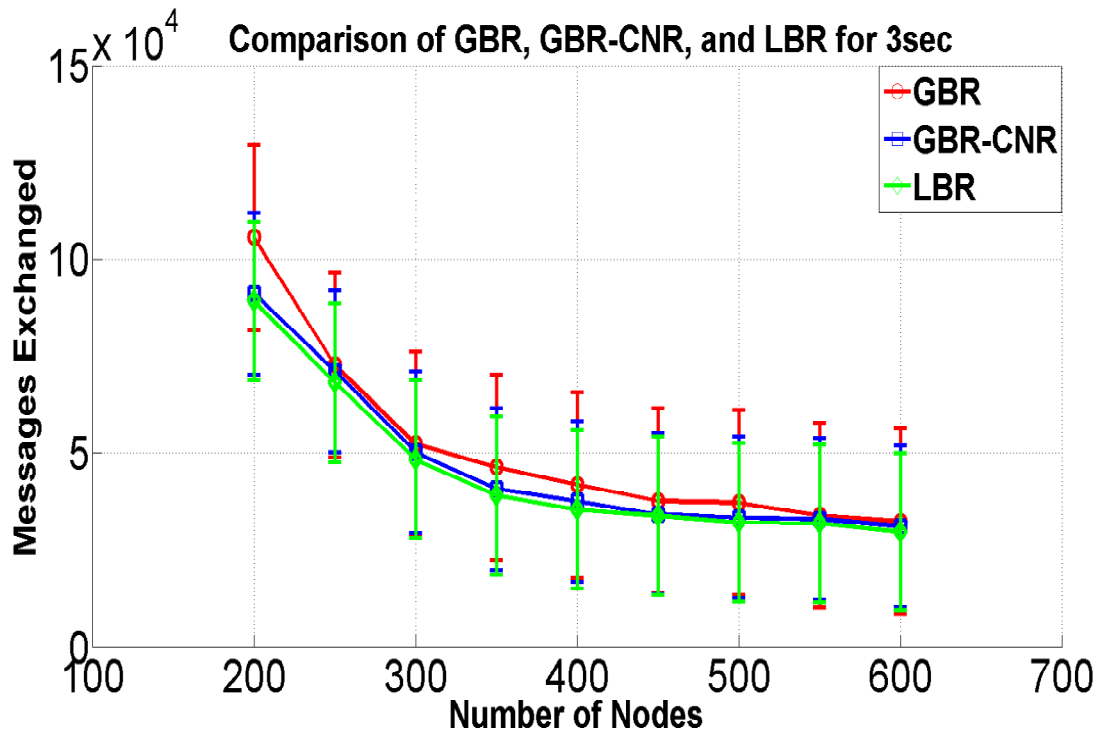
Figure 3.12: Message Exchange vs. Number of Nodes in Three seconds
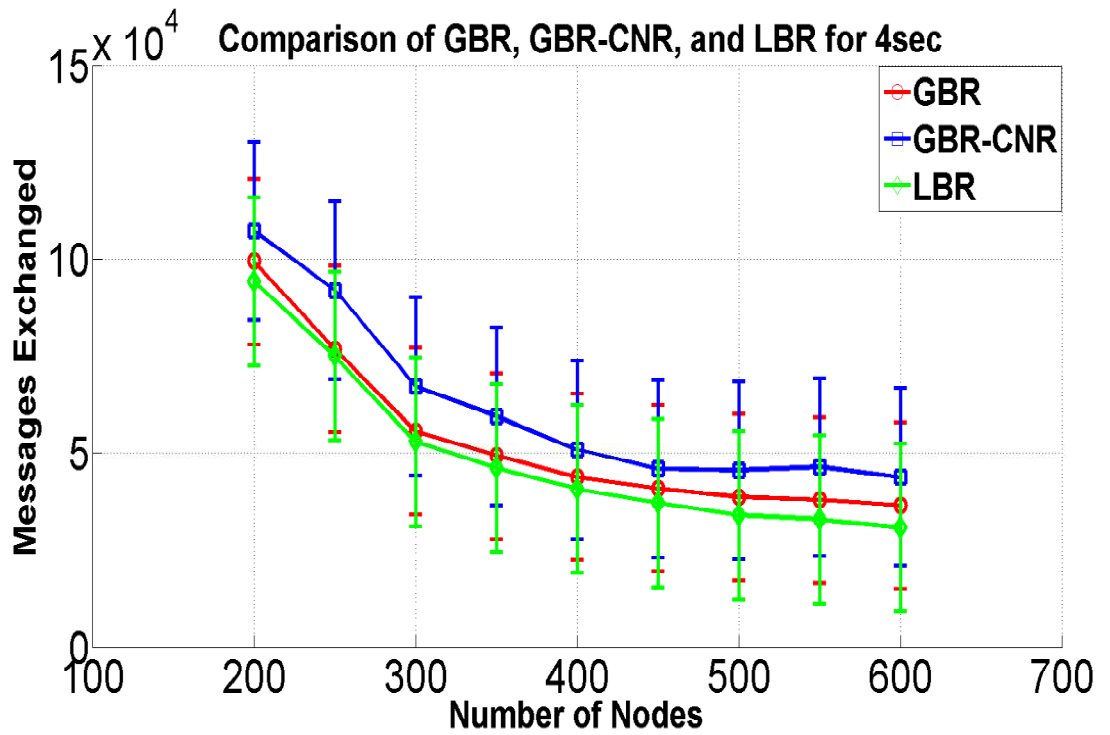
Figure 3.13: Message Exchange vs. Number of Nodes in Four seconds

We also report the results on the total delivered packets and packet delivered ratio when we use different time intervals. Following results show the total delivered packets and packet delivered ratio for GBR, LBR, and GBR-CNR, using different ranges of Hello Messages Interval and different number of distributed nodes in the experimental area.

From Figures 3.14 − 3.16, we can observe that when the same number of nodes and using different ranges of Hello Messages Interval, the total delivered packets will decrease when the interval will increase. This is because when the Hello Messages Interval time will increase that result paths will be broken, then the source of the connection will start a new route discovery process several times per interval. Moreover, a new connection will significantly increase the chance of lost packets that are in the buffers of the intermediate nodes. This concludes that the performance of GBR will decrease as number of nodes will decrease as well as the Hello Messages Interval time will increase.

Figures 3.17 − 3.19 show the PDR versus the number of nodes in different Hello Messages Interval time for GBR, GBR-CNR, and LBR. We find that in the same number of nodes and using different ranges of Hello Messages Interval the number of messages will sent increased when the Hello Messages Interval time decrease. Also, we notice that when the number of node will increase the algorithms will provide a considerably better quality of service in terms of path stability.
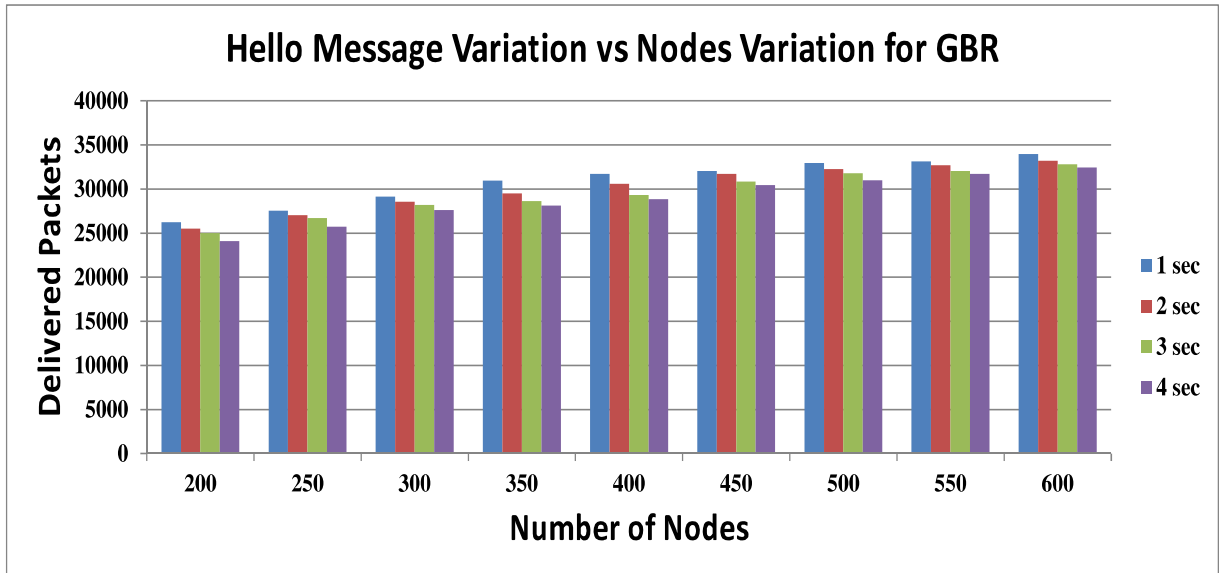
Figure 3.14: GBR: Total Delivered Packets
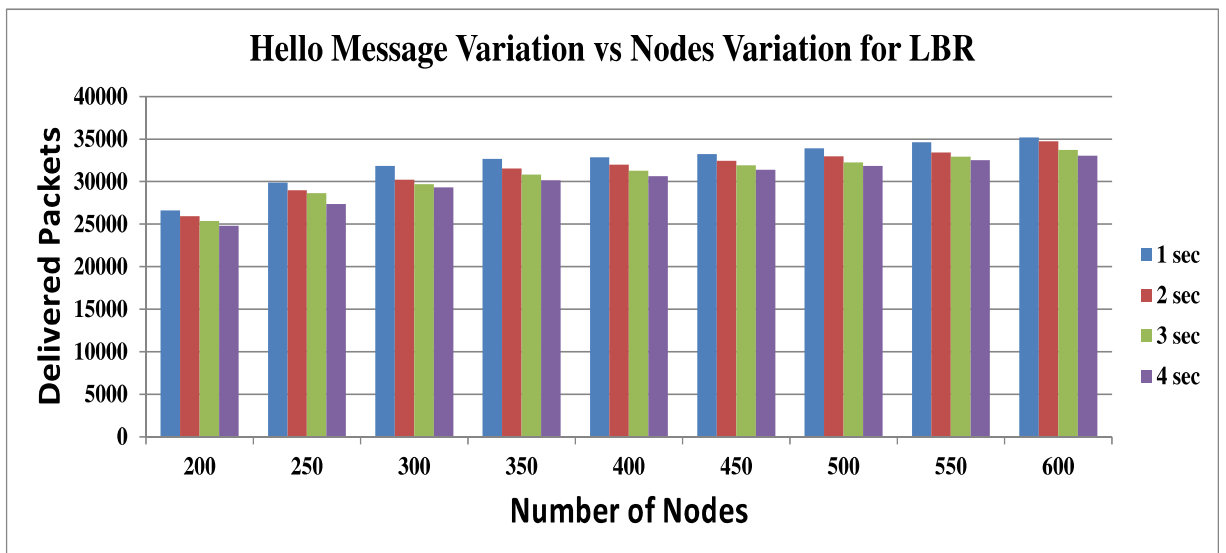
Figure 3.15: LBR: Total Delivered Packets
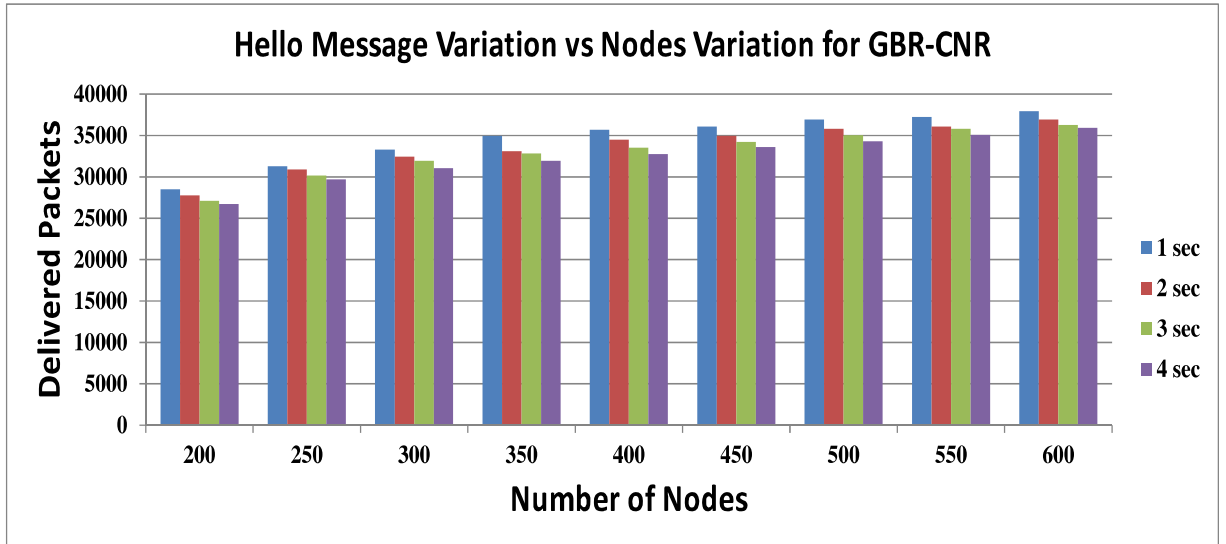
Figure 3.16: GBR-CNR: Total Delivered Packets
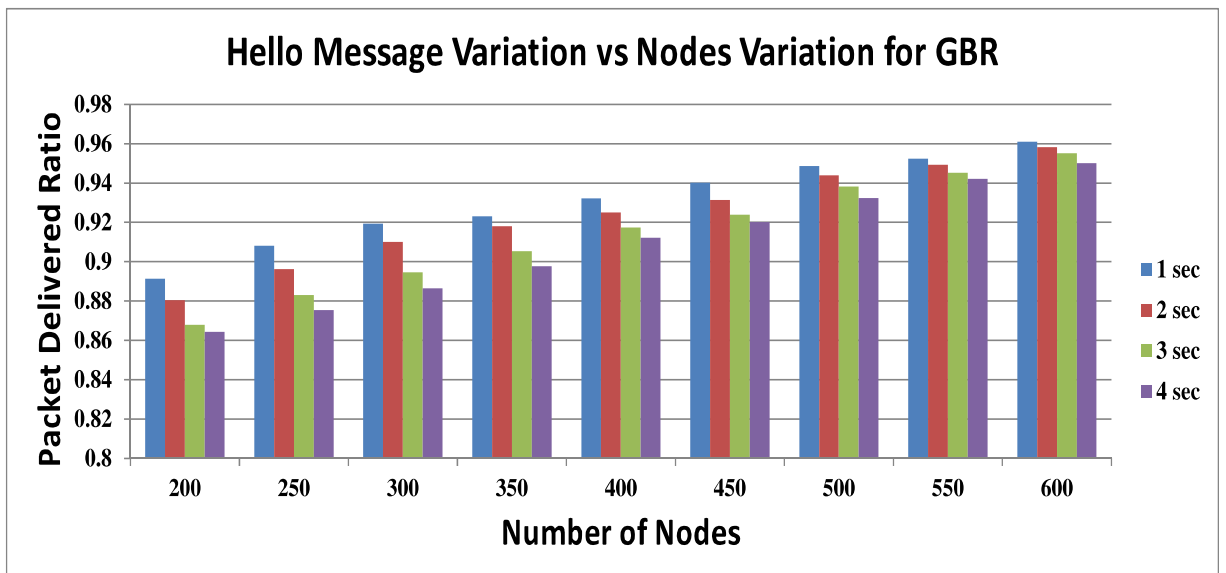
Figure 3.17: GBR: Packet Delivered Ratio
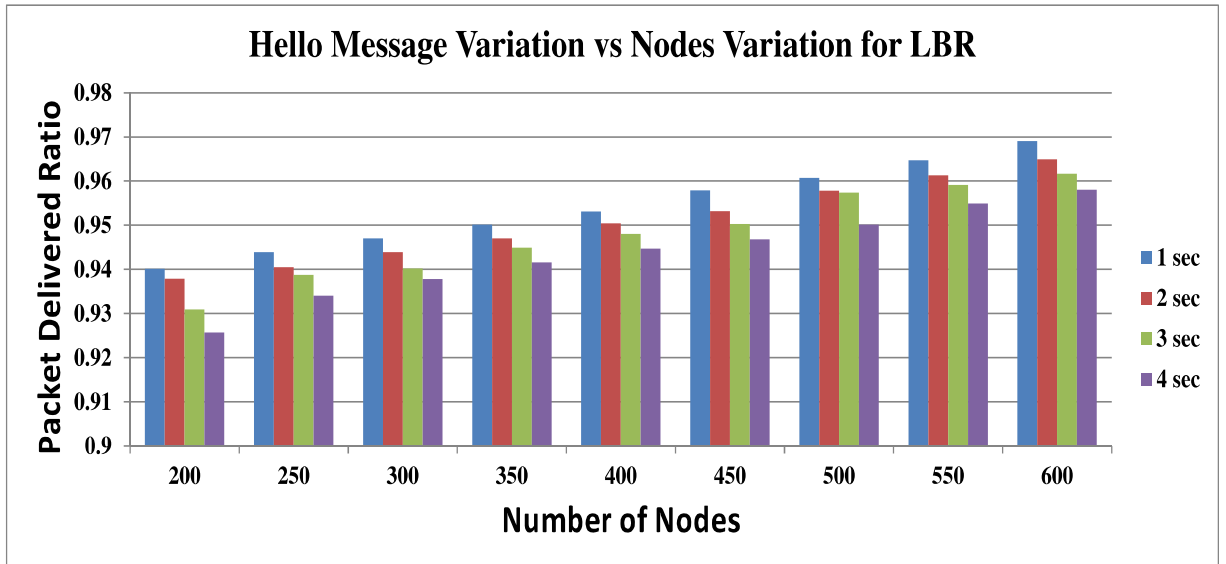
Figure 3.18: LBR: Packet Delivered Ratio
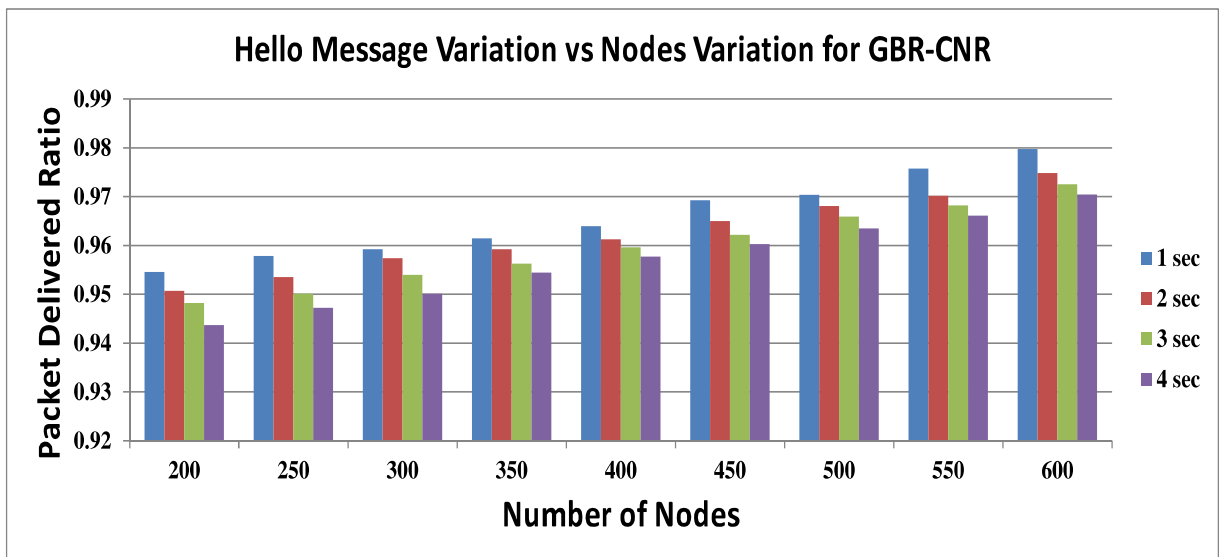
Figure 3.19: GBR-CNR: Packet Delivered Ratio

3.2.4 Effect of Varying Node Velocity: Results and Discussion

In MANETs, in order to achieve the greatest realism, mobility modeling must take into consideration. Mobile network models aim to represent the actions of mobile users, and how their location, transmission range, velocity and acceleration change over time. This group evaluated the adaptability of GBR, GBR-CNR, and LBR to dynamic topology; hence, the maximum node velocity V_{max} varied from 5 to 25 m/s to reflect the frequency of topology changes.

The purpose of this experiment is to study the effect of velocity on the stability of each link. We propose to conduct our experiment by keeping the number of nodes fixed while increasing the possible maximum velocity of each node by 5m/s, starting from 5m/s, until we reach 25m/s. Note that we kept a minimum velocity of 1m/s, which means that all the nodes were moving at different speeds. It is also noteworthy to mention that the velocities of the nodes were an important factor that affected the quality of transmission within an ad hoc network, according to the used algorithm. We compare our algorithm CBR-CNR, with the GBR and LBR, that we introduced in the previous sections.

