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EVALUATING URBAN DEPLOYMENT SCENARIOS FOR VEHICULAR WIRELESS NETWORKS

By

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To my mother and all her sacrifices.

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ABSTRACT

Vehicular wireless networks are gaining commercial interest. Mobile connectivity, road safety, and traffic congestion management are some applications that have arisen with this networking paradigm. Existing research primarily focuses on developing mobility models and evaluating routing protocols in ideal open-field environments. It provides limited information of whether vehicular networks can be deployed in an urban setting. This thesis evaluates the practicality of deployment scenarios for a vehicular ad hoc network with a wireless mesh infrastructure support. The deployment scenarios include: (1) a mesh-enhanced peer-to-peer ad hoc routing deployment model where both the mobile nodes and static wireless infrastructure nodes participate in routing, (2) a mesh-enhanced infrastructural routing deployment model where only the static wireless infrastructure nodes participate in routing and (3) a scenario where static wireless infrastructure nodes in deployments (1) and (2) have the ability to communicate over multiple wireless channels. These deployment scenarios are evaluated with a mobility model that restricts the movement of vehicles to street boundaries based on real world maps and imposes simple traffic rules. This study also proposes a method of capturing the effect of obstacles on wireless communication based on empirical experiments in urban environments.

The results indicate that (1) the mesh-enhanced infrastructural routing deployment yields significantly better performance compared to mesh enhanced peer-to-peer ad hoc routing deployment; (2) in the mesh-enhanced infrastructural routing deployment scenario increasing the density of infrastructure nodes is beneficial while increasing the density of mobile nodes has no significant effect; (3) in the mesh-enhanced peer-to-peer ad hoc routing deployment scenario, higher density of infrastructure nodes as well as mobile nodes can lead to decreased performance; (4) using multiple channels of communication on infrastructure nodes yields highly increased performance; and (5) the effect of obstacles could be represented in simulations through parameters, which could be set based on empirical experiments.

CHAPTER 1

INTRODUCTION

1.1 Motivation

A vehicular wireless network is comprised of wireless communication devices installed in vehicles in order to provide services to passengers. Recently, many commercial applications have evolved in this domain, including exchanging safety information, traffic monitoring and reporting, providing mobile Internet services, and entertaining passengers.

There are different ways to deploy a vehicular ad hoc network (VANET). A pure wireless vehicle-to-vehicle ad hoc network (V2V) is the most widely considered option. In this deployment model, there is no infrastructure support. The mobile vehicles act as relay nodes in the network. Hence, the locations and the mobility patterns of vehicles play an important role in network connectivity and performance. VANETS are comprised of highly dense and mobile network nodes. Vehicle speed varies as vehicles accelerate and decelerate. Nodes form queues and wait at intersections, which can lead to the formation of network-isolated clusters of vehicles.

In such a highly mobile and dynamic environment, the V2V deployment may not be the best choice as there would be frequent route breakages. One alternative is to provide infrastructure support, which adds stability to the network connections. It is usually in the form of static wired nodes, for instance the cellular network, where the infrastructure nodes communicate to the neighboring nodes via physical wires to provide end points to mobile nodes. Infrastructure support improves performance, but at the expense of physical wiring. A wireless infrastructure support could be much more economical and swift to deploy by erecting rooftop network relay stations.

Recently, a significant amount of research has been invested in an upcoming wireless technology known as mesh networking. A mesh network consists of static wireless routers relaying packets in a multi-hop fashion and provides high economic benefits over its wired counterpart. Today, mesh networks are primarily being used to provide broadband Internet access to residential subscribers in a neighborhood. However, mesh networks can also be used to provide infrastructure support to VANET, by deploying static wireless routers at street intersections and forming a mesh-like network backbone. Unlike a wired cellular phone network, a mesh network can perform wireless routing between mobile vehicles as well as the static infrastructure entities. Although more economical, the sharing of communication channels among neighboring mesh nodes may reduce network capacity and impose constraints on concurrent, bidirectional communication patterns.

A VANET with a mesh backbone of static wireless routers combines two recent wireless technologies. Consequently, the practicality of various deployment models and performance characterizations is not well understood. One scenario is where both mobile vehicles as well as infrastructure nodes participate in routing. The other scenario limits the routers to only the infrastructure nodes. The infrastructure nodes might have multiple wireless channels to enable concurrent, bidirectional communication as well as multiple transmissions among neighboring nodes.

Other factors in urban settings also complicate the analyses: traffic rules, street boundaries, and signal attenuations due to obstacles, which are commonly overlooked in studying ad hoc wireless networks. This thesis evaluates the feasibility of various VANET deployment models under various urban deployment constraints.

1.2 Contributions

This thesis evaluates the practicality of deploying a vehicular wireless network in light of the following factors:

- Vehicular mobility
- A static wireless infrastructure support
- Availability of multiple wireless channels in the infrastructure

- Presence of obstacles in the communication environment

Specifically, we study the practical ness of a particular deployment scenario by understanding the effect of the factors listed above on behavior of the routing protocol (AODV [1]) in that deployment scenario.

Following are the specific contributions of this thesis

1. Performance evaluation of a VANET routing protocol in the presence of wireless infrastructure support: The experiments included varying the ratio of infrastructure nodes to mobile nodes.
2. Testing the option of using only the infrastructure nodes as routers.
3. Exploring the availability of multiple channels for communicating among infrastructure nodes: The thesis includes an implementation of a static channel assignment algorithm.
4. A representation for obstacles in wireless network simulations through parameters that can be tuned as desired: This representation is based on empirical measurements around city blocks and buildings. Various VANET evaluations included the effects of obstacles.
5. The use of a traffic-rule-based mobility model for various VANET evaluations.

Two deployment scenarios are evaluated - A mesh-enhanced peer-to-peer ad hoc routing deployment where mobile nodes as well as infrastructure nodes participate in routing and a mesh-enhanced infrastructural routing deployment where routing is restricted to infrastructure nodes. The key observations made in this thesis are

1. The mesh-enhanced infrastructural routing deployment has a positive impact on VANET's performance and scalability as it limits the number of nodes participating in routing.
2. With both mobile nodes and static infrastructural nodes participating in the routing, the network performance is lower compared to the case where only the infrastructural nodes perform routing. This finding indicates that the performance of a routing protocol depends on the nature (static/mobile) of the participating nodes.
3. Multi-channel or multi-radio ability in the infrastructure improves the performance and scaling of routing protocol significantly. This kind of deployment can support a high

number of static and mobile nodes that participate in routing. Routing protocol performance is improved by increasing the number of available channels for communication; however, as the number of channels increase beyond three, performance degrades due to interference among adjacent channels.

4. Obstacles significantly hamper performance of routing protocols. Obstacles can be represented as a combination of an obstacle factor and a distance factor in wireless communications. Both can be set based on empirical experiments.

This thesis used the popular ns-2 simulations to conduct repeatable experiments under controlled variations of parameters, to explore a wide range of parameter space. Various contributions listed above are achieved through extending the ns2 simulator.

The remainder of this thesis is organized as follows. Chapter 2 reviews related research in the field of VANET and other fields relevant to deployment of VANETS. Chapter 3 discusses the urban setting under which deployment scenarios for VANET are evaluated. Chapter 4 presents details of the implementation of this work Chapter 5 evaluates the deployment scenarios by studying their influence on performance of routing protocol AODV. Chapter 6 describes the future directions and Chapter 7 summarizes the research contributions of this work.

CHAPTER 2

RELATED WORK

The related work includes mobility model development, routing protocol performance evaluations, studies in mesh networks and multi radio networks, and obstacle modeling in wireless communications. Although each area advances in isolation, this thesis unifies the state-of-the-art findings from all these areas to evaluate the practicality of urban V2V deployment.

2.1 Current work in VANETs

Many vehicular mobility models have been developed to study VANET performance. [2, 3] proposed vehicular mobility models for urban environment. [4] proposes VANET mobility models to capture different levels of mobility details. Apart from the mobility, how vehicles route message among themselves is an important factor for network performance. Several deployment scenarios are possible for connecting the in-vehicle systems as discussed in [5]: a pure wireless V2V architecture, a V2V architecture with a wired backbone and wireless last hops, and hybrid architectures with a combination of V2V and fixed wired infrastructure. Routing protocol performance has primarily been evaluated in wireless V2V networks. For instance, [6] introduced a mobility model and evaluated its routing protocol behavior in multihop V2V networks. [7] devised a protocol and distributed algorithm for propagation of data in VANETs without the use of fixed infrastructure. [5] proposed a mobility-centric data dissemination approach for ad hoc infrastructure-free V2V networks. The FleetNet Project [8] investigated multihop inter-vehicular communication where vehicles form separated clouds of ad hoc networks. Here, roadside installed Internet Gateways are introduced to provide Internet service to vehicles. The focus here is on protocol interoperability for Internet integration into vehicular systems. [9] studies characteristics of vehicular mesh networks and invents efficient routing algorithms in the context of commercial applications like distributed sensing and computing. Here, the vehicles are considered mobile routers that interconnect with a fixed infrastructure of gateways and form vehicular mesh networks. Limited efforts are devoted to studying the deployment alternatives for vehicular networks and evaluating their practicality. This thesis focuses on practical deployment of vehicular wireless networks with availability of a wireless mesh infrastructure support.

2.2 Mesh Networks and Multi Radio Networks

Mesh network is an upcoming wireless technology that is rapidly gaining research and commercial interest. Mesh networks are multihop wireless network of static nodes. A widely used commercial application is community networks, used by many companies as community networks or test beds for wireless broadband Internet access to subscribers. Research is being conducted at Microsoft [10] for deploying neighborhood community mesh networks. The Roofnet project at MIT [11] provides broadband Internet access to subscribers in Cambridge. Motorola has already provided mesh network solutions for intelligent transport systems and vehicular communication [12]. However, most effort is devoted to setting up and enhancing mesh networks for Internet access through community networks. This thesis examines the behavior of existing ad hoc routing protocols in scenarios with a wireless mesh infrastructure support to a vehicular network.