We report on the simulation results for the protocols GBR, GBR-CNR, and LBR in terms of total packets delivery in Figure 3.20, and the PDR in Figure 3.21. Both Figures show that the performance of all proposed protocols decreases when the velocities of the nodes increase, due to broken paths.
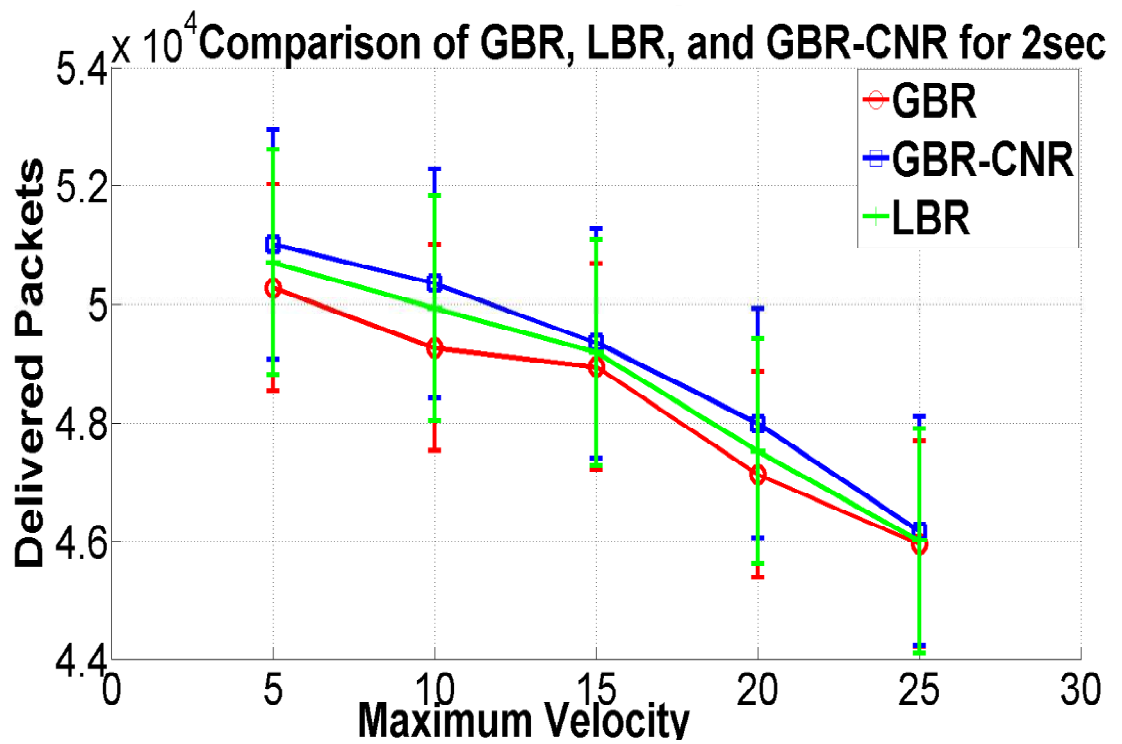
Figure 3.20: Total Packet Delivered
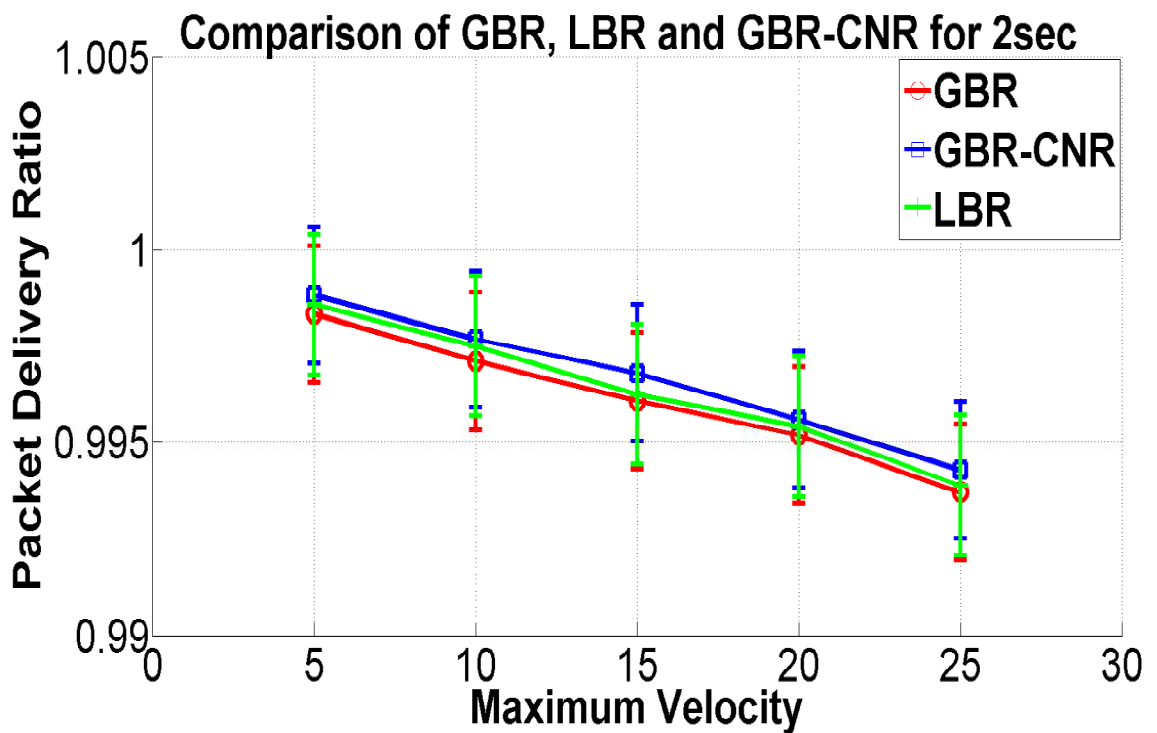
Figure 3.21: Packet Delivered Ration

3.2.5 Effect of varying the HELLO Interval Duration and the Node Velocity: Results and Discussion

This section shows the effect of changing both the node velocity and the duration of a HELLO interval beacon message, on the performance of the three schemes, GBR in comparison with GBR-CNR and LBR. As we mentioned previously, the mobility networks models are the most practical representations of the real world MANETs where the communication capability is completely dependent on the activity state of the nodes, and how their location, velocity and acceleration change over time. Also, the topology and movement of mobile nodes are key factors for the performance of the routing protocols. Once the nodes are initially placed, the mobility model dictates how each mobile node will move. Subsequently, the mobility of nodes causes a changes of topology due to the fact that a node can appear and disappear from the transmission range of other nodes without following any specific pattern which causes links between nodes to appear and disappear. Therefore, we study the effect of HELLO message duration with varying node velocity in order to evaluate the performance of the algorithms. Figures 3.24 − 3.25 present simulation results for GBR, LBR and GBR-CNR and show how well they performed in terms of total delivered packets.
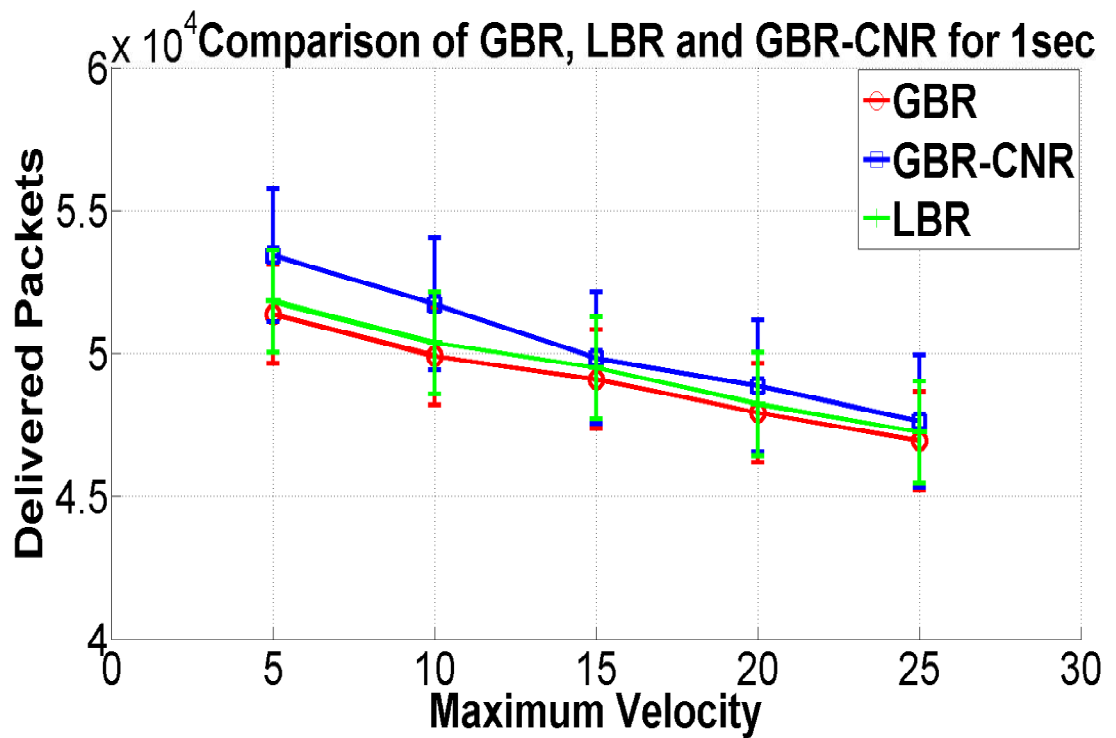
Figure 3.22: Delivered Packets in One second Interval
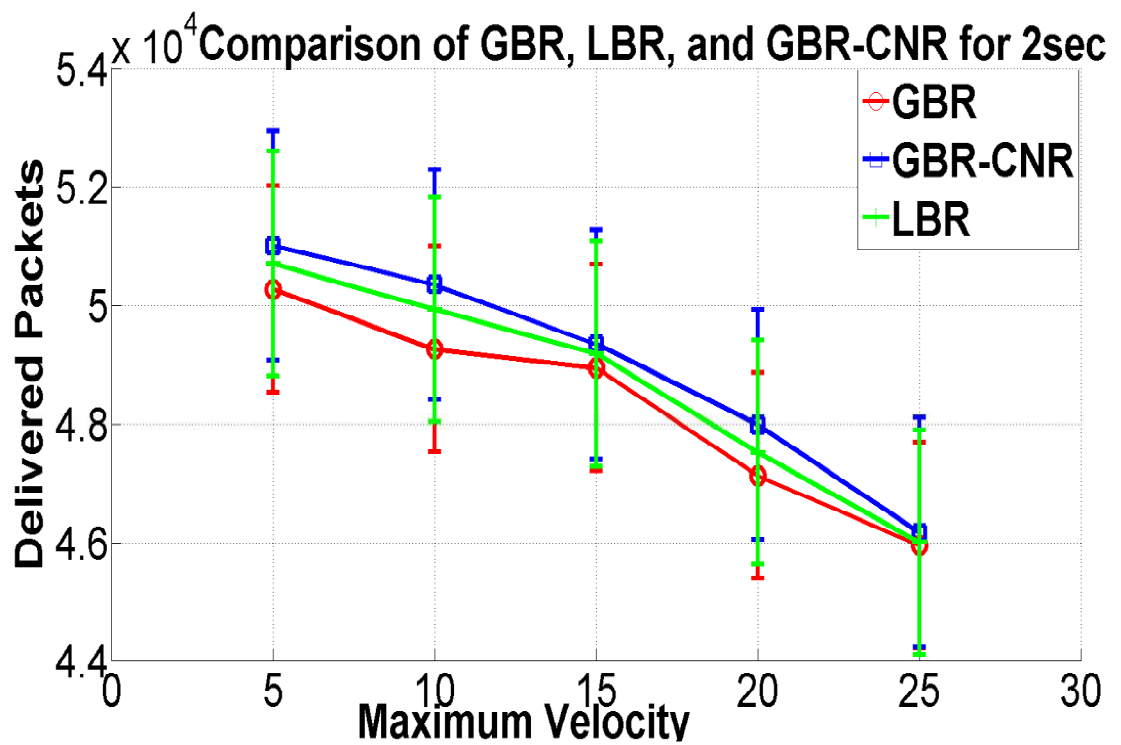
Figure 3.23: Delivered Packets in Two seconds Interval

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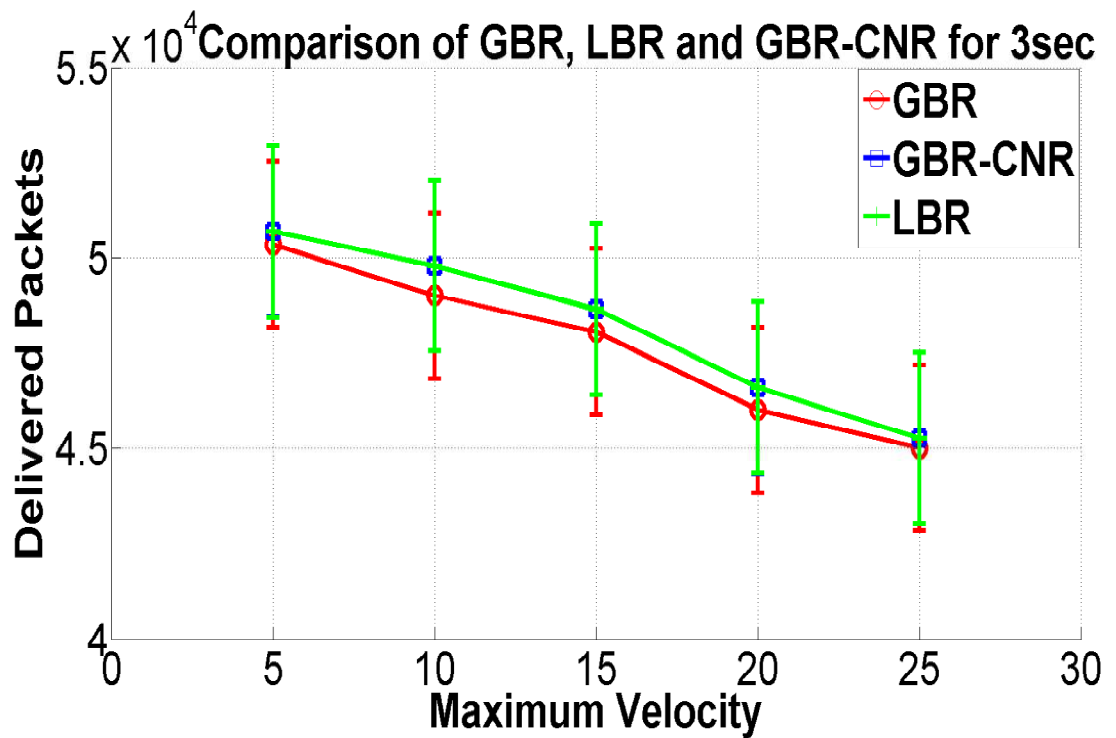
Figure 3.24: Delivered Packets in Three seconds Interval
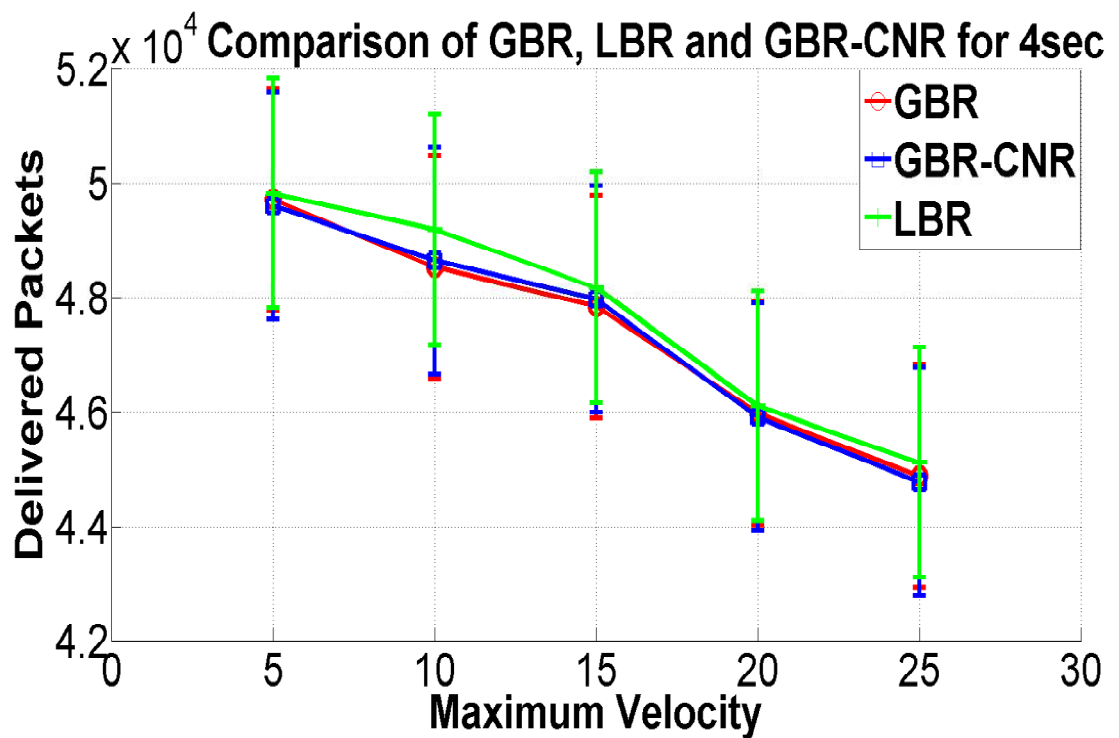
Figure 3.25: Delivered Packets in Four seconds Interval

Figures 3.28 – 3.29 present PDR simulation results for GBR, LBR and GBR-CNR and show how well they performed in terms of packet delivery ratio. The maximum velocity of nodes was set to different values ranging from 5 m/s to 25 m/s as indicated in each figure, as for the minimum speed, it was set to one meter per second for each experiment.
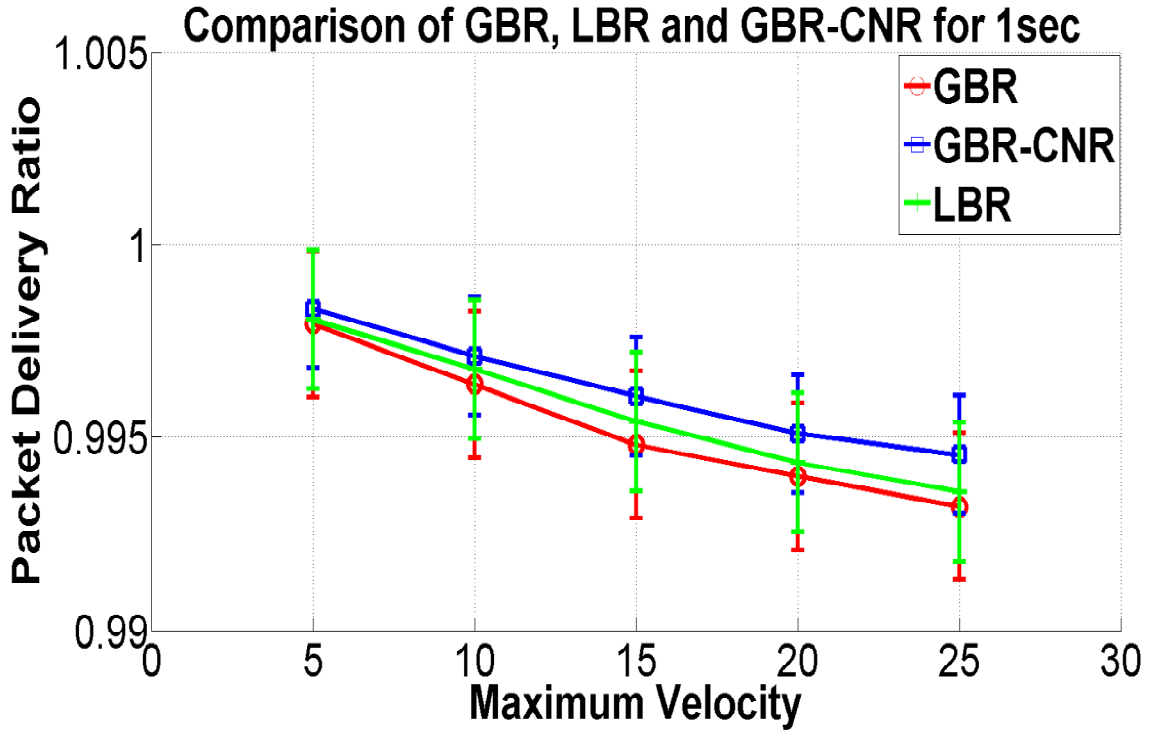
Figure 3.26: Packet Delivered Ration in One second Interval

In particular, Figures 3.30 – 3.32 indicate that when we used a small velocity with a small time of interval duration, the performance of all the protocols increase and the number of delivered packets to the destinations increases as well. Conversely, the algorithms did not perform well when both the velocity and HELLO interval time increase due to path broken several times during the interval for GBR and LBR. There is no need to backup path in GBR-CNR; however, it will be more difficult to construct paths in order to fulfill Equation 3.1. Therefore, it was not be able to

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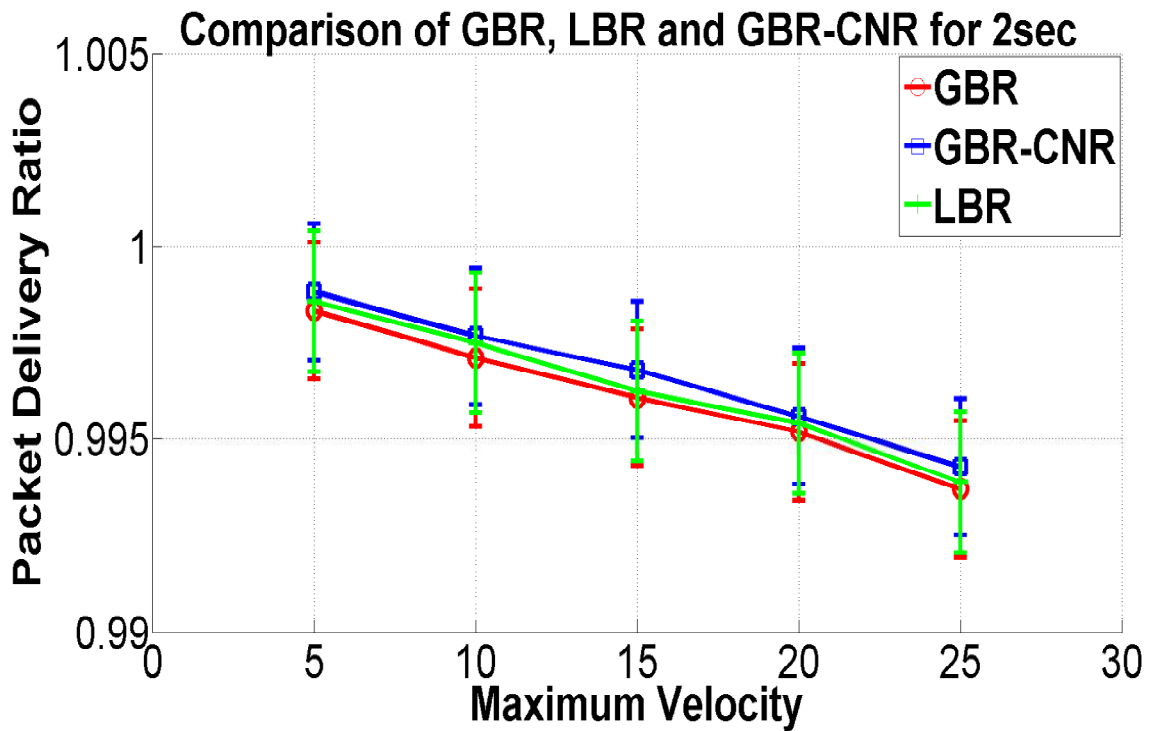
Figure 3.27: Packet Delivered Ration in Two seconds Interval
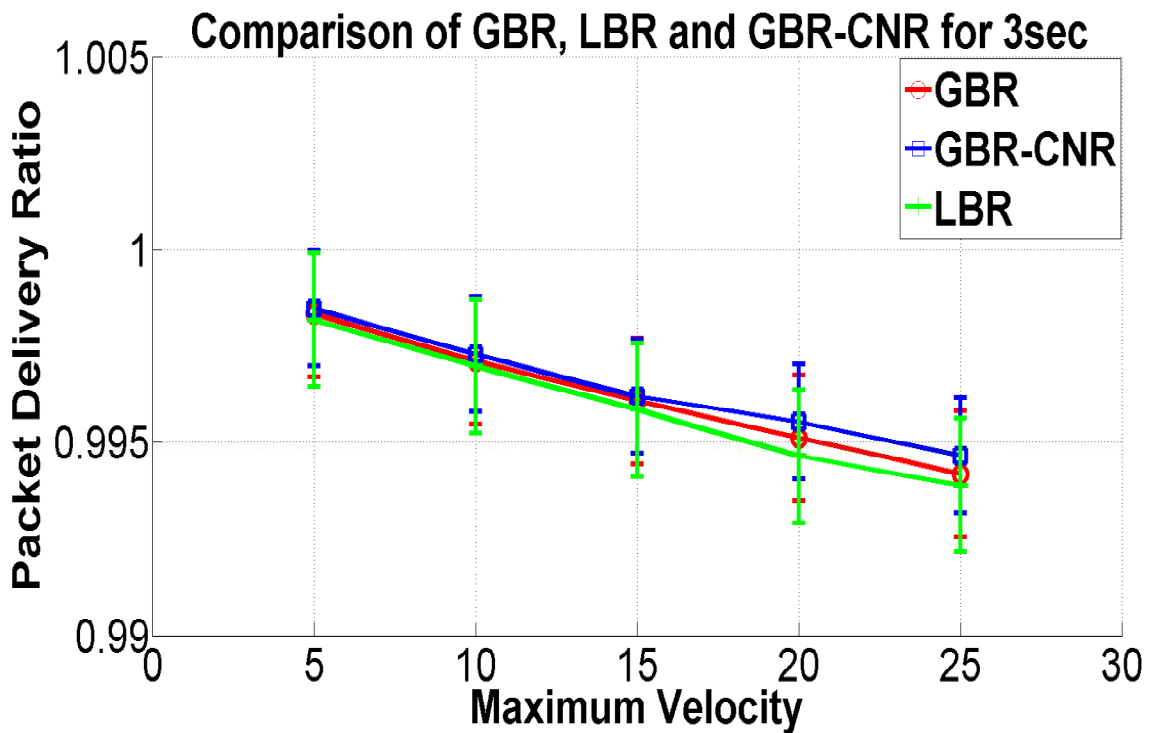
Figure 3.28: Packet Delivered Ration in Three seconds Interval
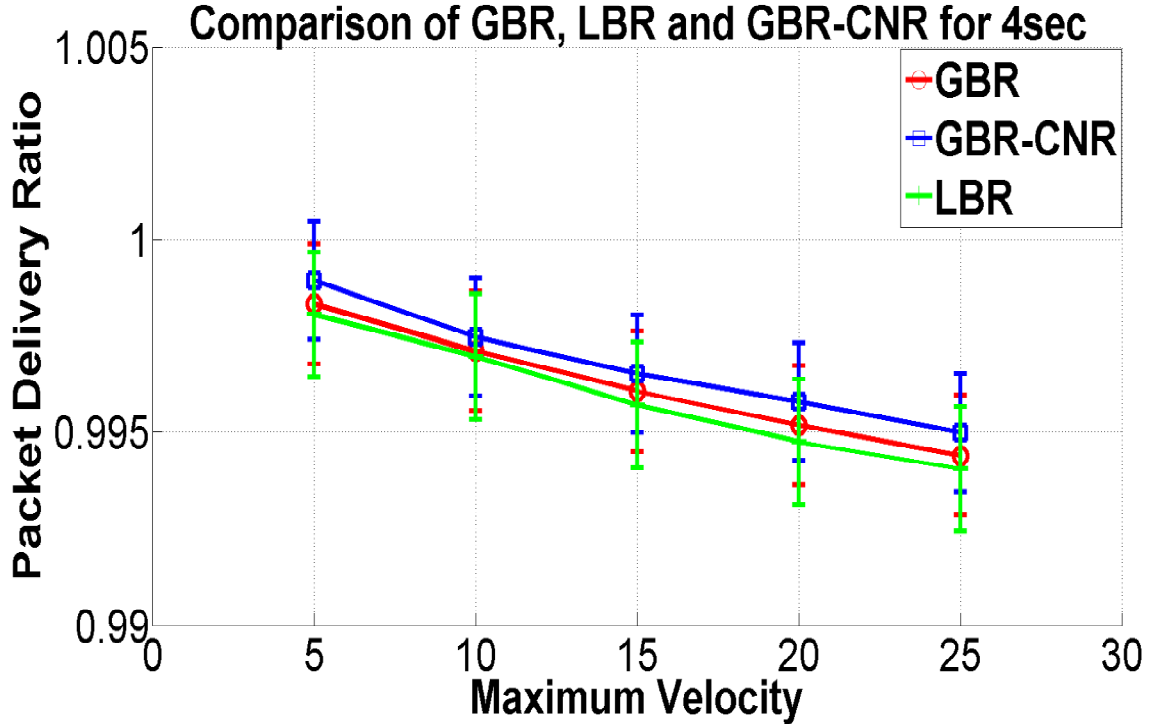
Figure 3.29: Packet Delivered Ration in Four seconds Interval

establish a path successfully in several times when both the velocity and HELLO interval time increase.

Figures 3.33, 3.34 and 3.35, show the obtained results of PDR for GBR, LBR, and GBR-CNR, respectively. We can observe that PDR figures show the versus the maximum of nodes velocity in different interval times for the three algorithms. Note that the performance of all protocols decreases as the interval time duration increases. So, we can observe that as the maximum of nodes velocity reach 25m/s, out of the packets sent per simulation time the total number of delivered packets will decrease compare to the lost packets, which will increase.
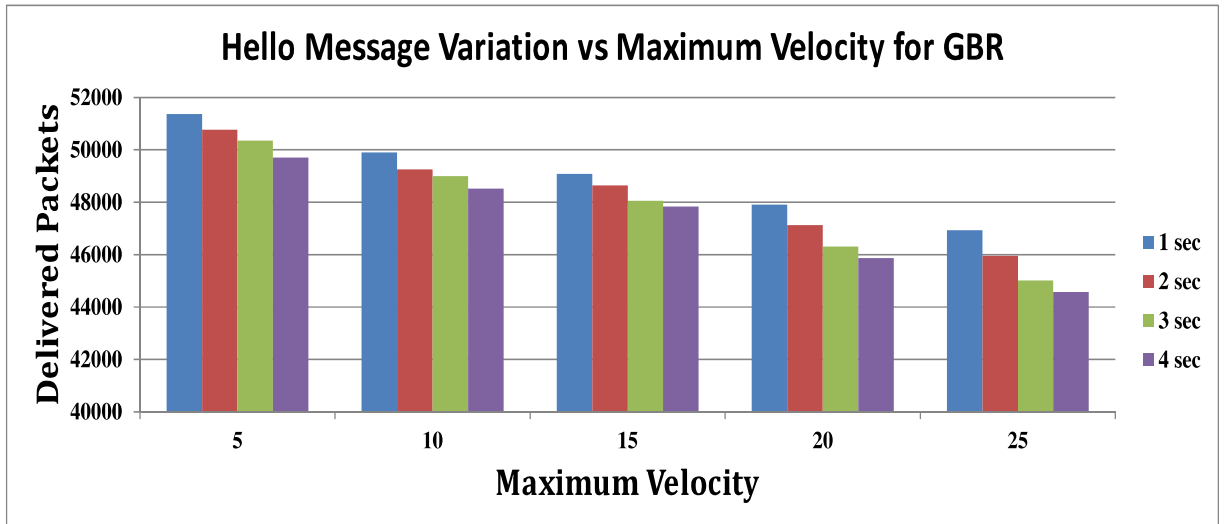
Figure 3.30: GBR: Total Number of Delivered Packets
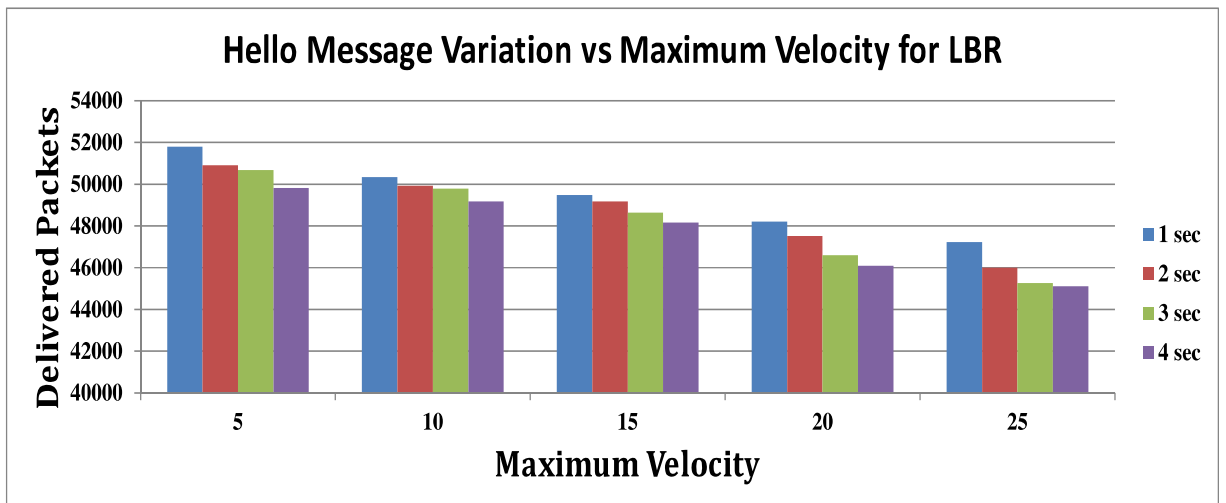
Figure 3.31: LBR: Total Number of Delivered Packets

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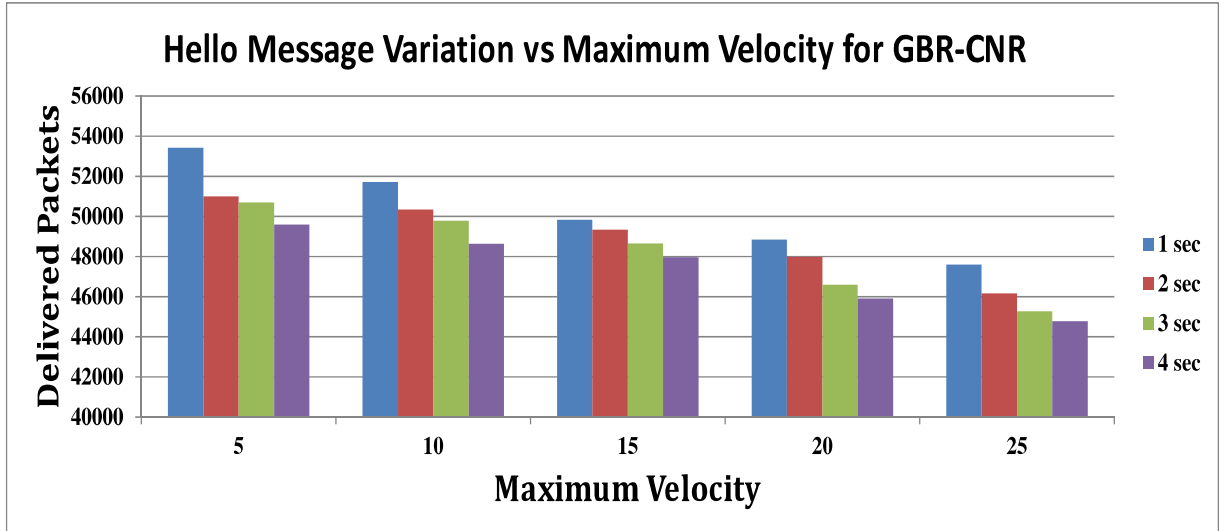
Figure 3.32: GBR-CNR: Total Number of Delivered Packets
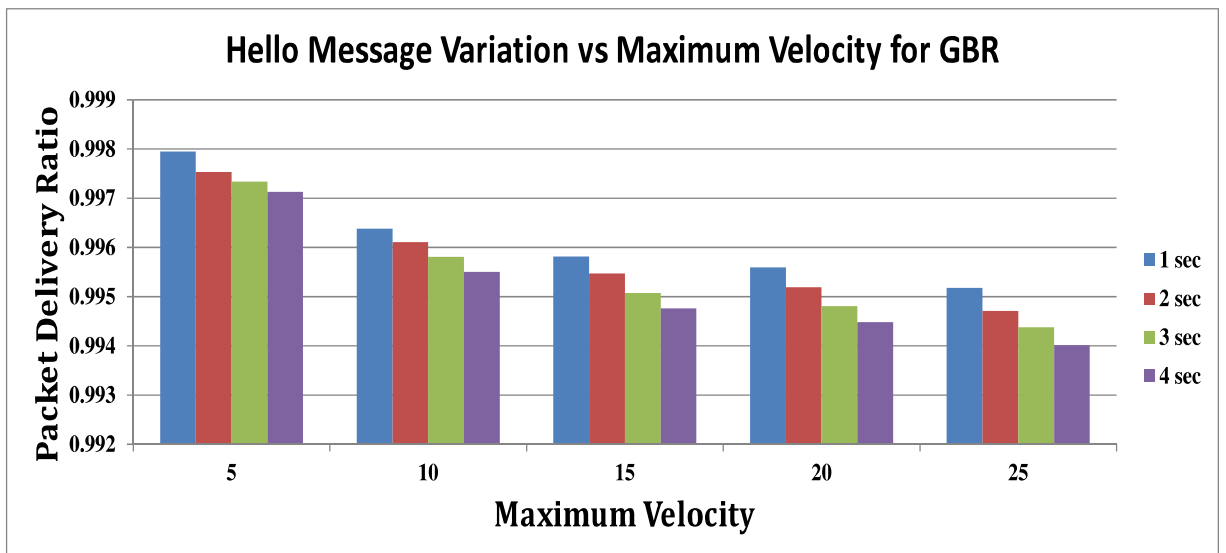
Figure 3.33: GBR: Packets Delivered Ration

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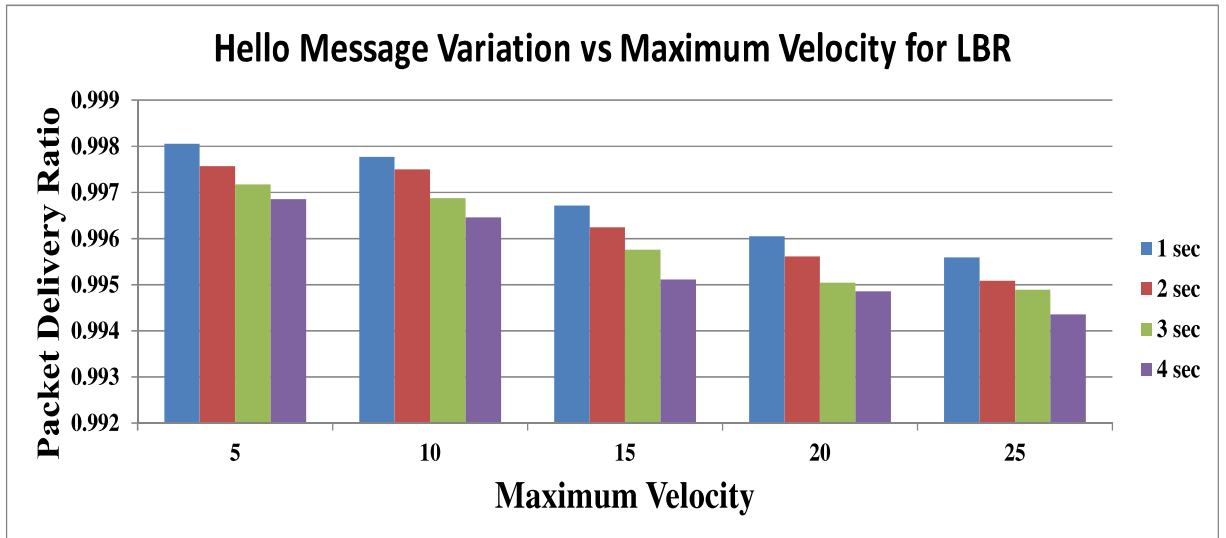
Figure 3.34: LBR: Packets Delivered Ration
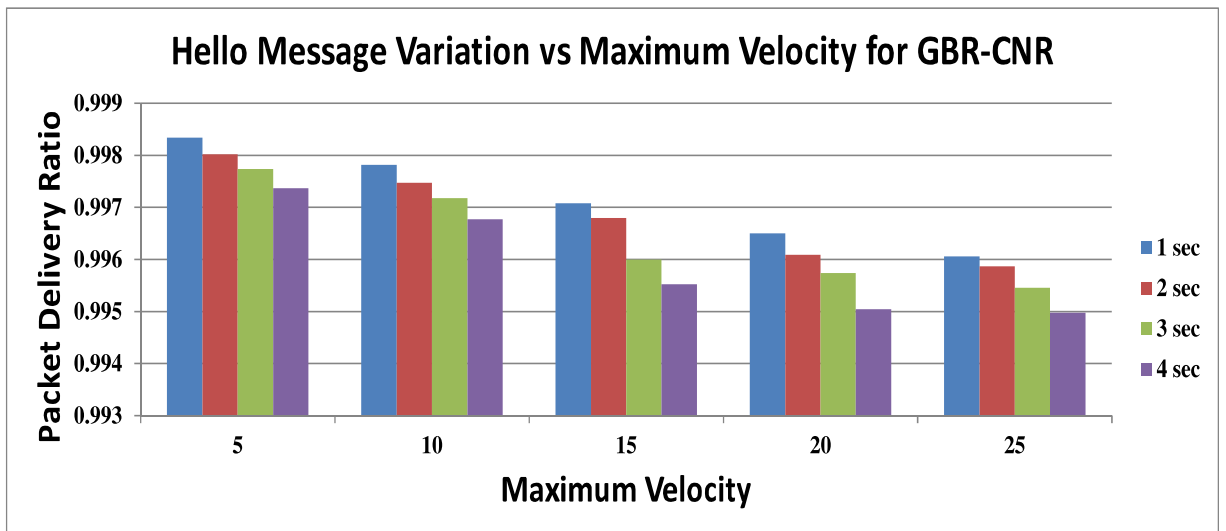
Figure 3.35: GBR-CNR: Packets Delivered Ration

3.3   Connections Stability Summary

We have proposed in this chapter several techniques that assure connections stability in MANETs. Specifically, our proposed protocol GBR-CNR is shown to be the best performing algorithm that maximizes the stability of connections that is measured in terms of throughput, while requiring the fewest number of routing control message exchanges in comparison to both algorithms GBR and LBR.