When the role of mesh networks is primarily carrying the backbone traffic, high network capacity is desired. One challenge of mesh networks is wireless channel interference with neighboring nodes. This effect is more pronounced due to the static nature of mesh networks. A resulting effort is providing multi-radio capabilities to these networks where every node can communicate over more than one channel. With multiple channels, efficient channel assignment among neighboring nodes becomes crucial, as many studies emerge solely to address the problem of efficient channel allocation for minimal channel interference and maximum utilization of bandwidth. [13] proposed channel allocation algorithms for multi-channel wireless mesh networks with commodity 802.11 hardware. Their work shows that with an efficient channel assignment of just two network channels per node, the network performance can result in improvement of a factor 8 over single channel networks. [14, 15, 16, 17, 18] followed a different approach by proposing ways to modify the MAC layer to support multi-channel ad hoc networks. [13] avoided per-packet channel switching and proposed the use of multiple NICS tuned to different channels. The multi-channel effect in mobile ad hoc networks has also been studied in [19] and involves the use of a proposed MAC protocol. Other routing approaches have been devised for multi-radio networks. [20] proposed a metric for routing in multi-radio multihop community networks. The behavior of IEEE 802.11 has been studied to some extent in vehicular communication. [21] noted that IEEE 802.11 cannot work efficiently in a vehicular environment due to high mobility. Instead, they devised a solution for a contention-free channel access scheme. This thesis evaluates the deployment of vehicular networks, with mulitple 802.11 MAC channels,available in the infrastructure mesh network. A static channel assignment approach is used here, where every pair of nodes tries to communicate on a different predefined channel.

2.3 Obstacles and Wireless Communications

The effect of obstacles on wireless communication has not been studied intensively to date. The most significant work in this area is by [22]. The work involves modeling of a terrain by the user by specifying the shapes and sizes of obstacles. The effect of obstacles on signal propagation is determined by a table-based lookup based on type of obstacle. This thesis proposes a way to represent obstacles in wireless networks simulations. This representation is in the form of tunable parameters. These parameters could be tuned based on actual experiments conducted in any given environment. This form of obstacle representation was obtained through empirical experiments conducted in an urban environment around city blocks.

CHAPTER 3

THE URBAN NETWORK SETTING

This chapter discusses the factors that comprise the urban setting under which various deployment scenarios are evaluated-(1) real world street maps, (2) a traffic-rule-based vehicular mobility pattern (3) a wireless infrastructure support for the vehicular network, and (4) a representation to capture effects of obstacles.

3.1 Real World Street Maps and Mobility Pattern

Maps define the boundaries within which node movement is confined. They represent the topographical area where the network performance has to be evaluated. Evaluations in this thesis are performed using a grid topology having a format similar to real world street maps. The purpose of using a synthetic grid topology is to enable evaluations with controlled variations in topology. Our simulations also permit the use of real world street maps instead of synthetic grid topologies. For instance, our earlier work in [23] studied various mobility models using real-world street maps as the first step to understand urban wireless networks. These maps are available from the US bureau TIGER database [24]. This database comprises of maps of every county in United States. Useful information can be extracted from these maps. The tool proposed in [2] extracts topographical information from the map for a given area in form of a file that contains information of all roads and street intersections in that area. These files can be used as maps in our network simulations in place of synthetic grid topologies.

After the topology has been chosen, the movement pattern of nodes over this area is the next crucial factor to be considered. The mobility pattern of nodes is a very important while considering a wireless network deployment. Routes form and break as nodes move towards and away from each other. The movement pattern decides how well connected the network is at any point of time. In vehicular networks considering mobility pattern becomes increasingly important due to the real world factors that govern motion of vehicles. For instance, vehicles always move along street boundaries and mostly in a single lane (on multi-lane roads), they accelerate and/or decelerate; they cluster together at traffic lights, halt briefly at stop signs and so on. Such factors that influence mobility need to be considered while evaluating the deployment of vehicular networks. Accordingly we use a new mobility model devised in our previous work described in [4]. This work points out the most important aspects of vehicular mobility that need to be considered while evaluating vehicular wireless networks. Based on the findings we consider node mobility in the light of following factors - movement along street boundaries in a single lane, vehicular acceleration and deceleration, presence of traffic lights and rules at intersections. This vehicular movement pattern is an important aspect of the urban setting under which deployment scenarios are evaluated.

3.2 The Wireless Infrastructure Support

The next factor in the urban network setting is the presence of a wireless infrastructure support for the vehicular network. By infrastructure support we mean a wireless backbone network of stationery nodes that provide services to the mobile vehicles. Such an infrastructure support to the ad hoc network is always beneficial as it would add more stability to the network. It is to be noted that this infrastructure is not to be confused with the infrastructure mode of operation in wireless networking that connects wireless and wired networks. The deployment in our case is completely wireless and the term infrastructure refers to a stationery wireless backbone network. The infrastructure support for the vehicular network is provided by a wireless mesh network of base stations positioned at street intersections. A mesh network is a wireless multi hop network of static nodes. Capacity of wireless mesh networks can also be enhanced with the ability to communicate over multiple wireless channels. Such networks are typically called as multi-radio networks. We now discuss different variants of mesh networks.

3.2.1 Single Channel Mesh Networks

A mesh network comprises of a network of static wireless nodes that forward each others packet in a multi hop fashion. All the nodes in the network participate in routing each others' packets. To gain some insight into the mesh architecture, consider the Internet. The core of the Internet consists of routers wired to each other to forward packets from one place to the other. In essence this architecture is mesh network architecture with the exception that it is a wired network. The prime reason for the high popularity of today's mesh networks is the economical edge of a wireless solution they provide over a wired solution. Today, mesh networks are being deployed to form neighborhood community networks that provide broadband Internet access to residential subscribers [10]. This architecture typically involves a network of wireless static nodes connected to home PC's in a neighborhood. Some of these nodes function as Internet gateways and all nodes participate in routing the information to and from the internet gateway. Another commercial application of mesh networks is last mile connectivity. This involves use of a wireless mesh network at the last hops of a wired core. The wireless mesh network provides services to mobile end points. Economic benefits are gained by employing wireless connectivity at the termination of the network core. In single channel mesh networks, all nodes communicate over a single wireless channel. One of the problems in single channel mesh networks is the reduced network capacity due to interference among multiple simultaneous transmissions. This effect is more pronounced due to the static nature of mesh networks.

3.2.2 Multi Radio Mesh Networks

Wireless communication takes place over a predefined frequency band that is specified by the wireless standard used. Typically, the frequency band is divided into a number of overlapping channels. The sender and receiver need to be tuned to the same channel in order to communicate. The most commonly used wireless standard IEEE 802.11 divides its frequency band into 11 channels that can be used for communication. Majority of the wireless networks use a single channel for communication where all nodes in the network are tuned to a single channel. Such networks are known as single radio networks. The obvious disadvantage of single radio networks is inefficient utilization of the frequency band available for communication. Multi radio networks, on the other hand, allow wireless communication over more than one channel. Nodes can be tuned to multiple channels (typically through multiple network interfaces) at the same time providing ability to send and receive simultaneously. This leads to efficient utilization of the frequency band as ideally all of the channels in the band could be utilized for communication. However as adjacent channels overlap, channel interference becomes a problem in multi radio networks. One of the most important problems in multi radio networks is that of channel assignment: How do we assign channel numbers to each network interface so as to utilize all the available channels with minimal channel contention. Section 4 discusses the channel assignment in multi radio networks in greater detail. Multi radio networks increase the network capacity. With availability of two channels network capacity is almost doubled as compared to network with a single channel. The advantages gained by use of multi radio networks could be highly useful in mesh networks where there is reduction in the total capacity due to interference in the simultaneous transmissions among the static nodes in close vicinity. Multi radio mesh networks are similar to single channel mesh networks except that the nodes can communicate over multiple wireless channels. This alleviates the problem of reduced network capacity observed in case of single channel mesh networks. Multi radio networks have already been deployed in community mesh networks to increase the capacity to carry the backbone traffic.

3.3 The Effect of Obstacles

Obstacles form an important component in modeling an urban network environment as they influence wireless communications. Typical obstacles encountered in an urban environment are buildings and/or houses in city blocks, the smallest area surrounded by roads on all sides. With the presence of obstacles, radio signals undergo reflection, diffraction, and refraction. This is in addition to the free space attenuation due to the distance between the transmitter and receiver. All these factors lead to a decrease in the signal strength (dB) at the receiving end. Typically, there is a signal-to-noise threshold at the receiver end for the signal strength for meaningful transmissions. If the signal strength falls below this threshold, the packet is dropped. Obstacles can lead to frequent route breakages and loss of control packets that establish routes. Even though the communicating nodes are in close vicinity, the presence of an obstacle in the communication path can lead to a complete loss of communication.

This thesis proposes a method for capturing the effect of obstacles in simulations while evaluating the deployment scenarios for vehicular wireless networks. Since this work evaluates urban network deployment, empirical experiments were conducted in an urban environment with city roads and blocks. Based on the empirical data, an obstacle representation is proposed and the deployment scenarios for vehicular wireless networks are then evaluated. Section 4.3 discusses the details of the proposed method to capture the effect of obstacles.

3.4 Summary

This chapter presents the factors that comprise the urban setting under which deployment scenarios for vehicular wireless networks are evaluated. The urban setting is modeled by use of real world street maps, a traffic-rule-based vehicular movement pattern, a wireless infrastructure support to the vehicular network, and ability to capture the effect of obstacles in the urban environment. The vehicular movement pattern is achieved using a state-of-the-art mobility model. Wireless infrastructure support is provided to the vehicular network by positioning base stations at street intersections. The base stations form a multihop mesh network and have the ability to communicate over multiple wireless channels. The various deployment scenarios for vehicular wireless networks are then evaluated in this urban setting.

CHAPTER 4

IMPLEMENTATION

This chapter presents the design and implementation details. The evaluation of the various deployment scenarios for vehicular networks is completed using network simulator ns2 version [2.29] [25]. The implementation details can be categorized as follows:

1. Topology and mobility pattern
2. The wireless infrastructure support
3. The deployment scenarios
4. The effect of obstacles

The implementation is comprised of developing external tools that work with ns2 network simulator as well as extending ns2 itself.

4.1 Urban Topology and Mobility Pattern

The evaluation is conducted over a grid topology of 1200m X 1200m with a typical urban block size of 200m X 50m. The lines in the grid represent roads while the crossing points represent the intersections. A mobility model tool from previous work [4] is used to generate vehicular movement patterns in the format that can be fed to ns2. In particular, this work used the Traffic Light Model. Among all features, the most important aspects of this movement are coordinated traffic lights at intersections and vehicle acceleration and deceleration. Note that even though the evaluation is performed over a grid topology, any urban map from the US bureau database [24] could be used to produce the mobility model, and the resulting movement patterns could be fed to ns2.

4.2 The Wireless Infrastructure Support

Infrastructure support is provided by static base stations positioned at a randomly chosen subset of street intersections. Changes were made to the mobility model tool so that the static base station nodes remain stationery throughout the simulation. Although the ns2 simulator provides the notion of base stations, the primary purpose of such nodes is to function as bridges between wireless nodes and a wired network. In contrast, the thesis requires complete wireless infrastructure support. Thus, the base stations are wireless nodes positioned at street intersections that serve as relay nodes in the network. The identity of the base stations and their respective positions are kept in a separate file, needed by implementation of the all-mesh deployment scenarios (Section 4.3.2).

4.3 Deployment Scenarios

The deployment scenarios evaluated are (1) a mesh-enhanced peer-to-peer ad hoc routing deployment model where both the mobile nodes and static wireless infrastructure nodes participate in routing, (2) a mesh-enhanced infrastructural routing deployment model where only the static wireless infrastructure nodes participate in routing and (3) a scenario where static wireless infrastructure nodes in deployments (1) and (2) have the ability to communicate over multiple wireless channels. The following subsections detail the implementation for each deployment scenario.

4.3.1 The Mesh-Enhanced Peer-to-Peer Ad Hoc Routing Deployment

In the mesh enhanced ad hoc deployment scenario, both the mobile nodes as well as static infrastructure nodes relay packets in the network. By default, the routing protocol AODV allows every node to participate in the routing. Thus, the complete deployment scenario is realized via the use of default implementation of AODV and a vehicular movement pattern generated by the mobility model with a subset of nodes positioned at intersections without movement.

4.3.2 The Mesh-Enhanced Infrastructural Routing Deployment

In this deployment scenario, only the static infrastructure nodes relay the packets in the network. They participate in routing and provide services to the mobile end points. Changes were made to the routing protocol AODV to limit the nodes that can participate in routing. The routing protocol distinguishes among the mobile nodes and static infrastructure nodes and allows only the latter to participate in routing. The information about the identification of static infrastructure nodes is available externally to the protocol. Most of the changes were made to the route discovery phase of the protocol. Thus by incorporating the infrastructure support, the vehicular movement pattern generated by the mobility model and the changes to the routing protocol AODV, a partial deployment scenario is realized.

4.3.3 Multi Radio Deployment

In multi-radio deployment, the static infrastructure nodes have the ability to communicate over more that one wireless channel. This could be achieved through the availability of multiple network interfaces. Several contributions have been made in the past for the provision of multiple network interfaces in ns2. This thesis used the ns2 extensions added by [26], which allows wireless nodes to be configured with multiple network interfaces that can be tuned to different channels.

The channel number is one of the 11 channels specified in the 802.11b/g 2.4 GHz spectrum. These 11 channels overlap in frequency band, with adjacent channels sharing a 5 MHz band. This gives rise to channel interference when communication occurs concurrently among adjacent channels in the band. Ideally, nearby nodes should be able to communicate simultaneously with no channel interference. Since the communication patterns and node location change, channel assignment in multi-radio networks is not straightforward. Despite mobility, it is important that two communicating neighbors share at least one channel. At the same time, channel interference with other neighbors has to be minimum and the aggregate bandwidth within a transmission region should be maximum. Channel assignment can be dynamic or static. Dynamic channel assignment algorithms tend to be based on the network load, while static channel assignment is fixed and predefined.

In this work, a static channel assignment approach is implemented. All infrastructure nodes have the same number of network interfaces tuned to a subset of channel numbers. For simplicity, every infrastructure node equally divides all of its neighbors among the selected channels for communication. The level of channel interference depends on the channel numbers selected for communication. This approach was implemented via modifying the extensions made by [26]. Changes were made to the AODV routing protocol to associate network interfaces with routes such that the network interfaces were used more evenly.

4.4 The Effect Of Obstacles

4.4.1 Obstacle Representation

The presence of obstacles hampers wireless communication. The signal strength is reduced as an obstacle is encountered between sender and receiver. This thesis proposes a representation to capture the effect of obstacles in wireless network simulations. Additionally, this method gives the ability to vary the effect of obstacles on received signal strength based on the terrain being simulated. The representation is in the form of parameters that can be set according to values derived from empirical experiments in the desired terrain. This representation was obtained by analyzing empirical data from urban environments. Details will be discussed in the next subsection. The form of obstacle representation is the following:

$$Pr = Pt + A - Blog(d) \tag{4.1}$$

Pr - Signal strength in dBm (decibels per milli-watts) at receiver

Pt - Signal strength in dBm at sender

d - Distance between sender and receiver in meters

A - Obstacle factor parameter

B - Distance factor parameter

The parameters A and B can be set based on logarithmically transformed regression equations based on observed signal strength. The received signal strength depends on two factors - the presence of obstacles and the distance between the sender and receiver. Accordingly, the variation of parameter A suggests changes in the terrain type or obstacle characteristics, while parameter B affects the distance between sender and receiver. Thus, A is termed as the obstacle factor while B is termed as the distance factor.

4.4.2 Empirical Experiments

Signal strength measurements were conducted in urban environments comprised of city roads and blocks. The purpose of these experiments was to collect and analyze empirical data and find a way to represent the effects of obstacles on signal strength in wireless communications.

The experimental setup comprised of an 802.11b/g wireless access point associated with a Linux version 2.6 machine with a wireless PCI card. Signal strength was measured using a Linux based tool - wavemon [27] for monitoring wireless devices. Experiments were conducted around city blocks in the Tallahassee downtown area. These blocks included a 100m x 100m block containing several mid-size buildings, a 200m x 50m block with one large building, and a few small buildings and a 50m x 50m block with trees. Signal strength measurements were taken at different points around the blocks. The empirical data collected comprised of a set of distances between sender and receiver and the associated signal strength. Logarithmically transformed linear regression on this data set generated the following equations: Experimental results yielded the following equations, with R^2 of 0.6836 and 0.9698.

Block 1: S = -29.773*log (d) - 25.809

Block 2: S = -33.012*log (d) - 20.089

where S : Recieved signal strength in dBm

d : distance in meters from source, where S was measured

4.4.3 Extensions to NS2

Changes were made to the radio propagation model of network simulator ns2 to account for this representation of obstacles. Equation 1 was used to calculate the received signal strength. The two-ray ground model uses two equations - the Friis equation for free space and the two-ray ground equation that accounts for signal reflection from the ground:

Friis Equation

$$\Pr(d) = \frac{PtGtGr\lambda^2}{(4\pi)^2 d^2 L} \tag{4.2}$$

Two Ray Ground Equation

$$\Pr(d) = \frac{PtGtGrht^2hr^2}{d^4 L} \tag{4.3}$$

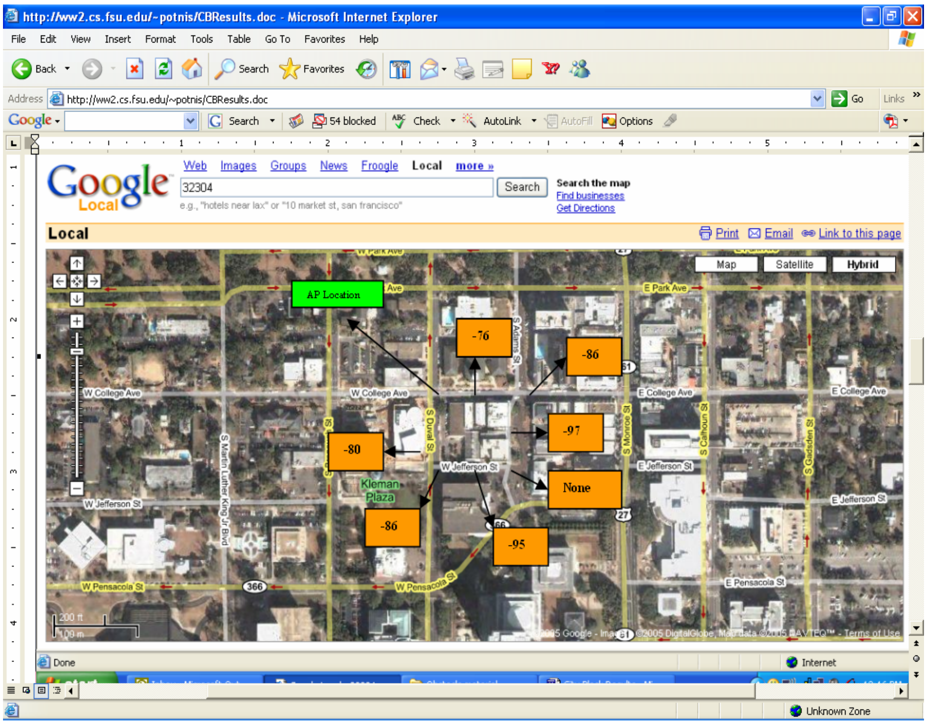

Figure 4.1. Figure shows experimental measurements taken around a city block in Tallahassee downtown area. AP is the access point location while the numbers indicate signal strength measured in dBm at various locations around the block

where,

Pr(d): received power at distance d in Watts

Pt: Transmitter power in Watts

Gt: Transmitter antenna gain, ht: Transmitter antenna height

Gr: Receiver antenna gain, hr: Receiver antennae height

L: System loss

λ: Wavelength

Both equations 4.2 and 4.3 could be represented in the form of equation 4.1, after converting watts into decibels per milli-watt (dBm).