Also, in this chapter, we have presented a node protection protocol, which led to the establishment of stable connections in MANETs, experiencing occasional node failure. The proposed protocol was tested with simulations of mobility networks where mobile users with time variant locations and velocities affect the communication reliability in MANETs. We show that this led to high network stability as well as a high packets delivery rate. The protocol was validated and compared with the link protection algorithm, as implemented by the GBR protocol. This shows a significant improvement in the number of delivered packets, and the delivery rate, when nodes may occasionally fail. The advantage of GBR-NP is particularly noticeable for the graphs with fewer nodes.

In previous research works, stability is preserved through the use of backup paths in addition to the primary connection path, whereas our work uses a conservative neighborhood range, where the links of the primary path do not break during the interval between HELLO messages. The results of our simulations indicate that the performance of GBR-CNR protocol is superior to that one of the GBR protocol in terms of connection throughput, particularly as the number of nodes increases. However, as we increase the HELLO interval duration, this GBR-CNR performance improvement eventually comes at the cost of a larger control message overhead than

for GBR.

Additionally, mobile devices have limited processing power, storage and energy, while the nodes have powerful resources to perform any tasks or communicate with the nodes. To allow an increase in the network lifetime additional mechanisms are done in routing protocols to verify other parameters beyond the hop count that accept a more intelligent route establishment. Therefore, part of our studs considering an energy efficient stable routing in MANETs, because minimizing the energy consumption in MANETs is one of the significant issues that needs to be investigated further to make wireless communication more reliable.

Chapter 4

Energy Efficient Stable Routing using Adjustable Transmission Ranges

In order to explore energy saving opportunities in MANETs, we propose to discard the nodes that are not involved in any data communications at a specific time interval by putting them under a sleep mode. Thus, our algorithm should be able to specify which nodes in the neighborhood of the emitting mobile node are involved, in order to select the nodes that should be active and the nodes that should be asleep. Considering a specific node, a such decision is based on the location of its next hop, velocity, direction, and the time interval.

4.1 Energy Aware Routing on MANETs

We consider a network topology of MANETs, where energy constrained nodes are deployed over a flat region such that each node knows its own location as well as the position of its neighbors and the destination node. We also, assume that all nodes in the network are assigned with a unique ID and all nodes are participating in the network and forward the given data. Additionally, these mobile nodes have limited processing power, storage and energy, while the nodes have powerful resources to perform any tasks or communicate with the nodes. To allow an increase in the network lifetime additional mechanisms are done in routing protocols to verify other parameters beyond the hop count that accept a more intelligent route establishment. The energy efficient routing algorithm proposed is used for making a decision on which neighbor a mobile node should forward the data message to. A node is selected to forward the data based on the location of the next hope, velocity, direction, and the interval time. We assume that the nodes, which are not selected in any of the paths will move to the sleep state in order to preserve energy.

4.1.1 Measuring Energy Consumption

The energy is usually consume by the network interface when a host sends, receives or discards a packet. Such consumption can be describe using different formulations. In [73, 74] Stojmenović and his colleagues assumed that the power needed for the transmission and reception of a signal uses the following formula:

$$E(d) = ad^\alpha + c \tag{4.1}$$

where $a = 1, \alpha = 4, c = 2 \times 10^8$ or $a = 1, \alpha = 2, c = 2 \times 1000$, and d is the distance between two nodes. Also, Kuruvila *et al.* [48] assumed that the power needed for the transmission and reception of a signal in Equation 4.1 with $a = 1, \alpha = 4, c = 2 \times 10^8$ or $a = 1, \alpha = 2, c = 2 \times 1000$. Following another approach, Feeney and Nilsson [20] measured the energy consumed by the network interface when a host sends, receives, or discards a packet using a linear ($\alpha = 1$) version of Equation 4.1, where a is the packet size. The relative magnitudes of the various d and c coefficients also indicate the amount of per-packet energy consumption overhead.

In order to try to develop a more energy-efficient variation of GBR, we consider the Energy-Efficient protocol LEARN proposed by Wang *et al.* [83] for static ad hoc networks. Assuming that the energy require d for a transmission from node u to a neighbor v is $E(\|uv\|)$, then LEARN chooses the next node during route discovery on the neighboring node with respect to a critical transmission radius r_0, which is the distance d, such that $d/E(d)$ is the maximum. For a node u, the authors defined the interior region of a 2-D cone CN, with respect to the destination node D with its apex at u and is centered on the line from u to D. It has a cone half-angle (the angle from center line of the cone to the side of the cone) of θ. They also defined the interior area of a 2-D torus, TO, which includes the region bounded by the distances between $\eta_1 r_0$ and $\eta_2 r_0$. These definitions apply for constant parameters θ, η_1, and η_2.

Furthermore, they defined a Restricted Neighborhood Area (RNA) for a node u to be the intersection of CN and TO. Then, during route discovery for the next hop from u, LEARN will choose the neighbor v_i with the maximum $\|uv_i\|/E(\|uv_i\|)$ in RNA. If none exists, then the neighbor closest to D in CN is chosen. If no such neighbor exists, then, by default, a neighbor is chosen as the one that would be

chosen by GPSR. During routing, a dynamic transmission range was used that had the minimum energy costs during transmission.

4.1.2 Dynamic Transmission Power

The battery lifetime of wireless devices is one of the most important issues that affect the energy stability in MANETs. Thus, many protocols have been proposed to improve the energy usage in MANETs through the control of the transmission power. The basic approach of assignment of different transmission powers to different nodes has been explored for static wireless devices [3] and centralized systems [38]. This leads to an extended battery life of nodes. Kim and Eom [43] presented a novel reprogramming scheme that used dynamic transmission power control to handle the energy consumption of each wireless sensor node and the network load distribution. Also, Wu and Dai [85] proposed the distributed solution based on reducing energy consumption and density of the virtual backbone network using adjustable transmission range combined with clustering. In the following section we will investigate the usage of adjustable transmission power that is dynamically dependent on the location of the next hop node in order to improve both the link stability and the energy efficiency for MANETs.

4.1.3 Stable Routing through Energy Efficient Routing on MANETs

Many research works have studied MANETs stability that was occasionally combined with energy efficiency, using reactive topology-based routing such as DSR [2, 84] and

AODV [76,87]. Hamad *et al.* [27] presented a routing protocol called Line Stability and Energy Aware (LSEA) which is a modified version of AODV. Some other protocols are based on multicasting, such as the protocol proposed by Zhang *et al.* [95] that uses multicast trees and a stability evaluation metric to insure a stability-based multicast routing. Also an energy-aware protocol using multicast trees is proposed by Mohamamdzadeh *et al.* [57].

As for static ad hoc networks, energy-efficient routing has been extensively studied by [12,20,48,72–74,83]. Considering position-based routing for static ad hoc networks, Seada *et al.* [72] uses an analytical link loss model to strike a balance between short high-quality links and long lossy links. Wang *et al.* [83] base their choice of neighbors for routing on a critical transmission radius for energy efficiency combined with dynamic transmission ranges which constitutes their Energy-Efficient protocol LEARN (Localized Energy Aware Restricted Neighborhood Routing for Ad Hoc Networks).

On the other hand, position-based routing for mobile ad hoc networks, uses the position information of the nodes to evaluate the links in terms of Euclidean distance and Link Expiration Time (LET) between two neighborhood nodes that participate in the path. To increase the stability of routing in MANETs and to provide a reliable end-to-end route, one approach is to select the most stable node among the available neighborhood nodes when choosing a next hop node [53]. Alternatively, to improve the stability along the path in the presence of expiring links, another approach is to maintain multiple paths along the connection. In particular, with GBR, Yang *et al.* [90] were able to achieve a reliable connection. This was done through the protection of the links between each pair of nodes participating in the primary path. Such a protection is established by maintaining local backup paths in parallel with

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each link in the path to be used, when that link expires. In the Sub-Section 3.1.1 we will introduce a variation of GBR by using only neighbors during routing from a conservative neighborhood range which maintains a stable path without the need to determine backup paths.

4.2 Energy Consumption Protocols

In this section, we focus on developing protocols to improve both energy consumption and communication stability. Furthering the work in [90,92], we propose to reduce the energy consumption while maintaining overall communication stability of the routing by using the idea of an adjustable transmission range, that has been adapted to take into account the mobility of the nodes. In the following, we introduce and discuss various routing protocols used to explore this idea.

GBR-DTR: if a node v_{i-1} wants to send a message to the node v_i, where the link has a link expiration time of $LET(v_{i-1}, v_i)$, it can conserve energy while maintaining the link by adjusting its transmission range from R to a range that is closer to the distance to v_i. For the selection of an adjustable transmission range R_a as shown in Figure 4.1, we assume that all packets have the same size and that the maximum transmission range is R. For energy considerations, at the beginning of each HELLO interval, we seek to use the smallest radius of transmission along the link from node v_{i-1} to node v_i in the connection, while not allowing the connection to break prematurely during the HELLO interval. Let I denote the time between HELLO messages, let L in Figure 4.1 be the distance from node v_{i-1} to node v_i, and LET is link expiration time which is calculated by using Equation 2.1. Then, we can define $W = (R - L)/\min(I, LET)$.

Since $\min(I, LET)$ is the time until the distance between v_{i-1} and v_i equals R (when $I \leq LET$) or makes it closest approach to R (when $I > LET$), then the value W is the velocity of v_i approaching the distance R in a radial direction. Then, the adjusted transmission range, R_a, can be calculated as $R_a = L + \max(0, W)I$.
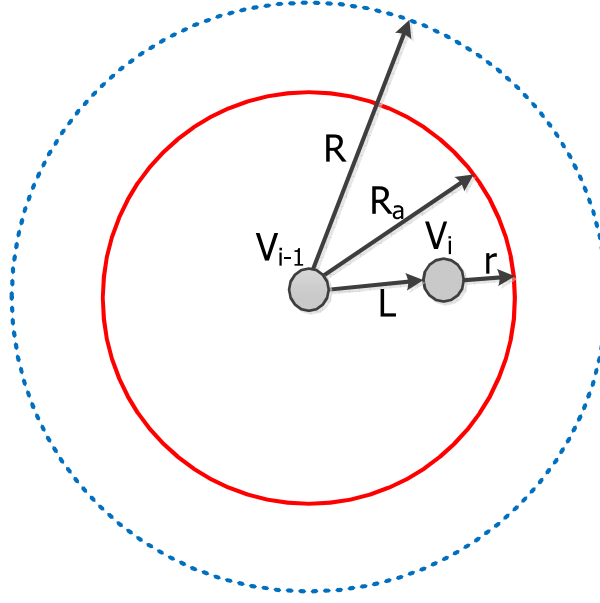
Figure 4.1: Adjustable Transmission Range R_a

The GBR-DTR protocol is the stable routing protocol GBR but uses a Dynamic Transmission Range (DTR) instead of R.

GBR-CNR-DTR:

As for the energetic behavior of MANETs, we study energy efficient variations of the routing algorithms in the context of maintaining stable connections between mobile nodes. We propose a position-based routing protocol, named GBR-CNR-DTR, that is both "link stable" and "energy efficient". The algorithm assures link stability through the choice of neighbors using our technique CNR that is illustrated in Sub-Section 3.1.1 that we combine with Dynamic Transmission Range (DTR) to assure energy

efficiency. For this extension of the GBR-DTR protocol, we used the Conservative Neighborhood Range (CNR) to take into account the possibility of nodes that can go out of range during the interval between HELLO beacon broadcasts. Subsequently, we avoid including them in the path selection. The CNR depends on the interval between HELLO message broadcasts and its range value, R_c, is defined in Equation 3.1. The GBR-CNR-DTR protocol is the stable routing protocol GBR with a Dynamic Transmission Range (DTR) while using the Conservative Neighborhood Range (CNR) for neighbor selection.

LBR: in order to try to develop a more energy-efficient variation of GBR, we also considered the Energy-Efficient protocol LEARN, proposed by Wang *et al.* [83], for static ad hoc networks. It is assumed that the energy required for a transmission from node u to a neighbor v is $E(\|uv\|)$. Then, LEARN chooses the next node during route discovery on the neighboring node with respect to a critical transmission radius r_0 which is the distance d, where $d/E(d)$ is maximum. For a node u, we define the interior region of a 2-D cone to be CN, with respect to the destination node D, with its apex at u and centered on the line from u to D, with a cone half-angle (the angle from center line of the cone to the side of cone) of θ. The interior area of a 2-D torus is defined as TO, which includes the region bounded by the distance between $\eta_1 r_0$ and $\eta_2 r_0$, The constant parameters θ, η_1, and η_2 are illustrated in Figure 4.2. Further, they define a Restricted Neighborhood Area (RNA) for a node u to be the intersection of CN and TO. Then, during route discovery for the next hop from u, LEARN will choose the neighbor v_i with maximum $\|uv_i\|/E(\|uv_i\|)$ in RNA, or if none exists, it then chooses the neighbor closest to D in CN. If none still exists, by default, a neighbor is chosen as would be chosen by GPSR.

To maximize the energy-efficiency properties of the stable routing protocol GBR, it would appear reasonable to replace the primary greedy routing algorithm GPSR with the energy-efficient algorithm LEARN. Therefore, we propose a variation of GBR by replacing GPSR with LEARN which we will simply reference as LEARN-based Backup Routing (LBR). The LBR protocol is the stable routing protocol which uses the fixed transmission range R.
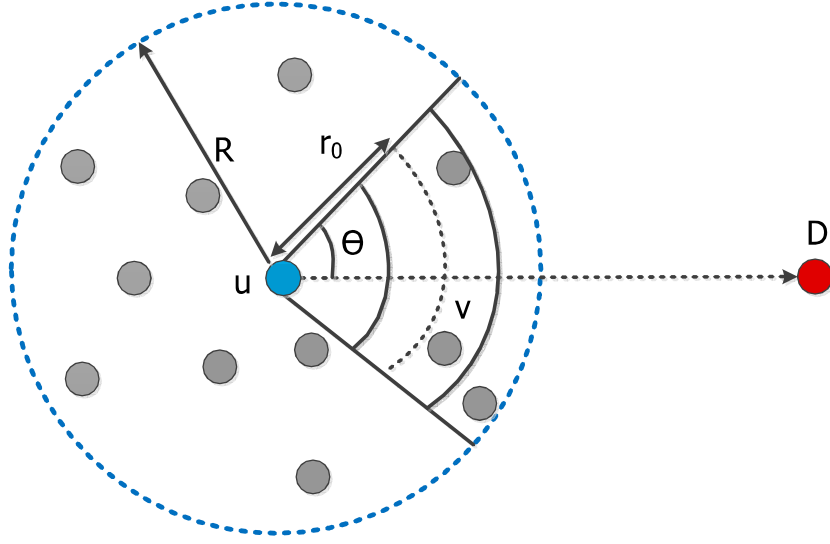
Figure 4.2: How LEARN chooses the next hop

LBR-DTR: the LBR-DTR protocol is the stable routing protocol LBR, with a Dynamic Transmission Range (DTR), which uses the adjustable transmission range R_a in order to reduce the energy expenditure during transmissions to neighboring routing nodes.

4.3   Experiments and Results

The simulation environment for this work is modeled using network parameters that are a network area of size $2200m \times 2200m$; a varying number of nodes from $200, 250, 300, \ldots, 600$; and a fixed transmission range of $R = 250m$. The direction in which a node can move is given randomly at the beginning of the simulation. However, when a node reaches the boundary, following the mobility model Random Walk with Wrapping and Reflection, we reflect the node traveling at the angle γ using the formula $\gamma + \frac{\pi}{2} + c$ [66]. For each different node density, we randomly distributed 40 connected graphs that were used as a starting network topology for each run of the simulation for all algorithms. There were 20 pairs of Constant Bit Rate (CBR) data flows in the network layer, and non-identical source and destination flows were randomly selected such that each flow does not change its source and destination throughout the simulations. For the studied algorithms, we constructed the primary path (and the backup path, if it is not a CNR based protocol), as described in Sub-Section 2.3.3, from the sources to the destinations. Each simulation ran for 600 seconds with enough packets assigned for the simulation time, and the presented results are averaged over the 40 graphs. The error bars in each figure represent 95% confidence intervals. Unless indicated otherwise, the velocity was set to be the same for all nodes at $V_{min} = V_{max} = 10m/s$, and the interval between HELLO beacon broadcasts was set to 2 seconds.

In the following, we study several protocols properties including link and node protection properties, the energy consumption properties, the effect of varying the interval between HELLO broadcasts, and the effect of varying the maximum speed of the nodes.

4.3.1 Energy Aware Techniques: Results and Discussion

For the algorithms GBR, GBR-CNR, and LBR, and their dynamic transmission range versions GBR-DTR, GBR-CNR-DTR, and LBR-DTR, we did energy cost calculation for the transmission over each link, from node v_{i-1} to node v_i, using the energy cost function $E(\|v_{i-1}v_i\|)$, as shown in the following Equation:

$$E(\|v_{i-1}v_i\|) = a \left(\frac{\|v_{i-1}v_i\|}{R} \right)^\alpha + c. \qquad (4.2)$$

We set the receiver cost to be a constant $E_{recv} = c$, and we assumed that there was no energy cost effect for idle periods or discarded packets. For energy calculations, we set $\alpha = 2$, $a = R^\alpha$, and $c = (\frac{R}{2})^2$. For the LEARN algorithm, we used the following constant parameter values: $\theta = \frac{\pi}{3}$, $\eta_1 = \frac{1}{2}$, and $\eta_2 = 2$. Since $c = (\frac{R}{2})^2$. From this, the critical transmission radius r_0 for LEARN is $\sqrt{c} = \frac{R}{2}$ [83].

In particular, we analyzed the effect of varying the node density on the stability and energy consumption for each protocol in MANETs. We mainly considered the following metrics: the PDR, the total energy expended, E_T, maximum energy expended per node, average energy expended per node, and the average energy expended per packet delivered, E_P. If T_P is the total number of delivered packets over the entire simulation period, then E_P is calculated as $E_P = \frac{E_T}{T_P}$.

Figure 4.3 shows the relative performance of the routing protocols in terms of PDR. Among all the considered protocols, GBR-CNR-DTR consistently outperformed over the various number of nodes. It was followed closely by both LEARN-based protocols, LBR-DTR and LBR. It may be noted that in terms of the number of delivered packets, packet delivery rates, and similar non-energy related performance

metrics, the GBR-CNR-DTR performs identically to its original GBR-CNR version. In comparison, GBR-DTR and GBR performed significantly worse in terms of energy expenditure. These results are explained by the fact that the selection strategy of nodes in a given path had an influence on the performance of the routing algorithm.
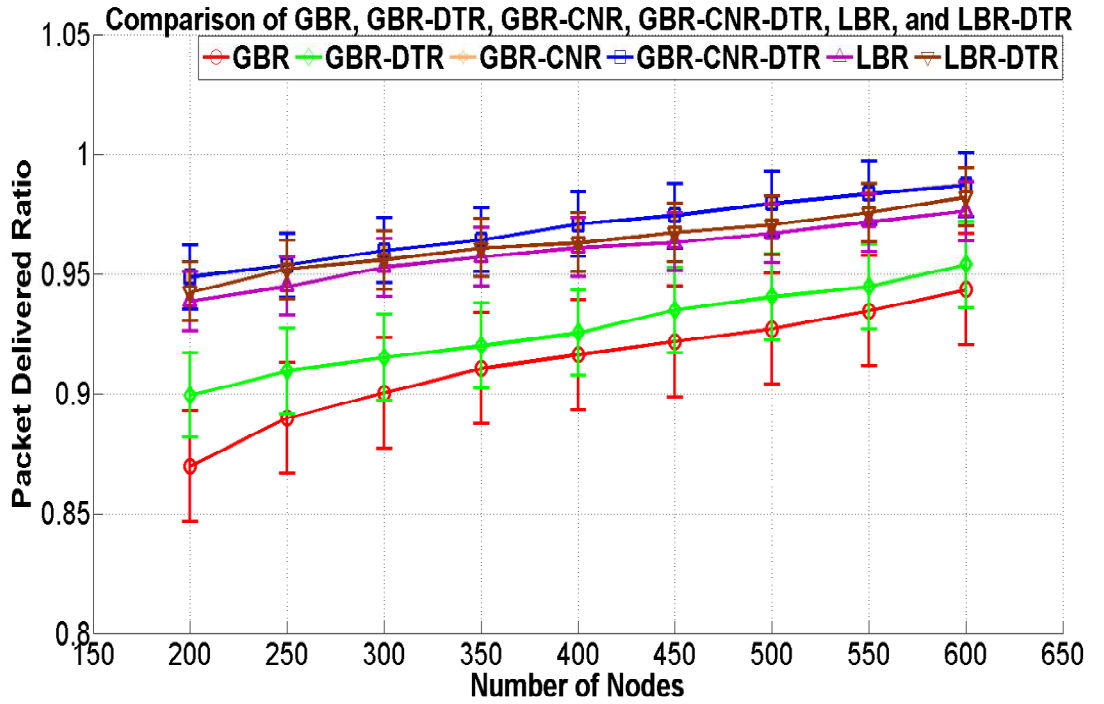
Figure 4.3: Packet Delivery Ratio

Therefore, the connections formed are much more stable than for GBR-DTR and GBR, where the next node chosen is closest to the destination. Thus, it was more likely to move out of transmission range before the next HELLO broadcast, more likely to break the connection such that the path had to be recomputed, and led to more dropped packets and a lower delivery ratio. However, for GBR-CNR and GBR-CNR-DTR, the next node was selected from the neighboring nodes that would not move out of range before the next HELLO message broadcast. Finally, following GBR-CNR-DTR and GBR-CNR, in terms of PDR, are LBR-DTR and LBR, since

these use LEARN to determine routing paths. Following LEARN, the next nodes are selected on the basis of being the closest to the critical transmission radius $r_0 = \frac{R}{2}$.