The conversion from Watts to dBm is given by

P(dBm) = 10 logP(w) + 30

From equation 4.2

Pr(dBm)

$= 10log(\frac{PtGtGr\lambda^2}{(4\pi)^2d^2L}) + 30;$

$= 10log(Pt) + 10log(X) + 30$; where X = $\frac{GtGr\lambda^2}{(4\pi)^2d^2L}$

= Pt(dBm) + 10 log (X);

= Pt(dBm) + 10 log ($\frac{\alpha}{d^2}$); where $\alpha = \frac{GtGr\lambda^2}{(4\pi)^2L}$

= Pt(dBm) + 10 log α - 20 log (d);

= Pt(dBm) + A - Blog(d);

The default values of A and B for the Friis equation are A = -31 and B =20 and for the two-ray ground equation, A = 7.5 and B = 40. Simulations were performed over variations of either A or B, with one of them set to the default value. The intention was to study the impact of each of the obstacle factors and distance factors on the signal strength. These experiments demonstrated a way to represent obstacles in wireless simulations and then evaluated deployment scenarios for vehicular networks in that context.

4.5 Summary

In this chapter we saw implementation details for deploying and evaluating vehicular wireless networks. The implementation comprised of 1) a traffic ruled based mobility model tool with ability to position static nodes at street intersections, 2) implementation for the mesh-enhanced ad hoc routing and mesh-enhanced infrastructural routing deployment scenarios, 3) multi radio deployment with implementation of a static channel assignment approach and 4) representation of obstacles in wireless simulations through real world experiments followed by analysis of the empirical data.

CHAPTER 5

PERFORMANCE

This chapter presents detailed evaluations of the two deployment scenarios: (1) a mesh-enhanced peer to peer ad hoc routing scenario where both mobile nodes and static infrastructure nodes participate in routing and (2) a mesh-enhanced infrastructural routing scenario where only the base stations participate in routing. The evaluation is based on the performance of AODV routing protocol, and experiments were conducted by varying three parameters for both deployment scenarios:

(1) number of mobile nodes
(2) number of base stations
(3) number of constant bit rate sources in the network

These results are followed by evaluation of multi-radio networks where multiple channels are available to communicate with the base stations. A parameter space was chosen where a high level of channel contention exists when using only a single channel. Further, this chapter presents the results obtained through the proposed method of representing obstacles in simulations.

The experiments were carried out in a grid topology of 1200m X 1200m area with 200m X 50m city blocks. Although block sizes vary significantly in the real world, 200m X 50m is an average city block size. Base stations were positioned at street intersections randomly. Each simulation was repeated 10 times for 10 different placements of base stations and movement patterns.

Table 5.1 presents a summary of the default values of the various parameters used.

In the following subsections, we discuss the evaluation results in detail.

Table 5.1. NS2 Wireless Simulation Default Parameters

Parameter	Default Value(s)
Simulation Time	900s (plus 450s warmup)
Routing Protocol	AODV
NS2 Version	NS2.29 for single-channel experiments NS2.1b9a for multi-channel experiments
Transmission Range	250m
CBR Sources	25 sources at 4 pkts/sec and 64 byte pkt
Mobility Models	TLM [4]
Topologies	1200 × 1200m Grid with 200m × 50m block size, 171 street intersections
Performance Metrics	Delivery Ratio End to End delay

5.1 Evaluation of Deployment Scenarios

5.1.1 Variation of number of Mobile Nodes

1. Mesh-enhanced VANET peer to peer routing

   Figures 5.1 and 5.2 show the effects of varying the number of mobile nodes on delivery ratios and end-to-end delay in the mesh-enhanced VANET deployment scenario where all nodes participate in routing. The number of base stations is fixed at two different values - 171 with one base station per street intersection and 40 base stations (approximately 1 base station per 4 intersections).

   As expected, as the total number of nodes in the network increase and the network becomes dense, the performance in the mesh-enhanced VANET deployment scenario degrades due to network contention. This is observed in the case of 171 base stations. On the other hand, in a sparse network, the network performance shows constant scaling with the addition of mobile nodes. This is observed in the case with 40 base stations. Clearly, the base case of 40 base stations with 30 mobile nodes has already achieved excellent network coverage and connectivity. The subsequent increase in the number of mobile nodes only reaches a total of 110 nodes, not enough to cause

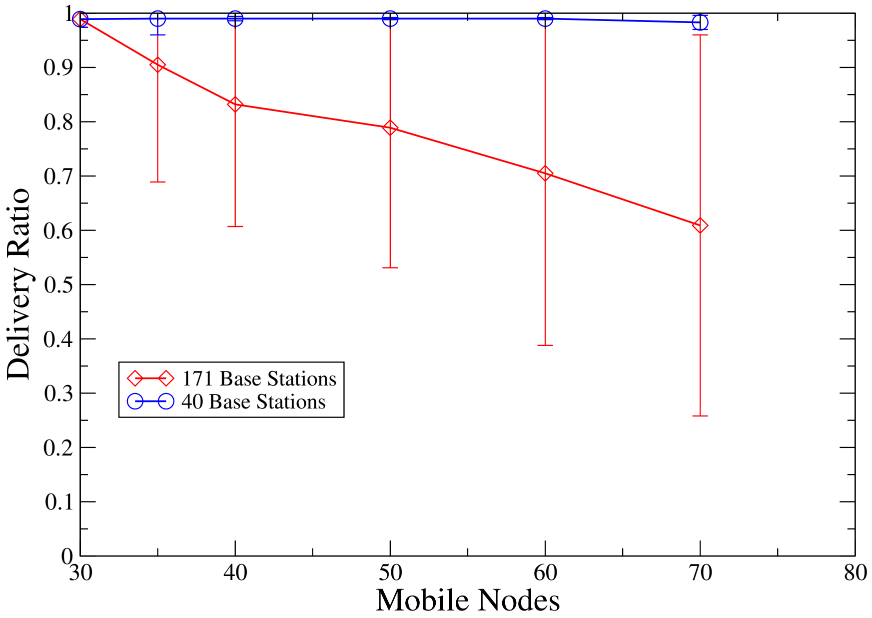

Figure 5.1. Variation of delivery ratio with number of mobile nodes where both mobile nodes and base stations participate in routing

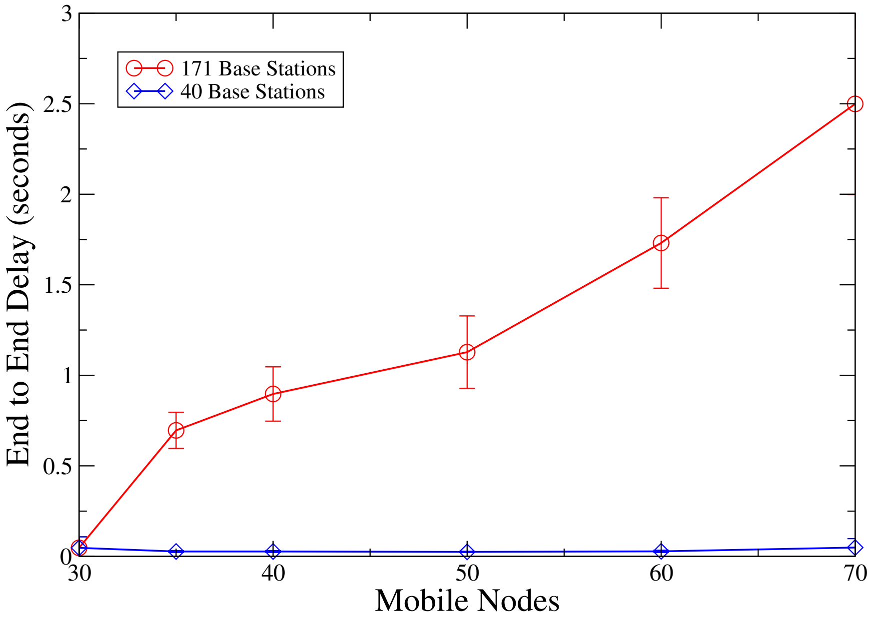

Figure 5.2. Variation of end to end delay with number of mobile nodes where both mobile nodes and base stations participate in routing

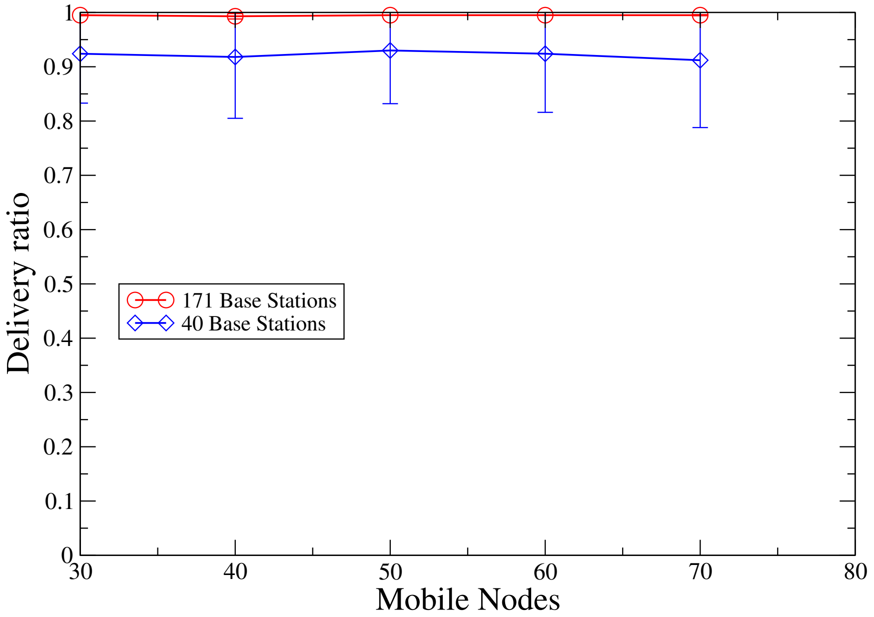

Figure 5.3. Variation of delivery ratio with number of mobile nodes where only base stations participate in routing

performance degradation, which occurs at around 205 nodes (171base stations and 35 mobile nodes).