Figures 4.4, 4.5, and 4.6 show the performances of the routing protocols in terms of various energy metric measurements (the units of energy used are the same for all equations and figures). In terms of maximum energy expended per node, as shown in Figure 4.4. As expected, the dynamic transmission range protocols fared the best with GBR-CNR-DTR again performing consistently best over the various number of nodes, followed GBR-DTR, and then by LBR-DTR. For a MANET containing nodes with limited capacity batteries, this means that the first battery failures are more likely to occur later for GBR-CNR-DTR than for the other protocols. Interestingly, the original version of GBR-CNR-DTR without using the dynamic transmission range, GBR-CNR, fared the worst compared to the other protocols while GBR-CNR-DTR. Therefore, in situations where energy considerations are important, GBR-CNR-DTR can be used while preserving the delivery rate and other non-energy related metrics. This makes GBR-CNR the best performing protocol in most other contexts.

When considering the average of the energy consumed per node, GBR-DTR performed best followed by GBR-CNR-DTR, and then by LBR-DTR, as shown in Figure 4.5. Interestingly, when we considered LEARN as an alternative algorithm to GPSR, and we measured the maximum and average energy consumption per node, we did not obtain any improvement for the energy-efficiency properties of the connections between nodes. Finally, base on the results' figures, we notice that when considering the average energy consumed per delivered packet, the GBR-CNR-DTR again consistently outperforms over the various number of nodes, followed by LBR-DTR and then by GBR-DTR. The worst performance for this energy metric was obtained by
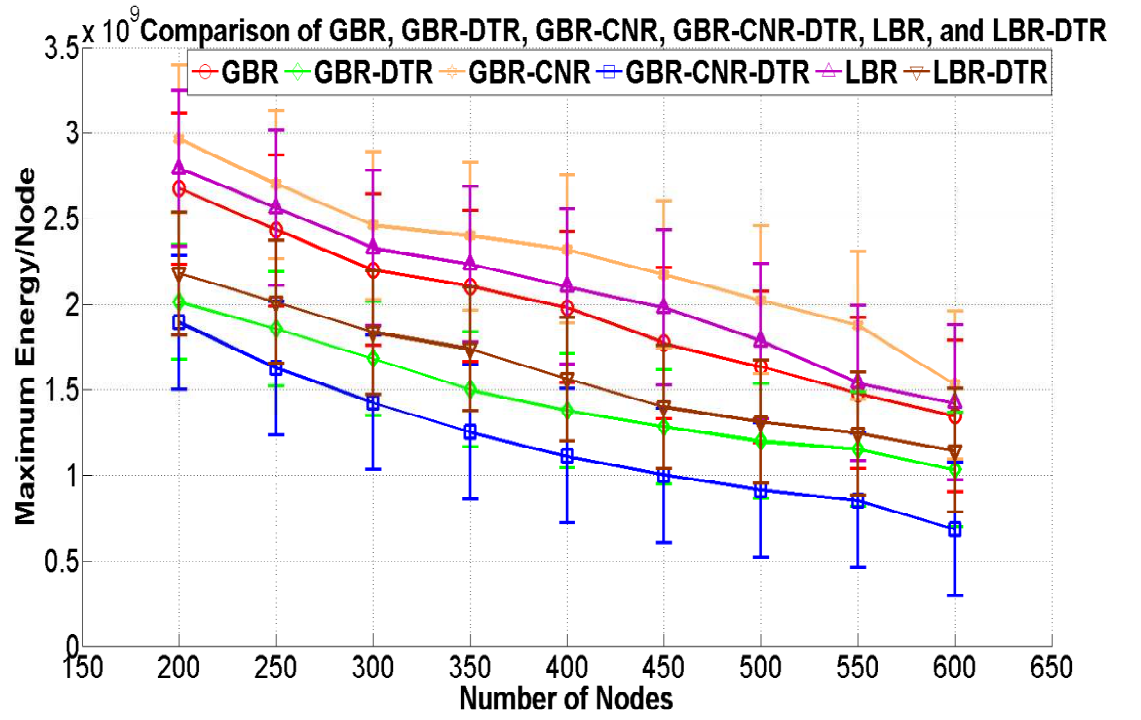
Figure 4.4: Maximum Energy per Node
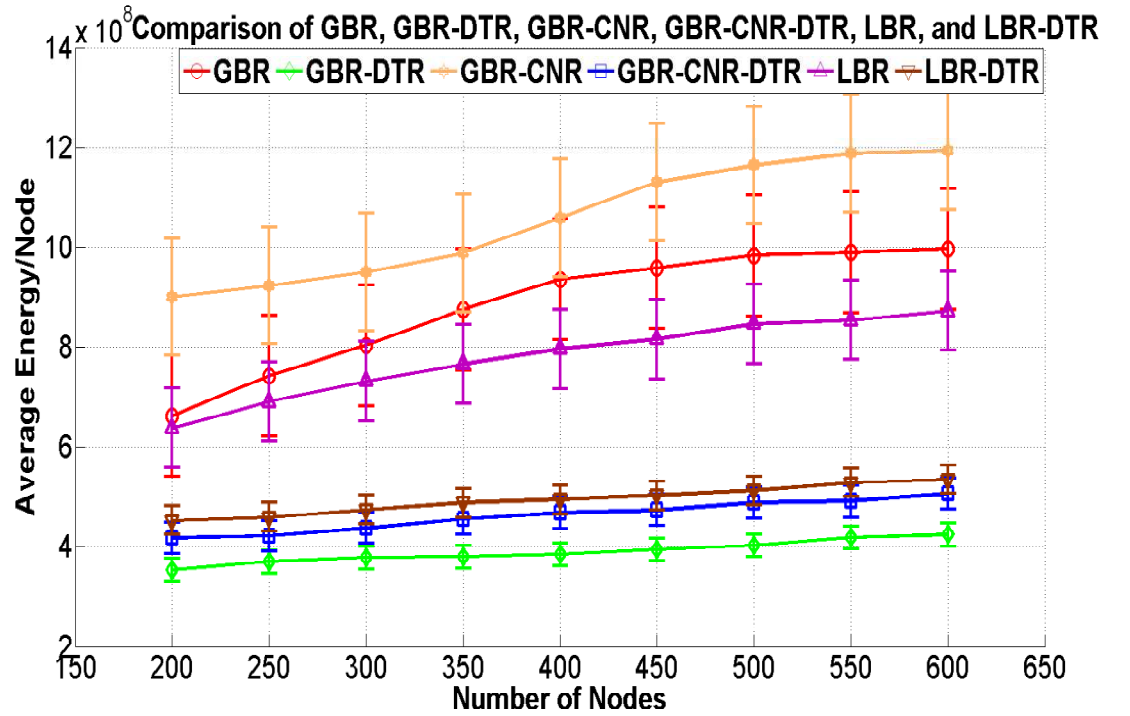
Figure 4.5: Average Energy per Node
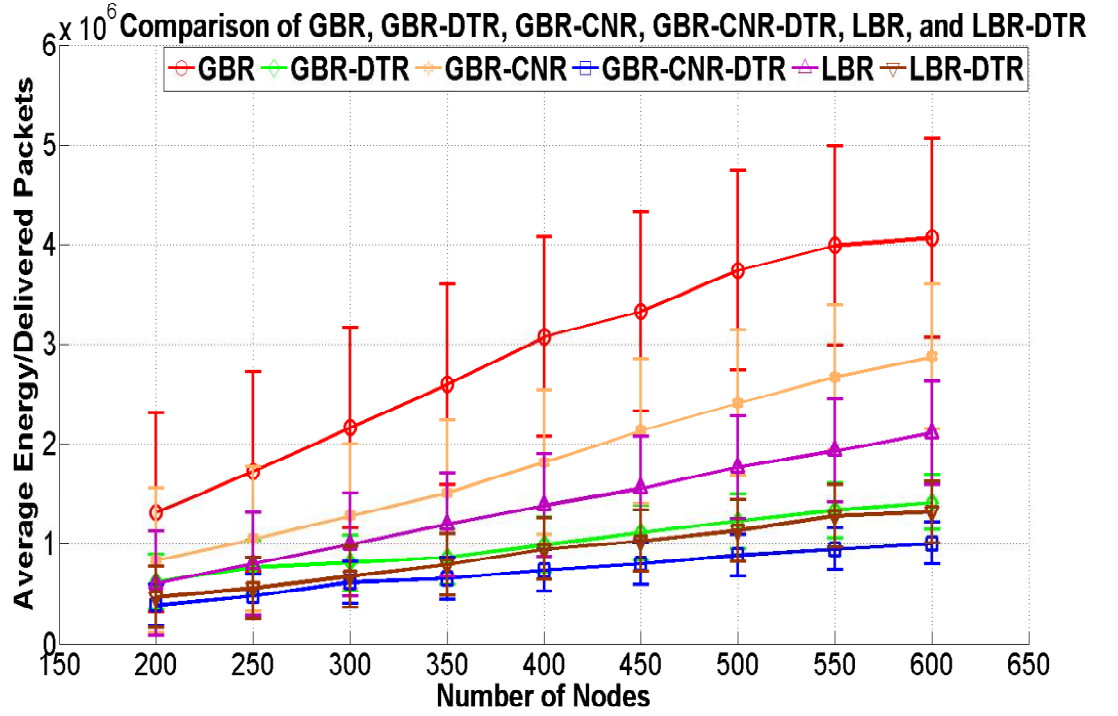
Figure 4.6: Average Energy per Delivered Packets

GBR.

As noted above, in terms of the number of delivered packets, packet delivery rates, and similar non-energy related performance metrics, the DTR version of GBR-CNR performed identically to its original non-DTR version. Which means, apart of using a dynamic transmission range, the choice of routing nodes and other protocol decisions were exactly the same for both GBR-CNR-DTR and GBR-CNR. Therefore, for the rest of the experimental results given below, we will only consider the original versions of GBR, LBR, and GBR-CNR.

Indeed the establishment of new paths and backup paths is energy consuming. We propose to compare the performances of the three protocols in terms of Calculating New Paths (CNP) and Using Backup Paths (UBP) when a primary path is broken during the interval. Thus, we run different scenarios for three algorithms (GBR, LBR,

and GBR-CNR), with different number of nodes varying from 200 to 600. Figures 4.7, 4.8 and 4.9, show the obtained results for GBR, LBR, and GBR-CNR, respectively. These results represent an average of the CNP and UBP numbers over 300 intervals for 20 pairs of sources and destinations, where the considered intervals are equal to 2 seconds and the total simulation time is equal to 10 minutes. The CNP and UBP are calculated based on PET as in Equation 2.2, and LET as in Equation 2.1, respectively.

The results of GBR and LBR as illustrated in Figures 4.7 and 4.8, respectively, show that when the number of nodes increases the average time of CNP decreases; however, the UBP time increases. This is due to the fact that a higher node density makes the primary path links more protected by the backup path nodes. We also notice that CNP decreases in GBR when the number of nodes reached 400. While the UBP decreases starting from 450 nodes which are explained by the fact that the node density increases when considering a fixed network area. For LBR we notice that gradually the CNP decreases while the UBP increases, which is explained by the fact that the node density increases when considering a fixed network area. In general, this means that after a certain threshold of nodes density, calculating new paths and using backup paths both start to decrease.

While the GBR and LBR algorithms need to have backup paths, the GBR-CNR algorithm shows that there is no need to such backup paths. Figure 4.9 shows that there were no UBP, but on the other hand the CNP is more considerable when compared with GBR and LBR. This is explained by the fact that all working paths in GBR-CNR algorithm must be active during the interval period, or in other words must fulfill the condition of Equation 3.1. However, the number of times of CNP decreases when the number of nodes increases.
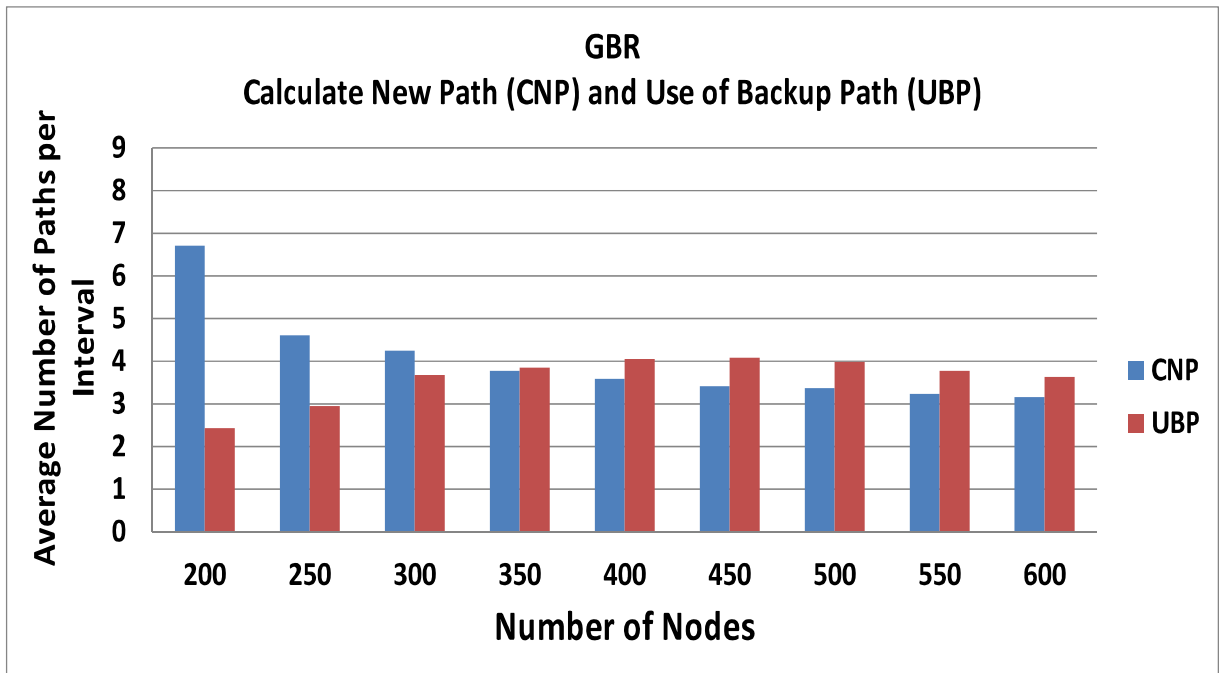
Figure 4.7: GBR: Average times of (CNP and UBP) during the interval
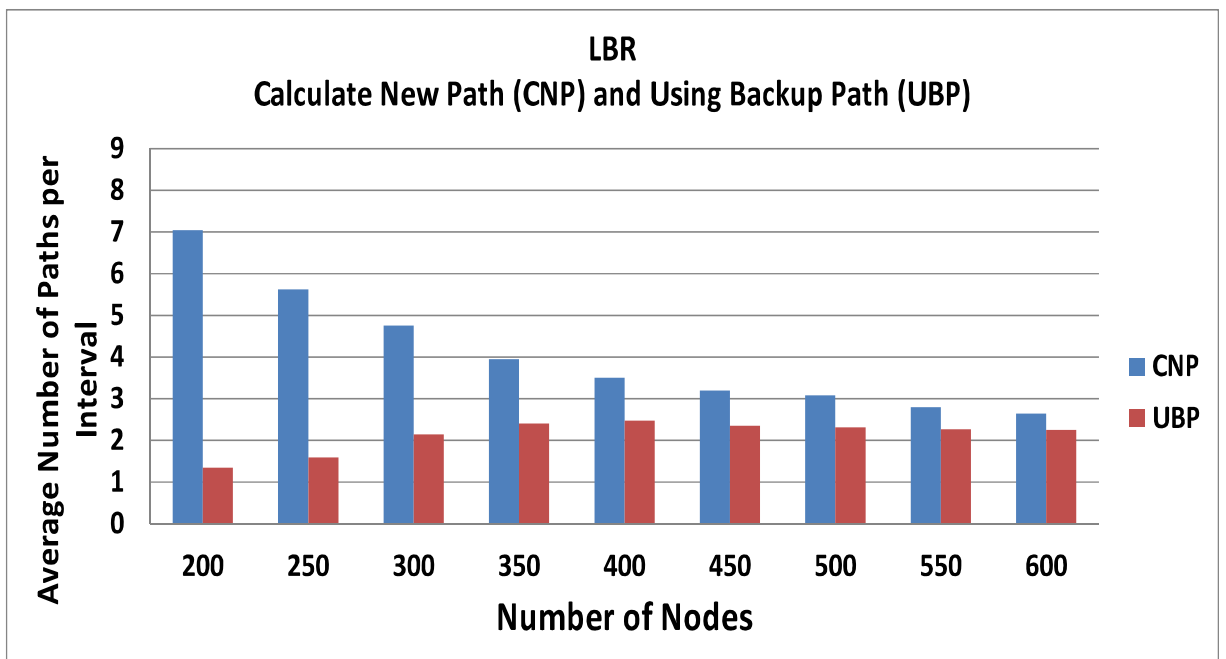
Figure 4.8: LBR: Average times of (CNP and UBP) during the interval
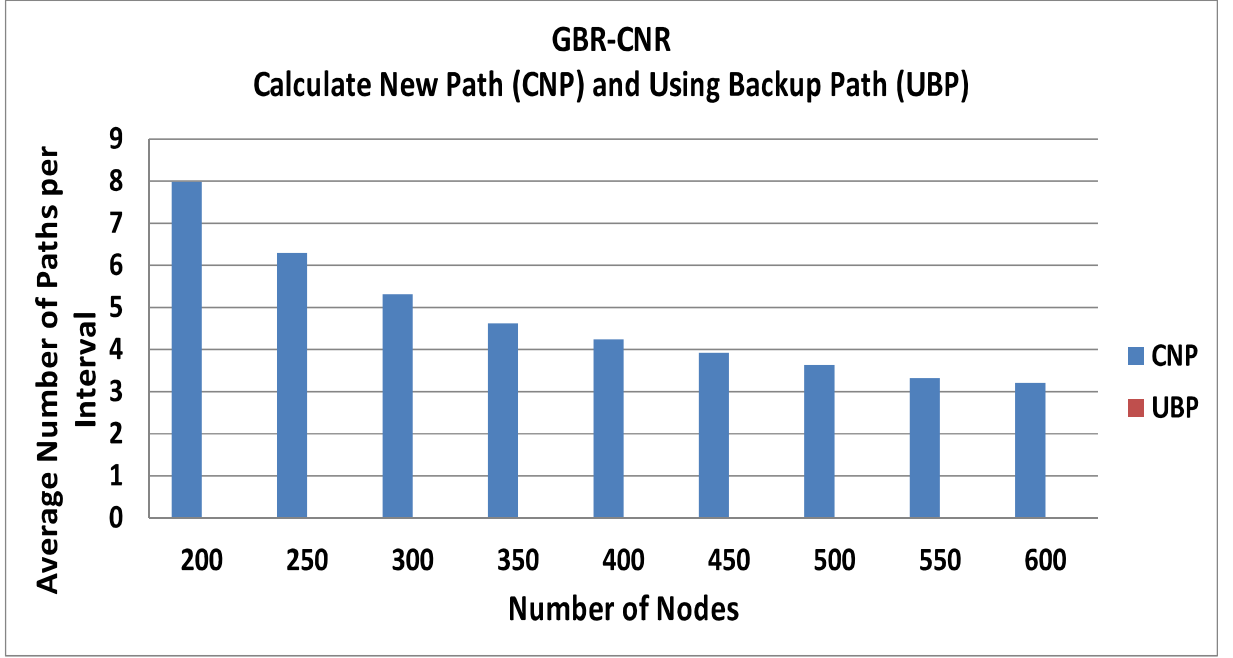
Figure 4.9: GBR-CNR: Average times of (CNP and UBP) during the interval

4.3.2 Energy Efficiency Summary

The overall conclusion that we reach in this chapter is the following. Our proposed protocol GBR-DTR-CNR was demonstrated to maximize both the stability of connections, measured in terms of throughput, as well as the energy-efficiency of these connections, while requiring the fewest number of routing control message exchanges. The only energy consumption metric for which GBR-DTR-CNR was not the most performing algorithm when compared with other protocols, was the average energy consumed per node, where it ranked second just after the GBR-DTR, considering various node densities.

For all the energy-efficiency measures, the use of the adjustable transmission range R_a significantly improved the energy consumption properties of the routing protocols,

as expected. However, the use of LEARN in place of GPSR in the stability routing protocol GBR did not lead to a more energy-efficient stable routing protocol. A byproduct of selecting routing nodes near the critical transmission radius r_0 was a higher throughput for LBR and LBR-DTR, as compared to GBR and GBR-DTR.

In MANETs, all nodes that have messages (packets) to exchange must transmit their packets concurrently to improve the network efficiency. Because nodes in MANETs systems are communicating wirelessly within a relatively limited and shared area, therefore we should maximize the number of devices scheduled in the time slot if there is no interference that can affect their communication. In other words, to achieve high network efficiency, parallel transmissions on more than one link must be considered by routing and scheduling protocols. Thus, the next chapter is dedicated to the development of new techniques that can minimize communication interferences for stable position-based routing in MANETs.