2. Mesh-enhanced Infrastructural routing

   Figures 5.3 and 5.4 demonstrate how the number of mobile nodes affects the delivery ratios and end-to-end delays when only the base stations perform routing. The number of base stations is again fixed at two different values: 171 with one base station per street intersection and 40 base stations (approximately 1 base station per 4 intersections).

   The results show that when only the base stations perform routing, the VANET achieves constant scaling for both cases with differing numbers of base stations. Since the mobile nodes do not participate in the routing, the number of mobile nodes in the network has little effect on the performance of the routing protocol. Interestingly, for the case of 40 base stations, since the routing coverage is not as good as the case where both mobile and base stations perform routing 5.1, the delivery ratio is only approximately 90

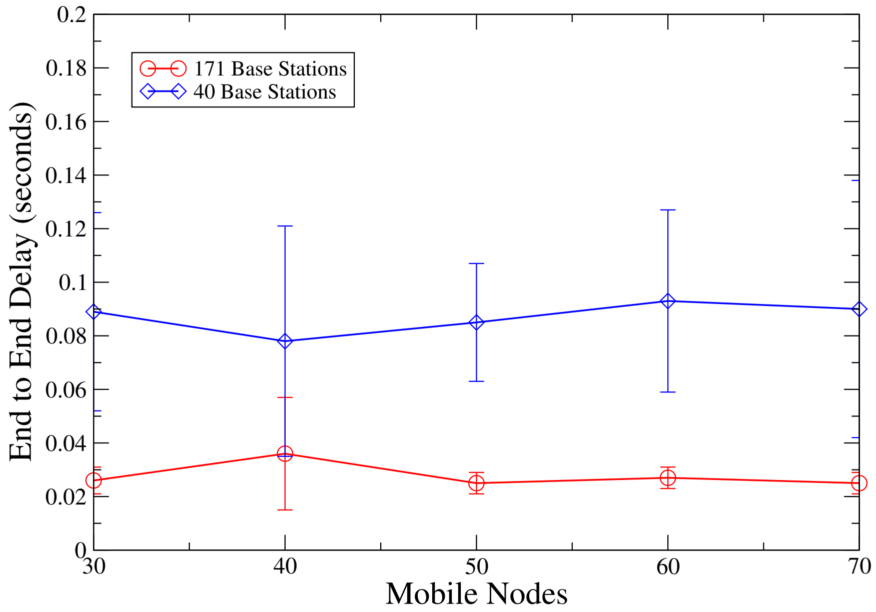

Figure 5.4. Variation of end to end delay with number of mobile nodes where only base stations participate in routing

5.1.2 Variation of number of Base Stations

1. Mesh-enhanced VANET peer to peer routing

   As shown in Figures 5.5 and 5.6, since both base stations and mobile nodes perform routing, a relatively few number of mobile nodes combined with base stations can achieve good routing coverage and delivery ratio. On the other hand, too many base stations severely limit the number of mobile nodes due to channel contention. This is seen in the case of 35 mobile nodes and 171 base stations in the above graphs.

2. Mesh-enhanced Infrastructure routing

   Figures 5.7 and 5.8 show how the number of base stations affects the delivery ratios and end-to-end delays when only the base stations perform routing. Cleary, a sufficient number of base stations are needed to achieve good routing coverage and delivery ratio. However, this deployment paradigm scales better when compared to the case where both mobile nodes and base stations perform routing because the communication paths among mobile nodes are more static, resulting in fewer route breakages and fewer route

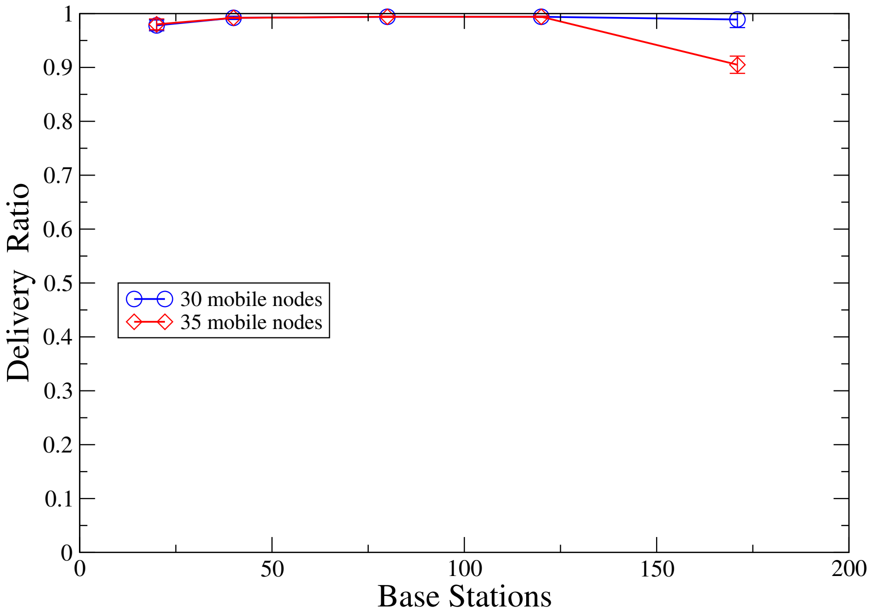

Figure 5.5. Variation of delivery ratio with number of base stations where both mobile nodes and base stations participate in routing

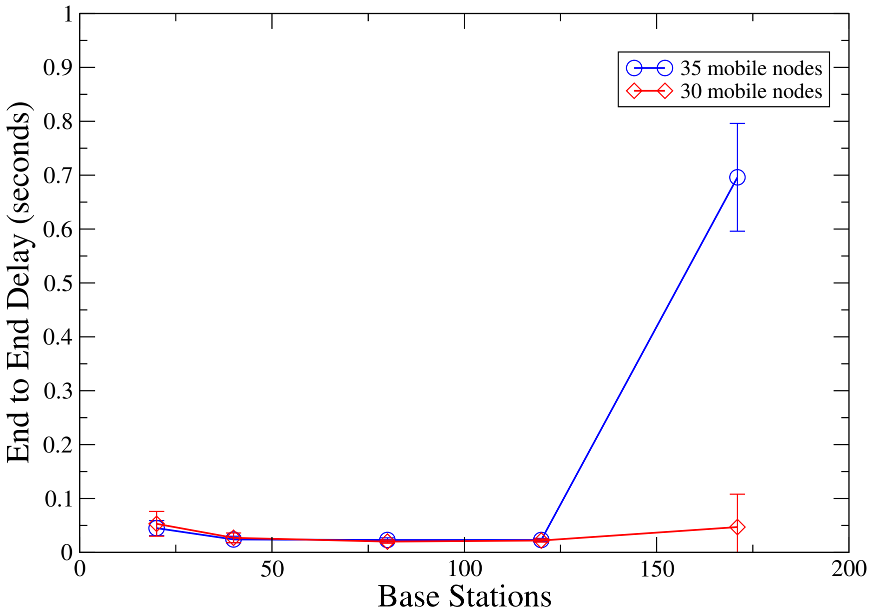

Figure 5.6. Variation of end to end delay with number of base stations where both mobile nodes and base stations participate in routing

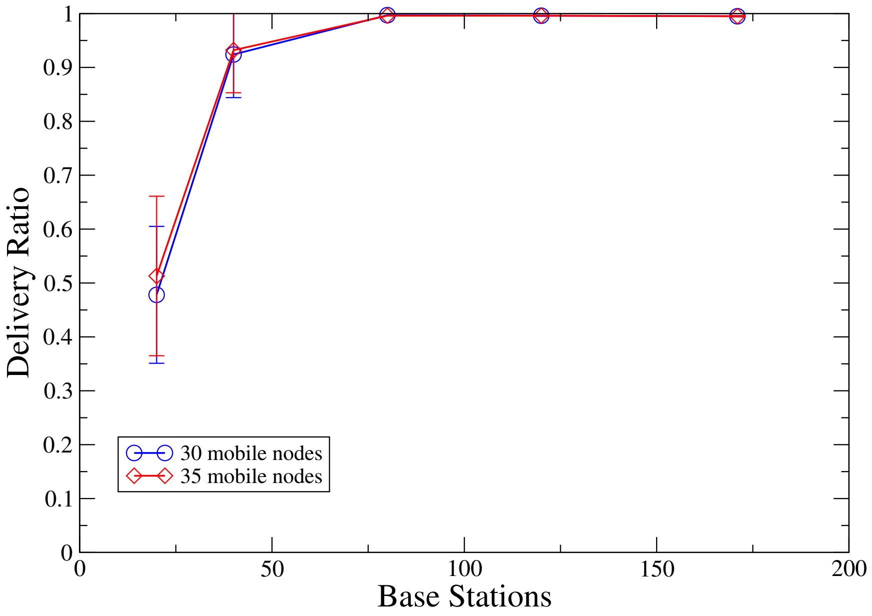

Figure 5.7. Variation of delivery ratio with number of base stations where both mobile nodes and base stations participate in routing

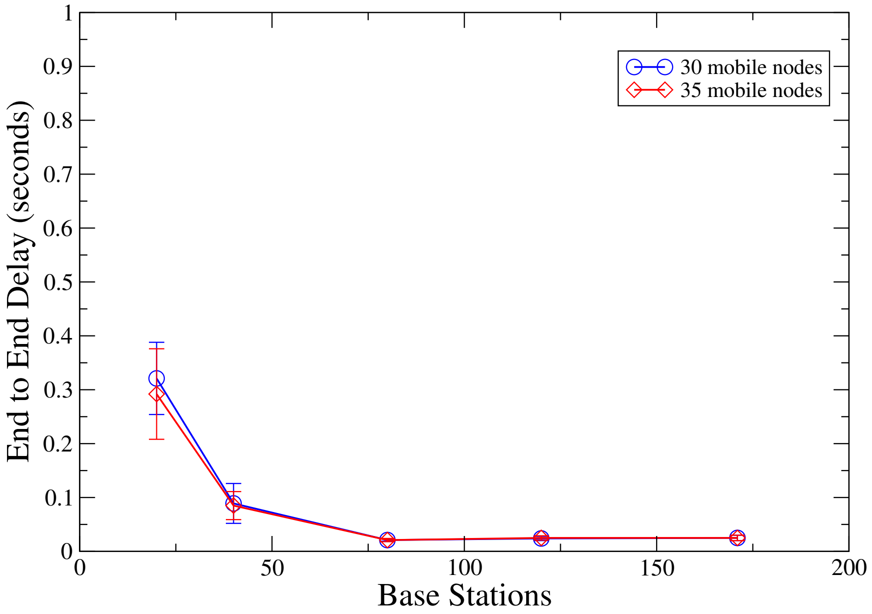

Figure 5.8. Variation of end to end delay with number of base stations where both mobile nodes and base stations participate in routing