Chapter 5

Minimizing Communication Interference for Stable Position-Based Routing

For efficient communication in a MANET that must cope with interference while performing multi-hop routing is of great importance. By establishing an interference-aware route, we can potentially reduce the interference effects in the overall wireless communication, resulting in an improved network performance. Typically, mobile devices, represented by nodes in a MANET, are used to broadcast limited shared media. Therefore, using both routing and scheduling mechanisms for wireless transmissions reduces both redundancy and communication interferences. We studied communication interference problems in the context of maintaining stable connection routes between mobile devices in MANETs. In this thesis, we extended our previous position-based stable routing protocol (namely, the Greedy based Backup Routing

Protocol with Conservative Neighborhood Range) in order to maintain connection stability, while minimizing the number of corrupted packets, in the presence of more general communication interference. Simulation results demonstrate the effectiveness of the new protocols.

5.1 Definition of Interference and Proposed Protocols

In MANETs, interference can have an adverse influence on the performance of the networks. This occurs due to the dynamic nature of the network structure as well as concurrent transmissions; therefore, interference modeling should be taken into account. The effect of interference on the efficiency of our proposed routing protocols is a critical and challenging issue.

5.1.1 Definition of Interference

Interference in MANETs is the possibility of a receiver node to be positioned in the range for any other neighborhood (other then previous node in the path) nodes carrier sensing range in the same network. Carrier sensing range for any node is the range in which a node can receive signals but cannot appropriately decode them. Therefore, in MANETs, when interference to be considering, the route from a source to a destination, in a specific path, may not be the optimal choice. That is, to minimize communication interference, the selected path may not be the shortest path and may increase the number of hops in the routing path.

5.1.2 Proposed Protocols

As discussed in the Sub-Section 5.3.1, we studied the idea of using a CNR which eliminates the need to establish backup paths while maintaining stability. This routing protocol, as defined previously, is called GBR-CNR. Without the requirement of backup paths to maintain stability, we expect it can be modified to reduce the interference better than the previously studied protocols where backup path mechanisms or multi-paths were used to maintain path stability. In the context of this part of our research, we introduce an approach based on GBR-CNR [92], a version of the original GBR [90], and the LBR original protocol named LEARN, which was proposed by Wang *et al.* [83] and discussed in Chapter 3, in order to establish the interference-aware stable paths.

5.2   Related Review to Minimize Interference

Interference limits the throughput of communication in MANETs by corrupting some of the packets that are exchanged among the mobile devices. Therefore, it is of critical importance to study the interference that affects the receivers in the MANETs environment. Pyun et al. [69] proposed a distributed topology control scheme in MANETs where the transmission power of each node was adaptively adjusted based on both the number of its neighbor nodes and the amount of interference that the node generated for its neighbors. To maintain the number of targeted neighbors, a mobile node may change (increase or decrease) its transmit power accordingly to it's number of neighbors.

Most of the prior work does not address the issue of how to handle mobility, an

inherent characteristic of MANETs that affects the accuracy of channel estimation and the effectiveness of spatial interference cancelation. This can lead to potentially over optimistic network performance. Therefore, Park et al. [64] studied the adaption of spatial interference cancelation to mobility and was observed to significantly improve the network performance, both in terms of outage probability and capacity, compared with the case without using adaptation.

De Rango et al. [15] considered a protocol that introduced the concept of interference in the choice of optimum routes in order to improve wireless system performance. Two distinct metrics were proposed: the first one was based on global interference perceived by nodes involved in the communication. The second one was based on the interference perceived only on the links belonging to the route from the source to the destination. The novelty of the proposal was, in the two metrics, adopted to select the optimal route from the source to the destination and in the route maintenance procedure. The proposed metrics were not based on the minimum hop number, such as with the AODV protocol, but on the global interference perceived by nodes (the first metric), and on the interference affecting the link involved in the transmission (the second metric).

The role of multiple antennas to void such strong interference was studied by Huang et al [34]. The study focused on canceling the strongest interference by using receivers which used zero-forcing beamformed. This method of zero-forcing beamforming interference management is widely used by many Media Access Control (MAC) protocols which effectively create an interference-free area around each receiving node through carrier sensing. This interference free area is usually called a guard zone. Optimizing this guard zone area can result in a significant transmission

capacity increase when a single-antenna in MANETs is used. Such a guard zone can help with interference cancelation and hence, would allow nearby transmitters to continue transmitting.

For instance, for a network with Poisson distributed transmitters and independent Rayleigh fading channels, the transmission capacity is derived, which gives the maximum number of successful transmissions per unit area. Mathematical analysis, from stochastic geometry, is applied to obtain the asymptotic transmission capacity scaling, and to characterize the impact of inaccurate Channel State Information (CSI). The effective interference model resulting from perfect interference cancelation is illustrated in Figure 5.1a. Also, as illustrated in Figure 5.1b, CSI estimation errors result in additional interference with respect to the case of perfect CSI.
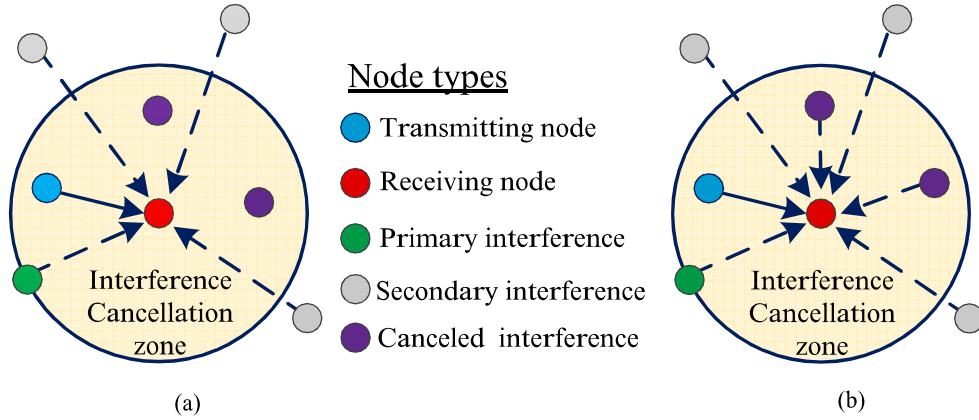
Figure 5.1: Effective interference model for a typical receiver canceling the two strongest interferers

In 2013, there was a study done by Gu and Zhu [25] and presented in the Interference Aware Cross Layer Routing protocol (IA-CLR). This is an interference aware routing protocol based on a node's sending and receiving capacities. IA-CLR builds

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the routes with the minimum bottleneck link interference by using the new routing metric that can comprehensively reflect the real network condition. In IA-CLR, when a node that is holding a packet, it will continue sending the Request-To-Send (RTS) control packets. It does so until it successfully occupies the channel after receiving the Clear-To-Send (CTS) control packets from the next hop or the number of retransmissions exceeds the threshold of six, as described in their work. Similar to channel reservation, the node will continue sending the packets until it successfully delivers the packet to the next hop or the number of retransmissions exceeds the threshold (three times).

Correspondingly, Zhou et al. [96] tackled the challenges of localized link scheduling posed by complex physical interference constraints. By integrating the partition and shifting strategies into the pick-and-compare scheme, they presented a class of localized scheduling algorithms with provable throughput, which guarantees the subject to physical interference constraints. The basic pick-and-compare scheme works as follows: at every time slot, a feasible schedule is generated that has a constant probability of achieving the optimal capacity region. If the weight of this new solution is greater than the current solution, it replaces the current one.

5.3   Routing Environments and Models

To accomplish efficient use of network resources, routing asymmetries, as well as QoS requirements, should be considered when building stable paths in MANETs. The aim is to develop a model, which can be able to serve big groups of users with high level of QoS they expect, while using network resources in an efficient way. This is a

challenge to be fulfilled as current broadcast protocols still have difficulties in dealing with concurrent transmissions.

5.3.1   Conservative Neighborhood Range Model

In the Sub-Section 3.1.1, we proposed an approach for position-based stable routing for MANETs, which we review it again here. Since nodes are in constant movement with different speeds and directions, a node positioned within the transmission range of another neighboring node at a certain time, might be out of the range at another time. In GBR [90], GPSR is used to construct the primary path such that each node considers the closest node to the destination within its transmission range as its next hop (see Figure 5.2). To maintain local link stability, GBR locally constructs backup paths. Due to the greedy manner of GPSR, a node may move out of transmission range before the next HELLO beacon will broadcast, resulting in no further received transmissions.

As we introduced in the Sub-Section 3.1.1, we modified GBR by introducing a CNR which takes into account the possibility of nodes that could go out of range during the interval and subsequently avoided including them in the path. This led to a significant reduction in the packet losses as well as increasing the reliability of communication.

The CNR in Figure 5.3, if node u is the sender and node D is the destination, then node u will pick the node v that is close to the destination as its hereafter node, if node v will not go out of transmission range of node v during that interval. Also, the CNR is defined by the conservative neighborhood transmission range R_c, which depends on the velocity of the node, the interval between the HELLO message broadcasts, and
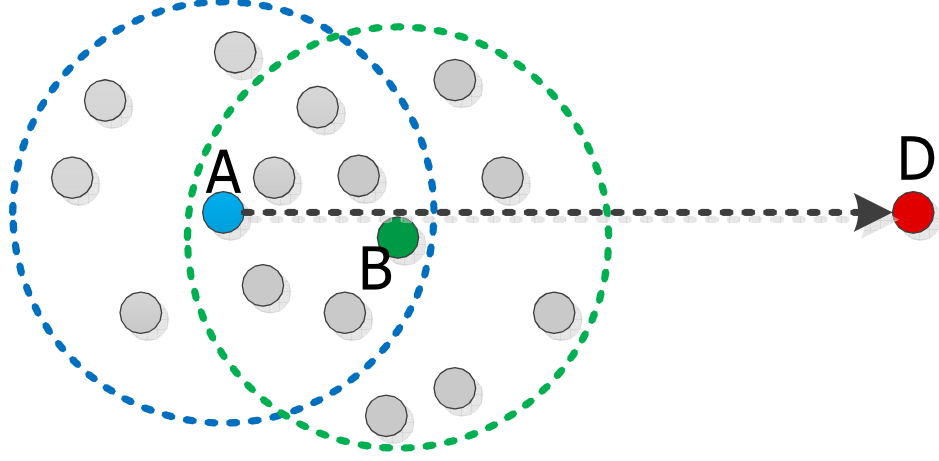
Figure 5.2: GBR-CNR selecting a next hop node: If node A is the sender and node D is the destination, then the GBR-CNR mechanism will be as follows: node A will pick the node B, the hereafter node in the path. Since node B is the closest destination node among all of node A's neighbors

the actual transmission range value. R_c is given by $R_c = R - (v_{max}t)$ where R is the actual transmission range, v_{max} the maximum node velocity, and t is the time interval between HELLO message broadcasts. If the next hop neighbor v_{i+1} is chosen within this conservative neighborhood range from v_i, then v_{i+1} will not go out of transmission range of v_i during this interval. Additionally, no links in the primary path will break before the next HELLO beacon will broadcast. There will be no need to back up the primary path. The result will be less communication interference compared to the multi-paths mechanisms. This is called a Greedy-based Backup Routing Protocol with next-hop neighbors chosen from the CNR (GBR-CNR).
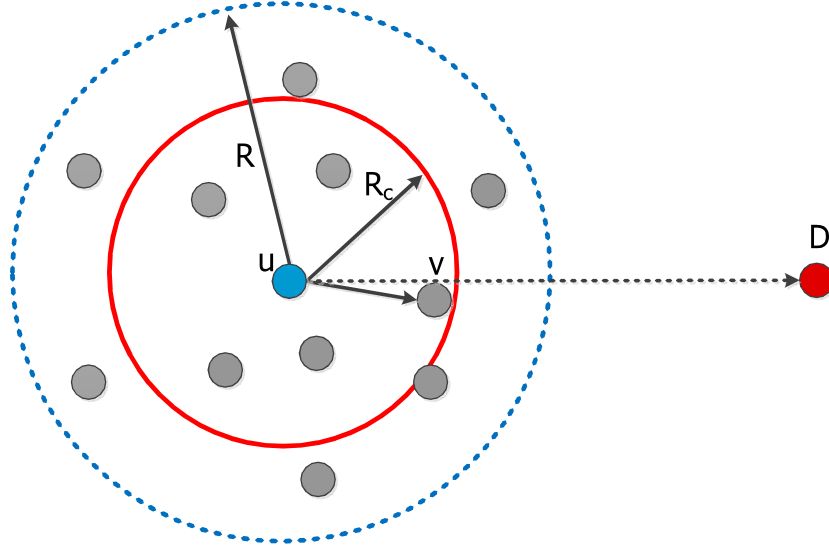
Figure 5.3: Transmission Range for GBR-CNR protocol: If node u is the sender and node D is the destination, then node u will pick the node v that is close to the destination as its hereafter node, if node v will not go out of transmission range of node v during that interval.

5.3.2   Interference Ratio Models

In MANETs, we modeled the locations of the nodes using a random uniform distribution. As there is no centralized station that manages the traffic, mobile device scheduling would determine which device should transmit at which times, what modulation and coding schemes to use, and at which transmission power levels a communication should take place at. In addition to its great significance in MANETs networks, developing an efficient scheduling algorithm is extremely difficult due to the intrinsically complex interference among simultaneously transmitting devices in the network.

Measurement of Interference

The Signal-to-Interference-plus-Noise Ratio ($SINR$) is commonly used in wireless communications in order to measure the quality of wireless connections [26]. If we consider a particular receiver located at position d, its corresponding $SINR$ is given by:

$$SINR(d) = \frac{P}{I + N} \tag{5.1}$$

where P is the sender transmission power, I is the interference resulting from the active transmission power of the neighborhood devices surrounding the receiver, and N is some noise term. In this research, in order to improve $SINR$, we focused on minimizing the interference I that affects the receiver by choosing the next hop node either with fewer neighbors or with the least usage in previous constructed paths. Indeed, interference takes place when a sender S communication is scheduled at a specific time slot during which one or more neighbors of the sender's receiver R are also scheduled. This causes the corruption of packets that are received by R. The interference I is defined as :

$$I = \sum_{i \in \tau} P_i h_i l(\parallel d_i \parallel) \tag{5.2}$$

where the summation for I is taken over the set of all interfering transmitters τ , P_i is the transmitting power, h_i is the random variable that characterizes the cumulative effect of shadowing and fading, and l is the path loss function, assumed to depend only on the distance $\parallel d_i \parallel$ from the origin of the interferer situated at position d_i in space. Often l is modeled as a power law, $l(\parallel d_i \parallel) = k_0 \parallel d_i \parallel^{-\alpha}$, or in environments where absorption is dominant, as an exponential law, $l(\parallel d_i \parallel) = k_0 exp(-\gamma \parallel d_i \parallel)$.

In a large system, the unknowns were τ , h_i, and d_i, and perhaps P_i, but it is the locations of the interfering nodes that most influences the $SINR$ levels, and hence, the performance of the network.

Interference Mathematical Model

The majority of previous studies have focused on reducing interference - primarily on the sending node. It has been proposed for topology based routing. This approach relied on probabilistic models to model the node neighborhood, etc., to decrease the interference. In order to reduce the interference, some researchers have proposed defining a restricted area in which no nodes should be used as a next hop. Wang *et al.* [83] based their choice of neighbors for routing on a critical transmission radius for energy efficiency, combined with dynamic transmission ranges, to define their Restricted Neighborhood Area. In this work, we define our restricted area by the Equation 5.3.

$$Area = \frac{R^2}{2}(\frac{\pi}{180} \times \theta - \sin\theta) \qquad (5.3)$$

where R and θ are illustrated in Figure 5.4.

In Figure 5.4, R is the transmission range, a is the coordinate of the sender, and $\theta = 2\alpha$. The restricted area α is calculated as $\alpha = \frac{\pi}{3}$ as used in [50,83]. This allows us to calculate the coordinates of the points b, c, d and e, thereby defining the restricted area as shown in Figure 5.4. Now, only nodes within this area will be considered by our algorithm as the next hop candidates. That is, if the sender node location is (x, y), then we confined the nodes that would have been considering (u, v), that should have been $x - \frac{R\sqrt{3}}{2} \le u \le x + \frac{R\sqrt{3}}{2}$ and $y + \frac{R}{2} \le v \le y + R$ respectively. However, the node chosen should fulfill two conditions: first, it should be the closest
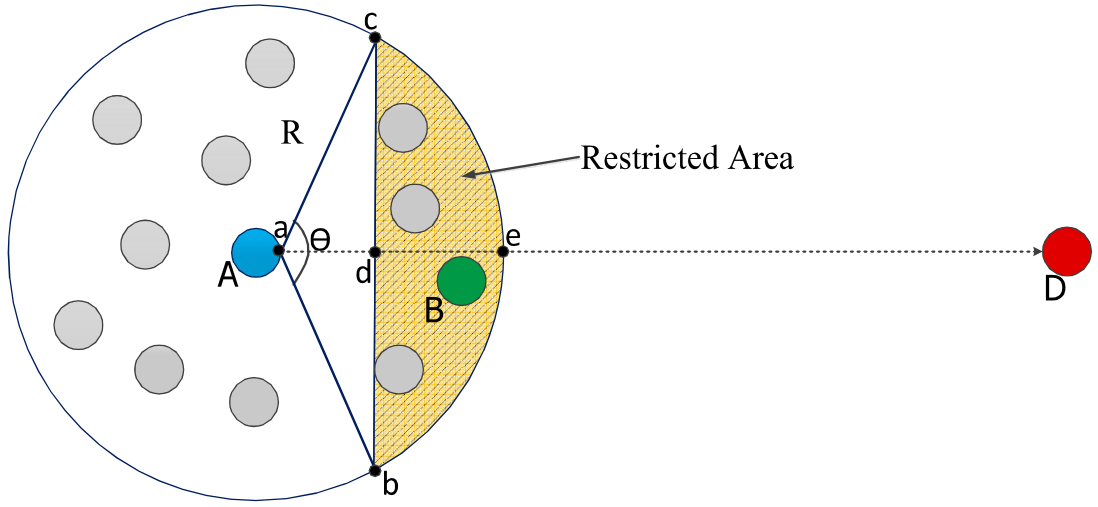
Figure 5.4: Calculate restricted area

node to the destination, and, second, either *i*) it is not being used in a path, or *ii*), it has the fewest number of neighbors. This was a greedy based selection. If the node was already in use, we selected the second closest node which satisfied the conditions, and so on.

5.4 Minimizing Interference Schemes

Our study focused on minimizing interference in order to maintain communication stability by decreasing the number of corrupted packets in the Position-based routing protocol. Furthering the work in [90,92–94], we propose to improve network efficiency (in terms of network through-put) and overall communication interference by using ideas such as choosing the hereafter hop either to be a node with few neighbors, or a node utilized in few paths, instead of simply using the closed node with the destination. Also, we assume that all nodes were uniformly and randomly distributed in a 2*D* space. Each node has a single channel Time Division Duplex (TDD) and the

same transmission range. For simplicity, we assume the interference range is equal to the considered transmission range of the nodes.

5.4.1 Minimizing Interference Using the Node with Fewer Neighbors

In order to develop a more interference-efficient variation of GBR-CNR, we considered the number of neighbors in the receiving node. The algorithm used was the GBR-CNR with fewer neighbors (GBR-CNR-LN). So, in Figure 5.5, we assume that if node A is the sender and node D is the destination, then node A will prefer, as the next hop, B_2 instead of B_1. This is because the number of neighbors belonging to B_2 are fewer than the neighbors of B_1. Fewer neighbors translates into a lower probability of corrupted packets; hence, an increase in network throughput.
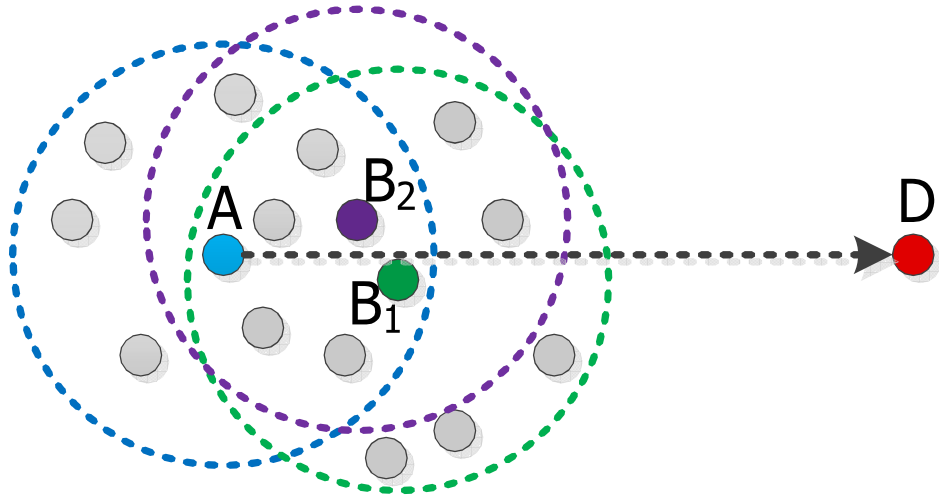
Figure 5.5: Next hop according to the number of neighborhood nodes

5.4.2 Minimizing Interference Using the Next Hop Node with Less Used

Exploring another variant of the aforementioned approach to achieve more interference-efficient routing using GBR-CNR, we considered the number of communications the receiving node was already participating in. The algorithm used was the GBR-CNR with the less used (GBR-CNR-LU) nodes chosen as the next hops. For example, in Figure 5.6, we assumed that there are two paths. For the first path, A_1 was the sender, D_1 was the destination, and node B_1 participated at the first path as the hereafter hop for node A_1. So far, when our protocol established the second path, it was assumed that node A_2 was the sender and node D_2, the destination. Consequently, node A_2 preferred, as a next hop, node B_2 instead of B_1, even though for node A_2, node B_1 was closer to the destination D_2 than node B_2. That was because node B_1 participated in more communications than node B_2. Thus, a node that participates in fewer communication paths is less susceptible to message corruption.