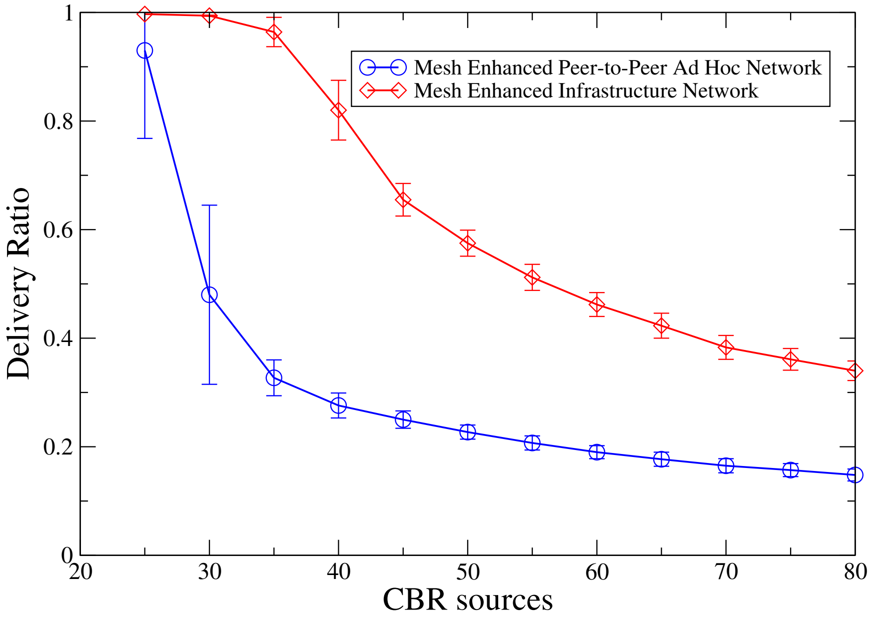

Figure 5.9. Variation of delivery ratio with number of CBR sources for both deployment scenarios

discovery and recovery events. As Figures 5.7 and 5.8 indicate, the delivery ratio and end-to-end delays across all numbers of base stations are not as sensitive to the number of mobile nodes.

5.1.3 Variation of number of Constant Bit Rate Sources

Figures 5.9 and 5.10 show the effects of varying the number of constant bit rate (CBR) sources on delivery ratios and end-to-end delays. Here, both the number of mobile nodes and the number of base stations are fixed at 80. By increasing the number of CBR sources, network traffic is increased.

The performance degrades in both deployment scenarios as the number of CBR sources increases. However, the mesh-enhanced infrastructural routing scenario consistently outperforms the mesh-enhanced peer-to-peer VANET routing, demonstrating how static infrastructural routing can scale better compared to a mixture of static and mobile routing nodes. Routing with mobile nodes significantly increases the number of route breakages and resulting recovery control traffic. On the other hand, static base station routing frequently

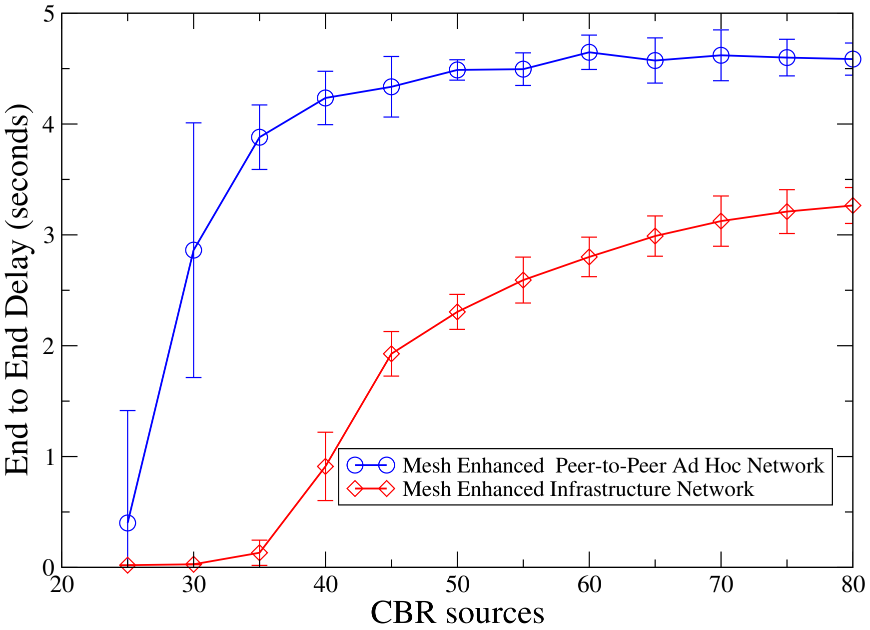

Figure 5.10. Variation of end to end delay with number of CBR sources for both deployment scenarios

limits route breakages to the end mobile points, especially when the CBR is low. Under a high CBR, a mobile node can also significantly interfere with the base station nodes.

5.1.4 Summary

Results from experiments in this subsection suggest that in a dense network, where the total number of nodes is high, mesh-enhanced peer-to-peer VANET routing can lead to decreased performance as a result of channel contention. In this case, the mesh-enhanced infrastructure routing scenario is preferable. In addition, mesh-enhanced infrastructural routing can scale better with increased network loads. On the other hand, in a sparse network with a fewer number of nodes, mesh-enhanced VANET peer-to-peer routing provides better routing coverage and higher connectivity.

5.2 Multi Radio Deployment

In multi-radio deployment scenarios, the base station nodes have the ability to communicate over multiple wireless channels through multiple network interfaces. The channel

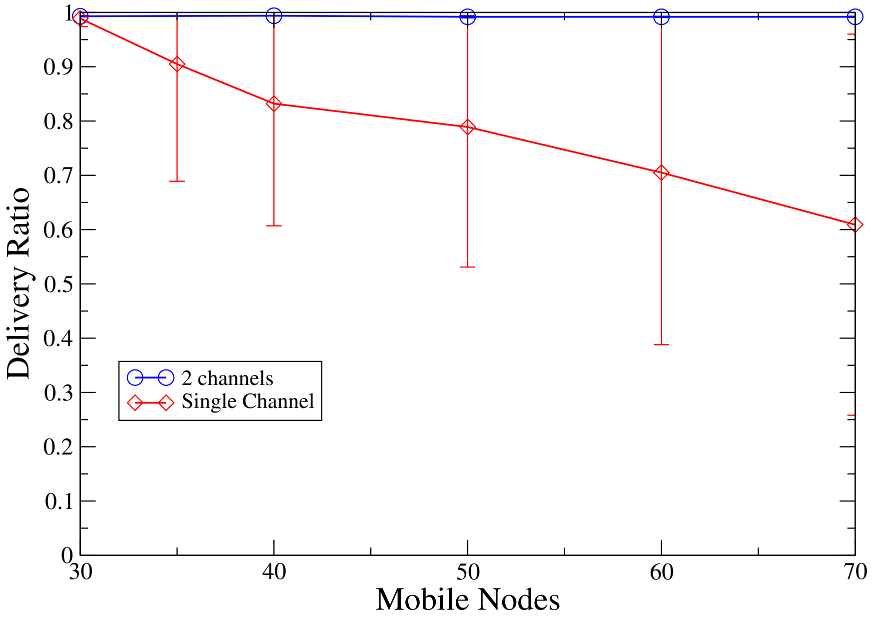

Figure 5.11. Comparision of variation of delivery ratio with number of mobile nodes where base stations have 1 and 2 channels for communication. Here both mobile nodes and base stations participate in routing.

numbers assigned to the network interfaces within the frequency band are as far as possible to reduce channel interference.

5.2.1 Number of Mobile Nodes

Figures 5.11 and 5.12 show how the number of mobile nodes affects the performance of single-radio and multi-radio deployments, where both mobile nodes and base stations participate in routing. With two channels, even mesh-enhanced VANET peer-to-peer routing can achieve flat scaling, confirming that the decrease in performance for single-radio deployment (Figures 5.1 and 5.2) results from channel contention. By providing an additional channel, channel contention is significantly reduced.