5.5 Performance Evaluation of Minimizing Communication Interference

This section presents simulation results comparing the algorithms GBR, GBR- CNR, LBR, GBR-CNR-LN, and GBR-CNR-LU. First, we discuss the simulation setup and give the simulation results.
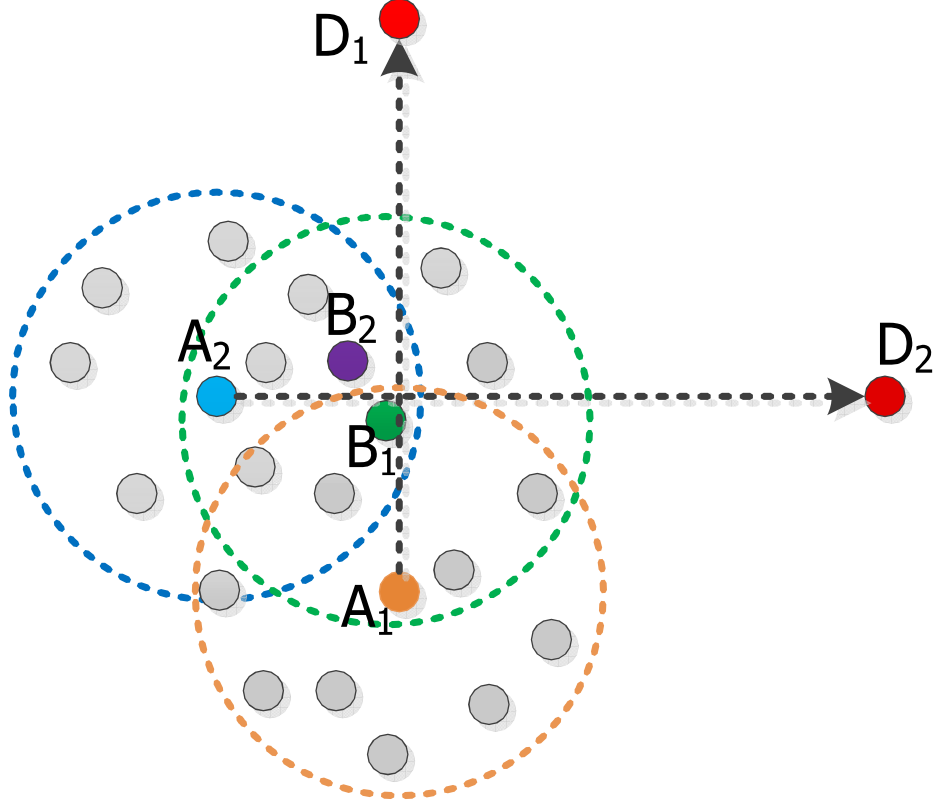
Figure 5.6: Next hop according to the number used

5.5.1 Simulation Setup of Communication Interference

For all the algorithms, we constructed the primary path as described in Sub-Section 5.3.1. In addition, for GBR and LBR, back-up paths were also determined. The simulation environment was modeled using network parameters that consisted of a network area of $2500m \times 2500m$, 400 nodes, and a maximum transmission range of $R = 250m$. Each simulation took 600 seconds with enough packets for the simulation time. There were 20 pairs of CBR data flows in the network layer and non-identical source and destination flows were randomly selected. Each flow did not change its source and destination throughout the simulations. The direction that a node could move

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was assigned randomly at the beginning of the simulation. When a node approached the boundary at angle ϕ, we reflected the node off the boundary by using the formula $\phi + \pi/2 + C$ [66]. For each different node density, 40 randomly distributed connected graphs were used as a starting network topology for each run of the simulation. For all algorithms, Matlab was used. This was done to get average performance results for better analysis. The velocity was chosen to be the same for all nodes at $V = 10m/s$, and the HELLO beacon interval, t, was set to two seconds. At the end of the two second interval, if a path was determined to fail within the next two seconds interval (from the path's PET value), then at the beginning of the next HELLO interval, a new path was determined between the source and the destination nodes.

5.5.2 Effect of Communication Interference: Results and Discussion

Our simulation results are presented in the following figures. As was noted in [92], the number of packets sent and delivered for the original GBR was much smaller (see Figure 5.7) than for the CNR based versions. This was due to the paths breaking and having to be re-established using a back-up path or requiring complete recalculation before the end of the HELLO beacon interval. Respectively, we can observe that the total number of delivered packets by GBR-CNR was greater than the total number of packets delivered by both LBR and GBR strategies, under the same network circumstances. Also, from Figure 5.8, as expected, we observe that GBR greatly used the nodes during the simulation. This was due to the number of times that the GBR reformatted the path as well as the need to backup the path, following LBR.

Both Figure 5.9 and Figure 5.10 show the total number of lost packets and the
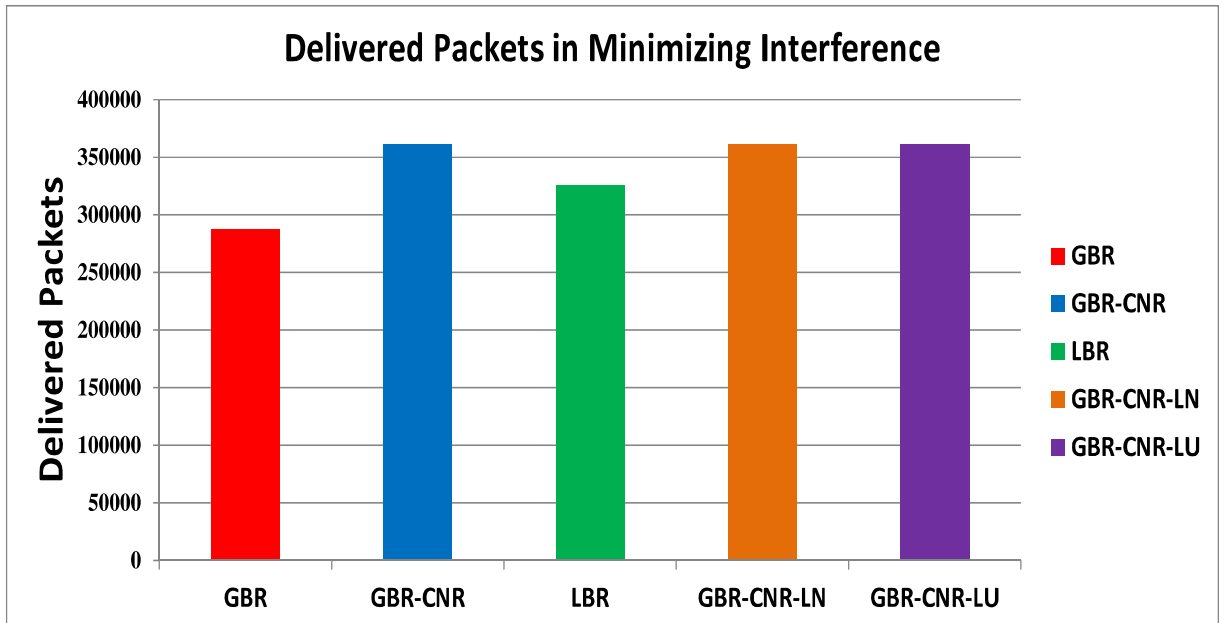
Figure 5.7: Total Number of Delivered Packets
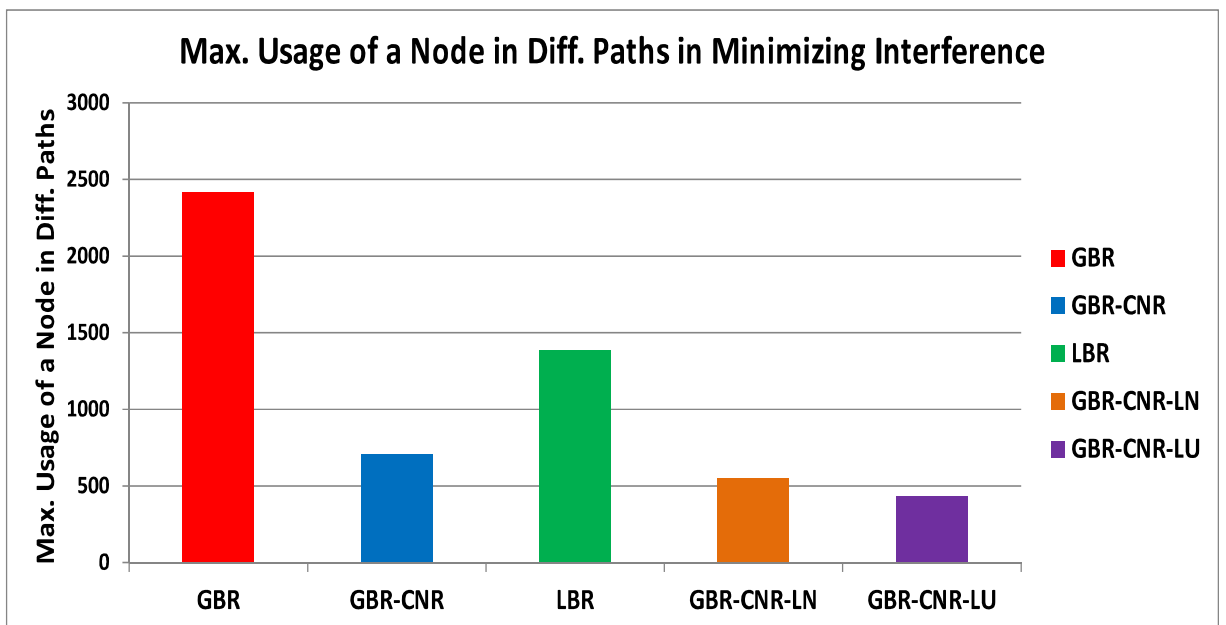
Figure 5.8: Most Highly Used Node in Different Paths

total number of corrupted packets respectively.
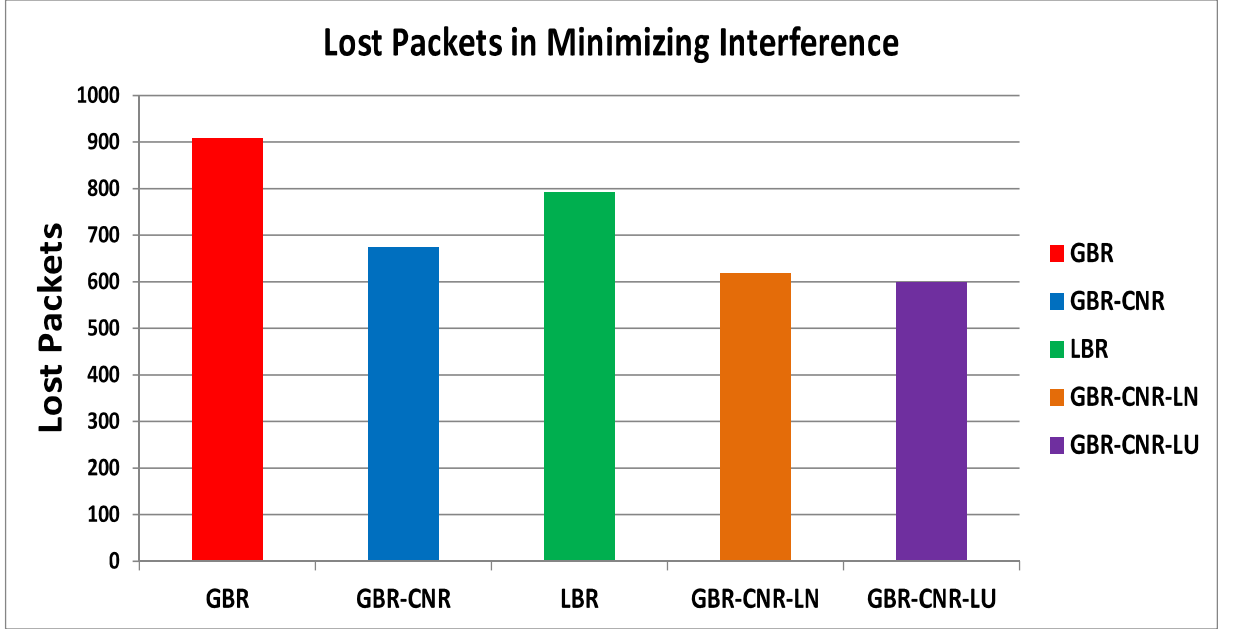
Figure 5.9: Total Number of Lost Packets

Correspondingly, the percentage of lost packets is highest for GBR followed by LBR, as shown in Figure 5.12. Of all the algorithms, the percentage of lost packets is the smallest for GBR-CNR-LU which seeks to use less utilized nodes as next hop nodes, with about 3.5% fewer packets lost as compared to GBR-CNR. Note that in Figure 5.11, the percentage of total number of delivered packets by the algorithms during the total simulation time will be the sum of the number non-corrupted and corrupted packets as showing in Figure 5.11.

As seen in Figure 5.13, GBR also had the highest percentage of corrupted packets and GBR-CNR-LU had the smallest percentage, with about 3.9% fewer corrupted packets lost as compared to GBR-CNR. The final metric we consider, being mindful that the percentage of over-utilization of certain nodes in MANETs, such as sensor
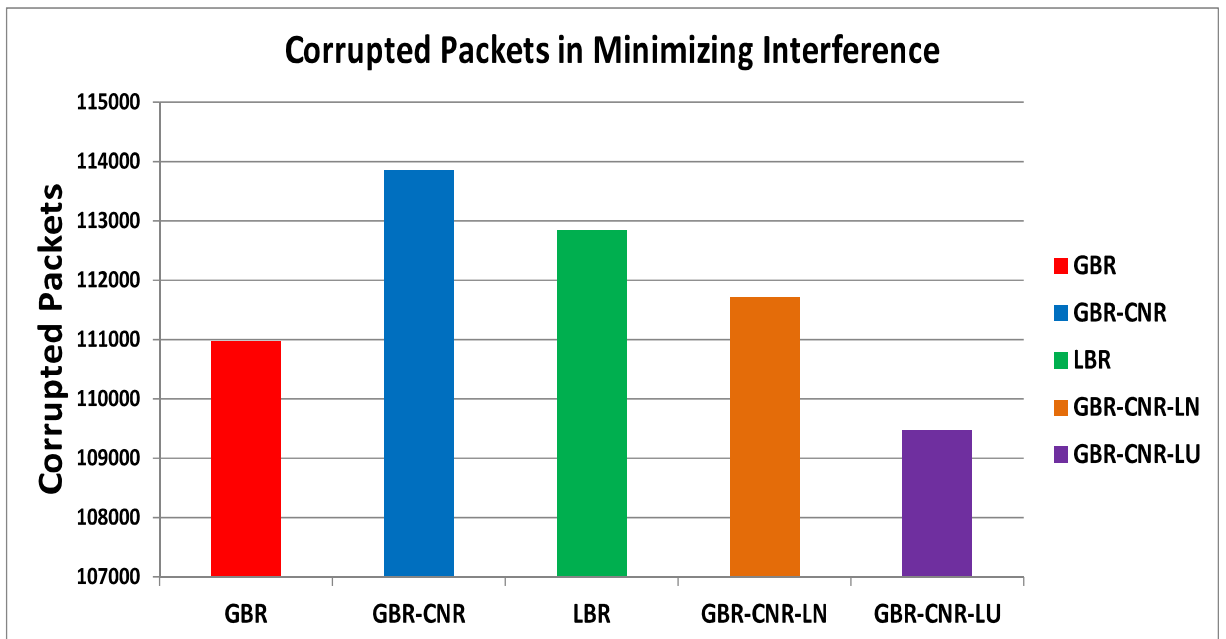
Figure 5.10: Total Number of Corrupted Packets

Figure 5.11: The percentage of total number of delivered packets

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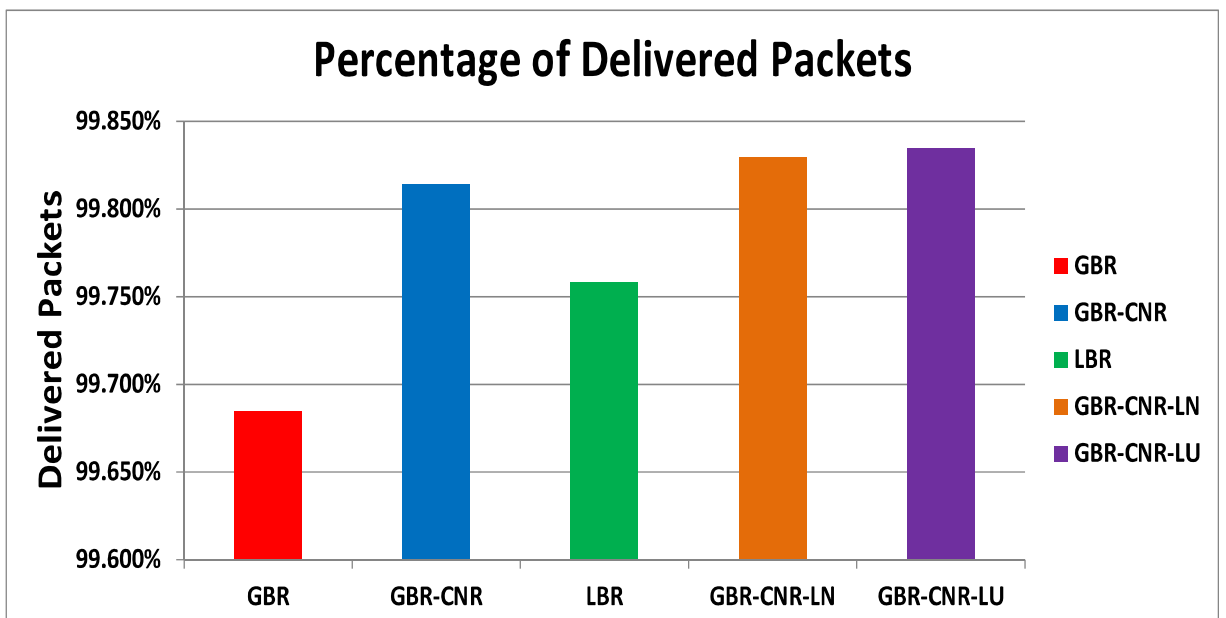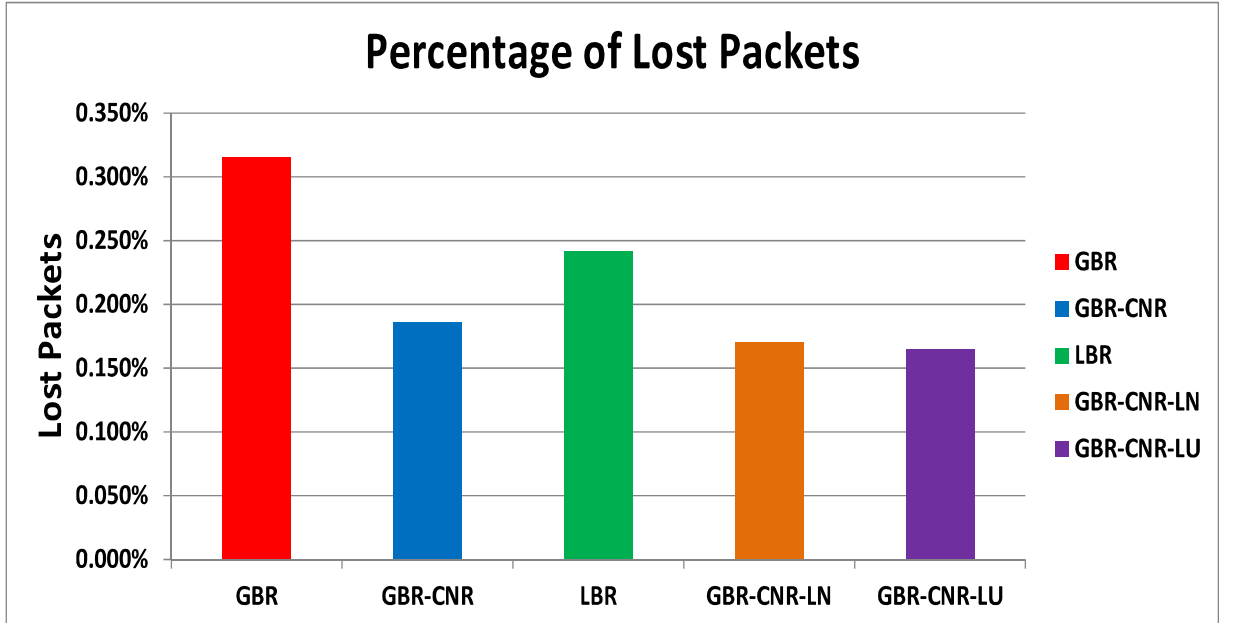
Figure 5.12: The percentage of packets lost during transmission

networks, that can lead to node failure, is the maximum number of different paths a node may be a member of.

In Figure 5.8, we can again see that the original GBR and LBR algorithms may max certain nodes by up to 5 times more than the corresponding maximally used nodes in the CNR versions. Again, GBR-CNR-LU had the smallest percentage of the maximum usage of nodes, with such nodes being used in 37.9% fewer paths as compared to GBR-CNR.

Constructing of new paths is requiring of message exchanges. We propose to compare the performances of GBR-CNR with the two protocols GBR-CNR-LN and GBR-CNR-LU in terms of Calculating New Paths (CNP) between the time intervals. Thus, we run different scenarios for the algorithms, with different number of nodes
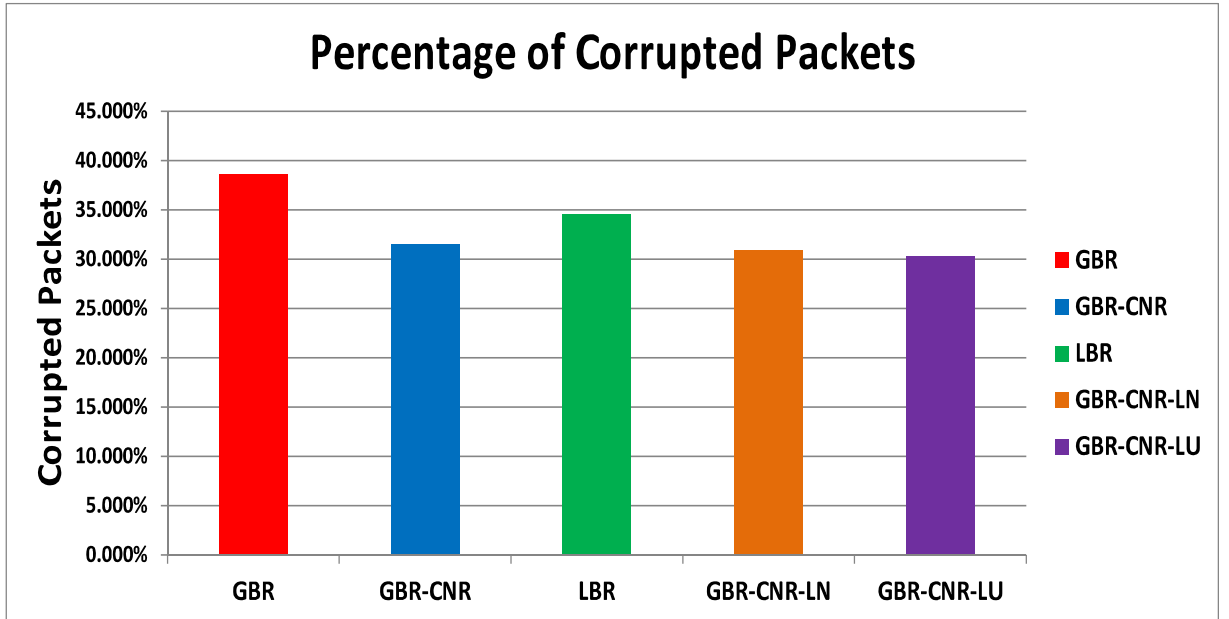
Figure 5.13: The percentage of corrupted delivered packets

varying from 200 to 600. Figure 5.14 shows the obtained results for GBR-CNR, GBR-CNR-LN, and GBR-CNR-LU. These results represent an average of CNP numbers over connections between 20 paths of source and destination nodes per interval, where the considered intervals are equal to 2 seconds and the total simulation time is equal to 10 minutes. Figure 5.15 shows the percentage decrease of the average number of new paths that need to be calculated CNP, an expensive operation, for GBR-CNR-LN and GBR-CNR-LU compare to GBR-CNR.
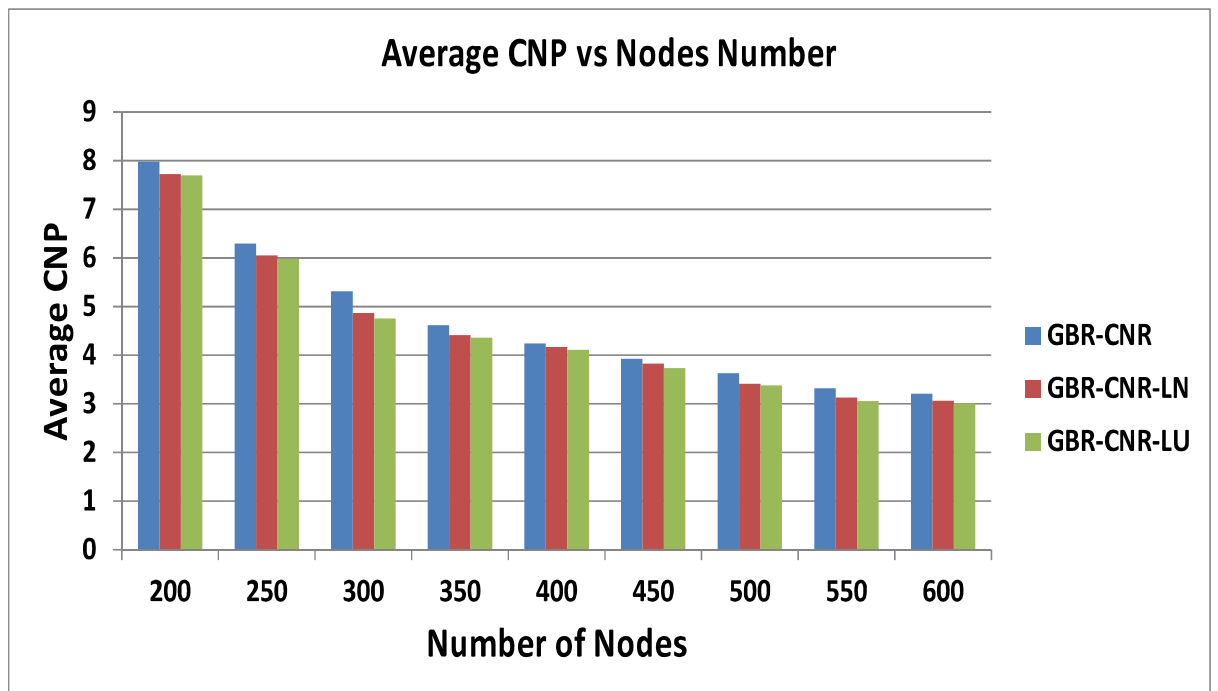
Figure 5.14: Average CNP vs Nodes Number
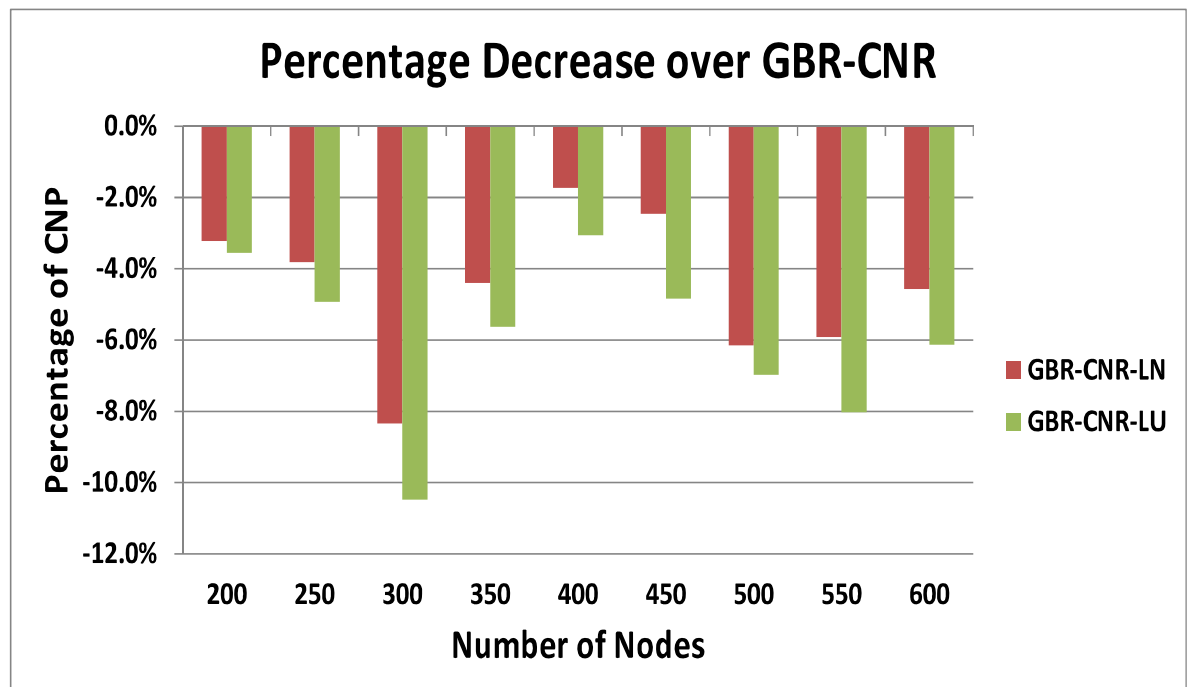
Figure 5.15: The Percentage Decrease of CNP over GBR-CNR

5.6 Minimizing Communication Interference Summary

In this chapter we have proposed a new approach to improving the performance of the GBR-CNR algorithm in terms of reducing the communication interference in MANETs. The approach was based on different strategies, namely the selection of next hop nodes that have the fewest neighbors, or the selection of nodes that have participated the least in previous constructed paths within the restricted area. We have validated our approach through several simulations that have shown our proposed algorithm significantly improved the performance of the packet delivery assuring higher network stability.

We have shown that using GBR-CNR-LU outperformed all the other versions of the algorithm as showed in Sub-Section 5.5.2. Nevertheless, this improvement was established at the cost of an increase of the number of hops between a source and a destination node when constructing the path. By comparing GBR with the other protocols in terms of the interference, GBR-CNR performed better. That was because both GBR and LBR had the backup path, which increased the number of nodes that participated in the overall communication in MANETs.

Chapter 6

Conclusion and Future Work

In this thesis, we have conducted a comprehensive study to validate several protocols for position-based routing for mobile nodes in order to maintain connection stability in several ways. We compared the application of backup paths for node protection with link protection. We considered the effect on delivery rates of using of more general backup paths, re-establishing broken paths from the last reachable node, or using a conservative range for neighbor selection. In addition, for networks where a substantial proportion of the devices are mobile, energy usage considerations are also important. Therefore, we also studied energy efficient variations of the routing algorithms in the context of maintaining stable connections between mobile nodes. Furthermore, since mobile devices typically represented by nodes in a MANET, are used to broadcast in limited shared media, therefore, we modeled new techniques, which are using both routing and scheduling mechanisms for wireless transmissions to reduce both redundancy and communication interferences.

6.1   Summary of the Thesis

In this thesis, the proposed protocols were validated and compared against GBR demonstrating their significant improvement to the previous available studies. The previous studies we selected in our experiments were the GBR, LBR and GBR-CNR, with source node path rediscovery. Our ideas showed a much greater overall improvement in terms of the network throughput and efficiency.

We studied the effectiveness of messages exchange, interval time, and node velocity on stable routing for MANETs in order to achieve high quality path lifetime, which will increase network throughput. To study this effect, in most of this study we have considered three contrasting position-based stable routing algorithms, namely, GBR, LBR, and GBR-CNR. For the GBR and LBR, stability was preserved through the use of backup paths in addition to the primary connection path; whereas, the GBR-CNR used a conservative neighborhood range where the links of the primary path did not break during the interval between HELLO messages. The results from our simulations indicated that the performance of the GBR-CNR protocol was superior to that of GBR and LBR in terms of connection throughput, particularly as the number of nodes increased.

Conservative neighborhood range is a technology used in our published papers and projects to denote the next major phase of mobile telecommunication standards beyond those previous studied. The most dramatic improvement was demonstrated when using a conservative neighborhood range where the use of backup paths for link protection is not needed, since the links of the primary path do not break during the interval between HELLO messages. The trade-off for this improvement is the need to know the maximum velocity of the nodes, and the use of regular intervals between

HELLO messages, in order to update the position of the nodes (and updating primary paths that are no longer reliable during the next interval).

6.2 Contribution of the Thesis

We have presented new protocols which were improved variations of the original GBR protocol using different ideas such as node protection, more general backup paths, rediscovering paths from last reachable node, and routing using only neighbors within a conservative neighborhood range. We studied these new protocols in terms of varying HELLO interval duration, varying node velocity, energy consumption, and reducing communication interferences. For each variation, when simulated using a mobility model of the MANET, higher network stability as well as higher packet delivery rates were obtained. The overall conclusions we can reach are the following:

- First of all, we have presented a node protection protocol GBR-NP that allowed for the establishment of stable connections in MANETs and which experienced occasional node failure. The proposed protocol was tested with simulations of model of mobility networks. The simulations consisted of mobile users with time variant locations and velocities that affect the communication reliability in MANETs. We showed that this led to a high network stability as well as a high packet delivery rate. The protocol was validated and compared against the link protection protocol, as implemented by the GBR protocol, showing a significant improvement in number of delivered packets and delivery rate when nodes may occasionally fail. Hence, the presented node protection protocol GBR-NP can be used to improve the communication stability in MANETs under increasingly

realistic conditions of node movement and occasional failure.

- Secondly, we presented improved variations of GBR using ideas such as, more general backup paths GBR-MBP, rediscovering paths from the last reachable node GBR-RPLRN, and routing using only neighbors within a conservative GBR-CNR. For each variation, when simulated using a mobility model of the MANET, higher network stability as well as higher packet delivery rates were obtained. The most dramatic improvement was demonstrated when using a CNR, where the use of backup paths for link protection was not even needed since the links of the primary path did not break during the interval between HELLO messages. The trade-off for this improvement for GBR-CNR was the requirement that both the maximum velocity of the nodes be known and the use of regular intervals between HELLO messages to update the position of the nodes (and updating primary paths that are no longer reliable during the next interval).

- Thirdly we sought to further explore and challenge the GBR-CNR protocol with energy in terms of maximum energy expended per node in the MANET's environment. Our proposed protocol, GBR-CNR-DTR, was demonstrated to maximize both the stability of connections, measured in terms of throughput, as well as the energy-efficiency of these connections, while requiring the fewest number of routing control message exchanges. The only energy expenditure measure, for which GBR-CNR-DTR did not outperform over the other protocols over various node densities, was for the average energy expended per node where it was second only to GBR-DTR. For all the energy-efficiency measures, the use of the adjustable transmission range R_a consistently improved the energy

consumption properties of the routing protocols, as expected. However, the use of LEARN, in place of GPSR for the stability routing protocol GBR, did not lead to a more energy-efficient stable routing protocol. A byproduct of selecting routing nodes near the critical transmission radius r_0 had a higher throughput for LBR and LBR-DTR, as compared to GBR and GBR-DTR.

- Fourthly, we studied the effect of interval time duration on stable routing GBR-CNR for MANETs in order to achieve prolonged path lifetimes that will increase network throughput. To study this effect, we considered three contrasting position-based stable routing algorithms, namely, GBR, LBR, and GBR-CNR. In the first two, stability was preserved through the use of backup paths in addition to the primary connection path; whereas, the last algorithm used a conservative neighborhood range where the links of the primary path did not break during the interval between HELLO messages. The results from our simulations indicated that the performance of the GBR-CNR protocol was superior to that of GBR in terms of connection throughput - particularly as the number of nodes increased. However, as we increased the HELLO interval duration, this improved GBR-CNR performance eventually came at the cost of a larger control message overhead than for GBR.

- Fifth, we challenged our GBR-CNR protocol by changing both the velocity and duration of the HELLO interval beacon message on the performance of the three schemes - GBR-CNR in comparison with GBR and LBR. Although a small node velocity and small size of HELLO interval duration led to good performance for GBR-CNR, GBR-CNR did not perform as well when both the velocity and HELLO interval size were increased.

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- Finally, interference will deteriorate the performances of weak control networks. It is crucial to consider the effects of wireless interference when considering both routing with general backup paths mechanism, and routing just with neighbors within a conservative neighborhood range. We observed that the impact of GBR-CNR-LU outperformed all the other versions of the GBR, GBR-CNR, LBR, and GBR-LN algorithms, in terms of minimizing the communication interference in MANETs. To conclude, the proposed improvements to GBR-CNR had a significant impact on the quality of service and communication stability in MANETs.

The aim of this research was to provide stability oriented connections in MANETs. The proposed approach, the GBR-CNR protocol, dispenses with the need for backup paths. It was validated and compared against different protocols on different environments. The simulation results showed that GBR-CNR outperformed other routing protocols in performance metrics. If energy considerations are also important, then the dynamic transmission range version, GBR-CNR-DTR, preserved the performance of GBR-CNR while dramatically reducing the energy usage.

6.3   Drawback of our approaches

In our research work we designed and implemented a complex mobility distributed systems in MANETs, following a brief discussion about downside of distributed systems and backup paths. In decentralized system, it is very complicated to control and maintain traffic, priority, shortest path, queuing, fairness, and over all communication. Also, by using backup path mechanism it will be quite difficult to reduce

message exchange and duplication at the receiver side of the mobile device, nor does it provide a uniform service to all mobile devices. Furthermore, since all nodes have equal responsibility to make a decision that will make issues like security and privacy more difficult to control during communication.

6.3.1   The drawback of distributed networks

In ad hoc distributed networks, the communications done through a broadcast, therefore the data needs to pass through multiple hops before it reaches its final destination. This leads to a waste of bandwidth as well as an increased risk of data corruption, security, privacy, potentially, and higher energy consumption due to establishing the paths and the required error control mechanism. On other hand, if the source and destination nodes are in each others transmission range, MANETs networking can be more efficient and reliable. Although, MANETs networks are more flexible than centralized networks, they are less suitable for the design of scalable mobile topology and low energy consuming mobiles. The assumption is that mobiles will always have a limited amount of energy; whereas, the wired base-stations will have virtually unlimited energy. Therefore, in a centralized system, the base station can be equipped with more intelligent and sophisticated hardware, that likely have significantly higher energy consumption than the hardware required in the MANET systems. Portables can then be offloaded with some functionality that will be handled by the base station.

6.3.2   The drawback of using backup paths

Setting up a backup path in MANETs for protecting the primary path is one way to achieve higher reliability and communication stability in MANETs. One straightforward solution to this problem is to find two disjoint paths, and to protect the primary link between the two nodes participating in the path, or by protecting the node itself. However, this requires at least twice the amount of network resources used by a single path. For a restoration objective, like single path failure recovery, links on the backup path can be shared between different active paths such that single path failure restoration is guaranteed.

6.4   Conclusions

The aim of this research was to provide stability oriented connections in MANETs.

We have proposed a new routing protocol called GBR-CNR to maintain routing stability, which is shown to outperform many existing routing protocols in different environments. We have used an approach to reduce the message overhead through the elimination of backup paths. Moreover, we have measured the impact of different performance criteria on the quality of communication e.g. Interval Times and Nodes Velocities. We have also presented an energy aware protocol called the GBR-CNR-DTR that preserves the performance of GBR-CNR while dramatically reducing energy usage. Finally, we have proposed new approaches to reduce the number of corrupted packets caused by interference, leading to the improvement of the quality of communication.

6.5 Future Work

We have shown the performance of distributed protocols improved routing performance in several types of sophisticated mobility scenarios by reducing the energy consumption, control overhead, and interference. There are several studies that could be considered for further research. The following list includes, but is not limited to, some potential future research:

- **GBR-CNR Routing in 3D Networks:** this thesis research focused on the problems of link expiration, node protection, energy consumption, interference, and overall communication stability routing in $2D$. However, in real world scenarios, nodes can be distributed in $3D$ space rather than $2D$ space; therefore, it's possible to extend the $2D$ applications to the 3D space. In $3D$ MANETs, a symmetric graph can be considered where two nodes can communicate only if they are within mutual transmission range of each other. Research could explore the same techniques (e.g. backup path, conservative transmission range, protecting the link between a pair of nodes in a path, and protecting intermediate nodes of the path instead of just the links between two neighboring nodes, energy consumption, and interference) for $3D$ ad hoc networks of mobile nodes.

- **Energy Consumption on Mobile Networks:** upsurge energy costs have placed extreme pressure on designing mobile devices and topologies to develop energy efficient mobile devices and systems for users to utilize. To achieve a stable path along the generated path, the appropriate interval time, node direction and velocity at the defined protocols are selected to minimize the energy consumption.

- **Interference in Cloud Mobile Networks:** as each device in MANETs is working in standalone, it is efficient to explore our collaboration algorithms in order to reduce the interference between neighborhood nodes. Therefore, it is much more practical to focus on minimizing the communication interference on cloud environments through the extension of the handover management to heterogeneous. This could, in mobile networks, lead to the optimization of resource usage and minimization of interference, which also leads to an efficient configuration.

6.6 Publications

Refereed Publications

- A. Zadin and T. Fevens, "Minimizing Communication Interference for Stable Position-Based Routing in Mobile Ad Hoc Networks," The 6th International Conference on Ambient Systems, Networks and Technologies (ANT-June 2015 **"Best Paper Award"**), 2nd *June* 2015.

- A. Zadin and T. Fevens, "Energy Efficient Stable Routing using Adjustable Transmission Ranges in Mobile Ad Hoc Networks," in 13th International Conference on Ad-Hoc Networks and Wireless (AdHocNow), 22th *June* 2014.

- A. Zadin and T. Fevens, "Effect of HELLO Interval Duration on Stable Routing for Mobile Ad Hoc Networks," in 27th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), 04th *May* 2014.

- A. Zadin and T. Fevens, "Maintaining Path Stability with Node Failure in

Mobile Ad Hoc Networks," The 8th International Symposium on Intelligent Systems Techniques for Ad hoc and Wireless Sensor Networks (IST-AWSN), 25th *June* 2013.

- A. Zadin and T. Fevens, "Stable connections using multi-paths and conservative neighborhood ranges in mobile ad hoc networks," in 26th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), 08th *May* 2013.

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