5.2.2 Number of Constant Bit Rate Sources

Figures 5.13 and 5.14 show how the number of CBR sources affects network performance for both channel and routing configurations. With two channels, both routing configurations perform better as compared to their single-radio counterparts. This is because the network

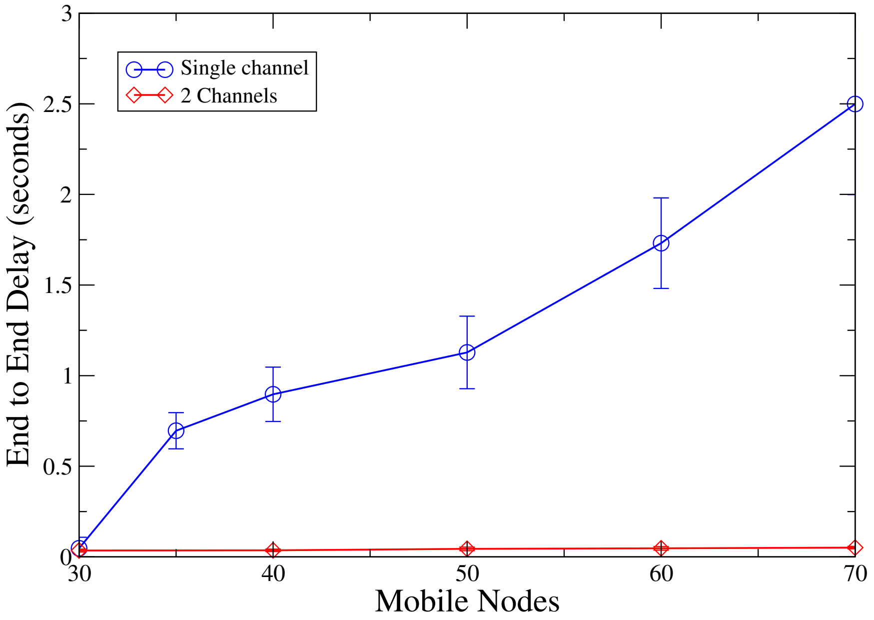

Figure 5.12. Comparision of variation of end to end delay with number of CBR sources where base stations have 1 and 2 channels for communication. Here both mobile nodes and base stations participate in routing

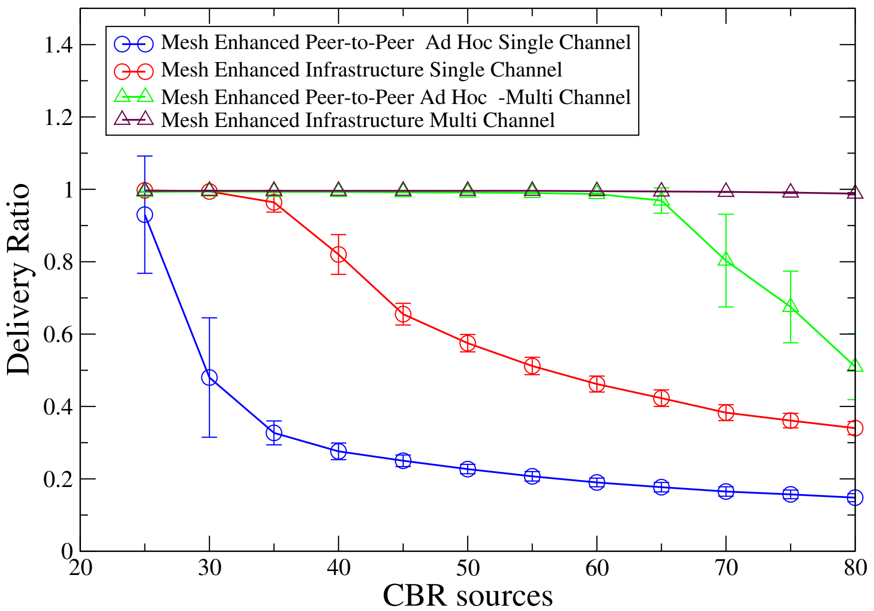

Figure 5.13. Comparision of variation of delivery ratio with number of CBR sources where base stations have 1 and 2 channels for communication. Here both deployment scenarios are evaluated.

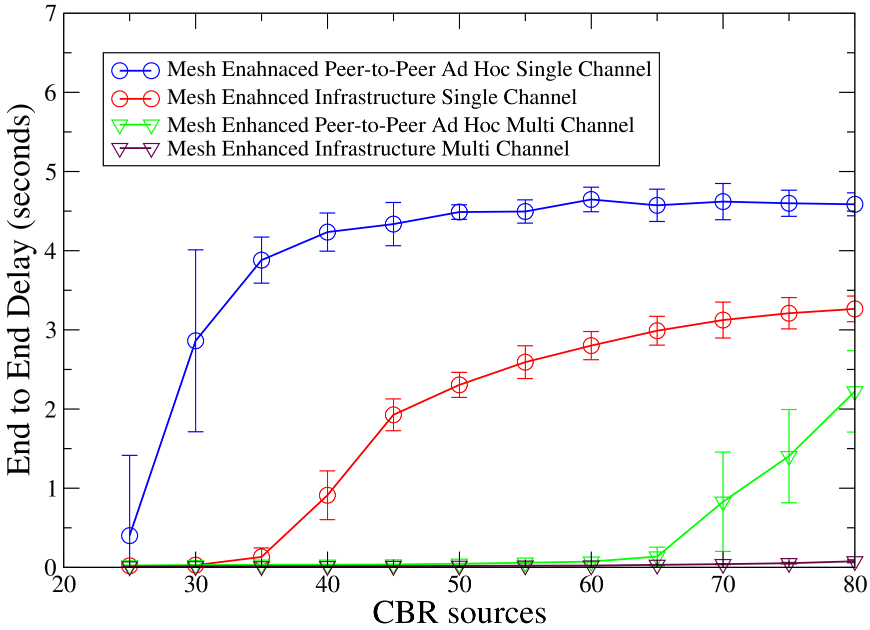

Figure 5.14. Comparision of variation of end to end delay with number of CBR sources where base stations have 1 and 2 channels for communication. Here both deployment scenarios are evaluated

capacity to carry traffic is almost doubled. The performance of mesh-enhanced peer to peer routing does not exhibit channel contention until a high number of CBR sources are employed. Mesh-enhanced infrastructure routing with two channels results into a very high capacity network that can handle high network loads.

5.2.3 Number of Channels

Figures 5.15 and 5.16 show how the number of channels used for communication affects network performance for the mesh-enhanced VANET peer-to-peer routing scenario. As the number of channels increases, the delivery ratio peaks at three channels, followed by degraded performance for four and five channels. Intuitively, more channels available for communication should increase network capacity and hence performance. However, according to the 802.11 standard, among the 11 channels, communicating through a single channel can interfere with the two channel numbers above and below. The maximum number of channels that can be assigned for concurrent transmission without interference is three (1, 6, and 11). Beyond that, it is no longer possible to use more channels without interfering with

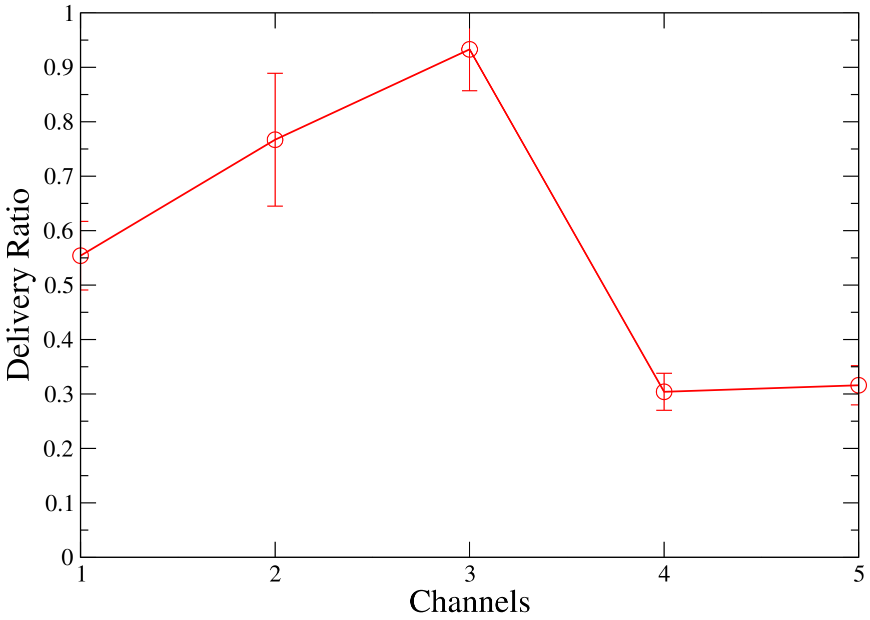

Figure 5.15. Comparision of variation of delivery ratio with number of channels available for communication to the base stations. Here both mobile nodes and base stations participate in routing.

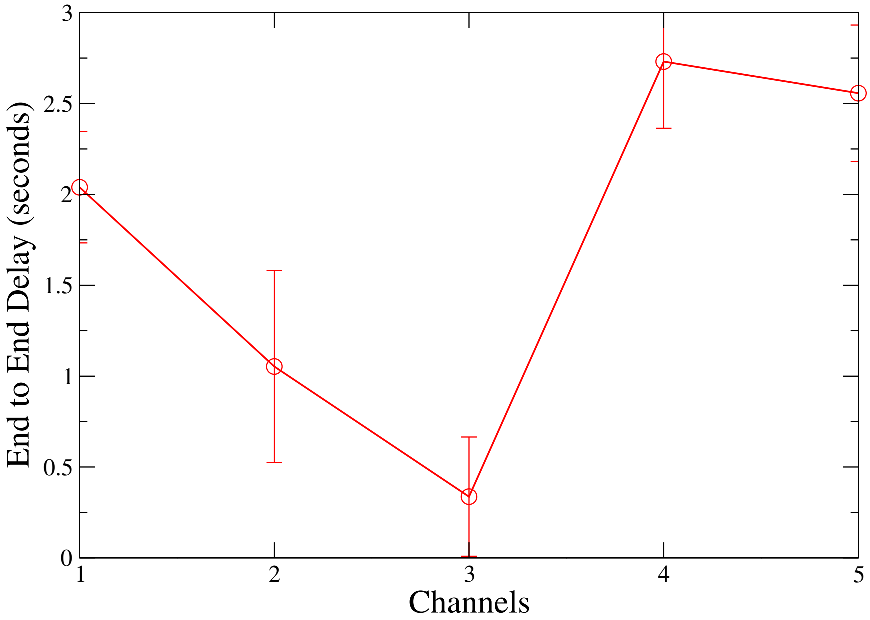

Figure 5.16. Comparision of variation of end to end delay with number of channels available for communication to the base stations. Here both mobile nodes and base stations participate in routing

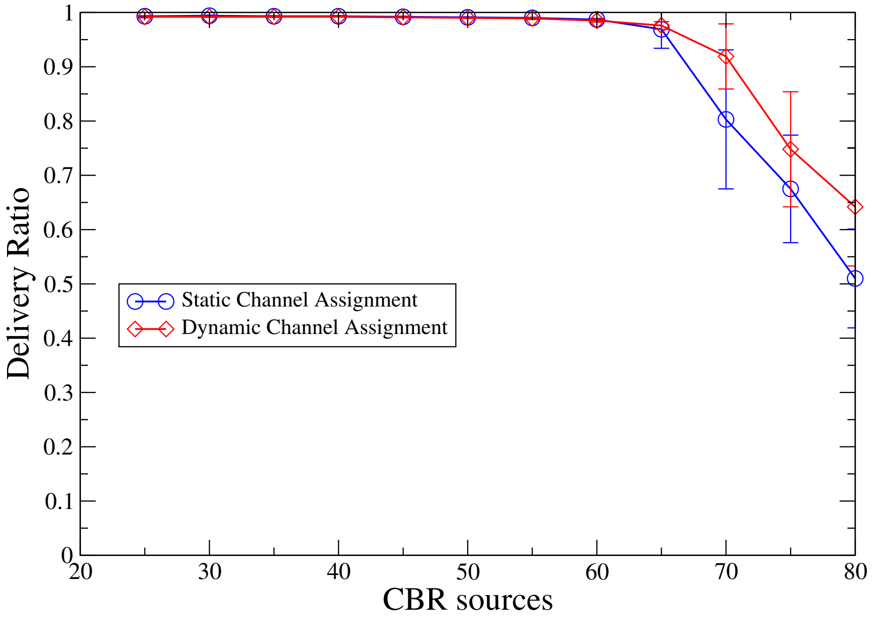

Figure 5.17. Comparision of variation of delivery ratio with channel assignment approach. Channel assignment approach decides how neighbors are distributed among available channels for communication. Here both mobile nodes and base stations participate in routing

adjacent channels. Alternatively, performance degrades when the number of channels exceeds three. It is interesting to note that performance with 4 channels is lower as compared to that with a single channel. This is primarily due to channel interference. The 802.11 RTS/CTS mechanism is used within a single channel and not across multiple channels. Hence in case of 4 channels even though a channel is clear to send, it may not be free of interference from other channels.

5.2.4 Channel Assignment Approach

Figures 5.17 and 5.18 demonstrate how the number of CBR sources affect network performance with dynamic and static channel assignment methods (Section 4.2). The experiment includes two channels and uses mesh-enhanced VANET peer-to-peer routing. In the static approach, every node distributes its routes to neighbors equally among its network interfaces. The channel number associated with a particular interface is fixed over time. In the dynamic channel assignment approach, the interface, and hence the channel number chosen for communication with a neighbor may vary at packet arrival times. The

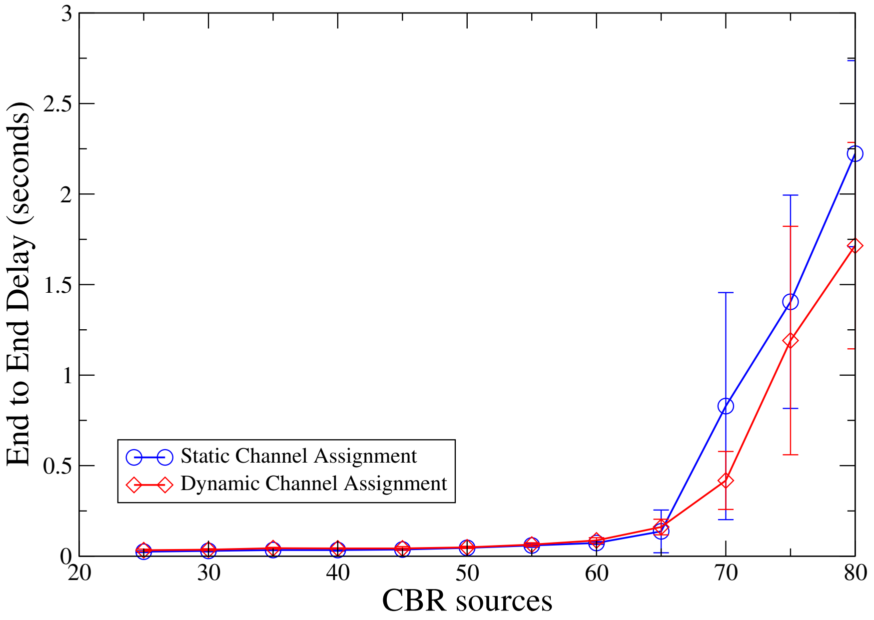

Figure 5.18. Comparision of variation of end to end delay with channel assignment approach. Channel assignment approach decides how neighbors are distributed among available channels for communication. Here both mobile nodes and base stations participate in routing

dynamic approach has an edge over the static one as any available channel can be chosen for communication. This advantage is illustrated in Figures 5.17 and 5.18 and can be seen with high numbers of CBR sources.

5.2.5 Summary

Results from the experiments presented in this subsection show that using multiple wireless channels enhances network performance significantly for both mesh-enhanced routing models. Thus, multi-radio deployment of vehicular wireless networks is highly desirable. As number of channels increase, adjacent channel interference hampers performance beyond three channels.

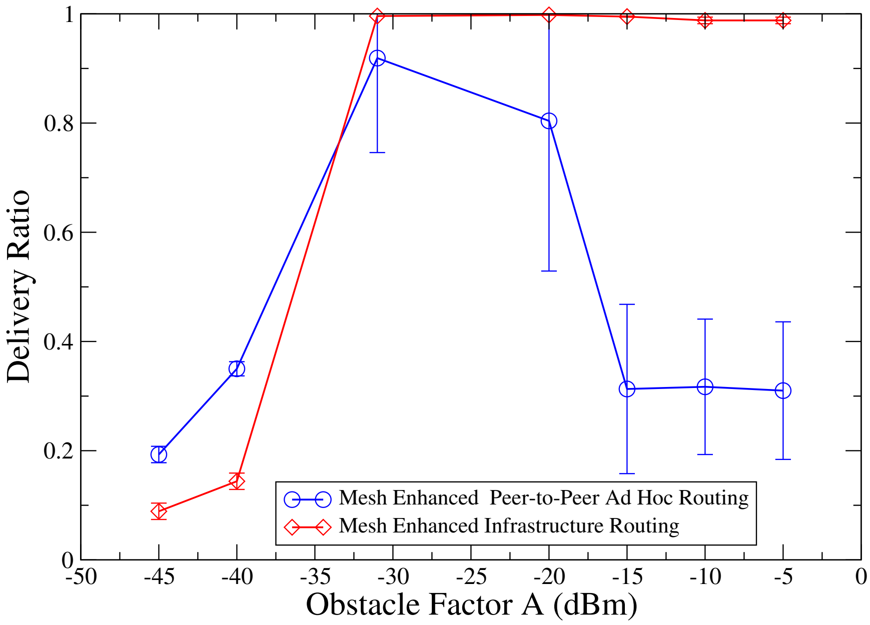

Figure 5.19. Variation of delivery ratio with obstacle factor A in equation (4.1). Both deployment scenarios are evaluated

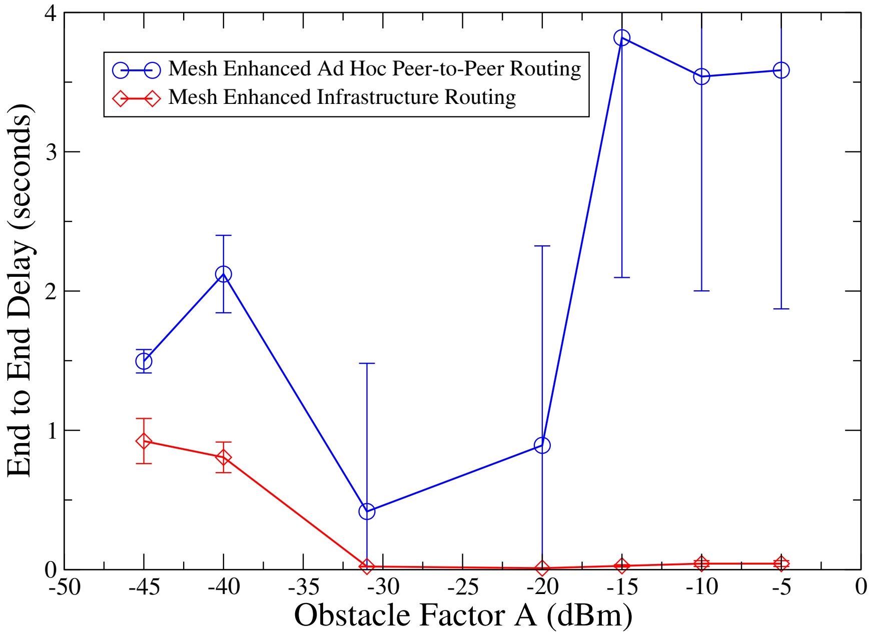

Figure 5.20. Variation of end to end delay with obstacle factor A in equation (4.1). Both deployment scenarios are evaluated

5.3 Obstacle Representation

5.3.1 Variation of Obstacle Factor

Figures 5.19 and 5.20 show how obstacle factor A (Section 4.3) affects network performance for both routing configurations. According to equation 4.1, an increasingly negative value of obstacle factor A should lead to a decrease in signal strength at receivers and decrease performance. This is observed when A < -35 for both routing configurations. The default value of A in the ns2 propagation model is -31, which corresponds to a total absence of obstacles. However, it is interesting to note that in the mesh-enhanced VANET peer-to-peer routing scenarios, when A > -15, performance degrades. For such a decreased negative value of obstacle factor A, the signal strength at the receiver is high enough to cause unwanted reception and interference among these receptions. This is not observed in the case of infrastructural routing scenarios because the static base stations maintain a fixed distance from one another throughout the simulations.

5.3.2 Variation of Distance Factor

Figures 5.21 and 5.22 show how the distance factor B (Section 4.3) affects network performance for both mesh-enhanced routing configurations. According to equation 4.1, a higher positive value of distance factor B should reduce signal strength at receivers and decrease performance. This is observed in cases of values of B > 21 for both routing configurations. However, mesh-enhanced VANET peer-to-peer routing performs better as compared to infrastructural routing. This is the result of the mobile nodes' participation in routing to enhance connectivity and coverage. For a high value of distance factor, network connectivity is still better in the mesh-enhanced VANET peer-to-peer routing as more nodes are reachable through the mobile nodes.

5.3.3 Summary

Results from the experiments in this subsection demonstrate that obstacles could be represented in network simulation through variable parameters. The evaluation of the routing configurations for mesh-enhanced VANETs was conducted in the context of this

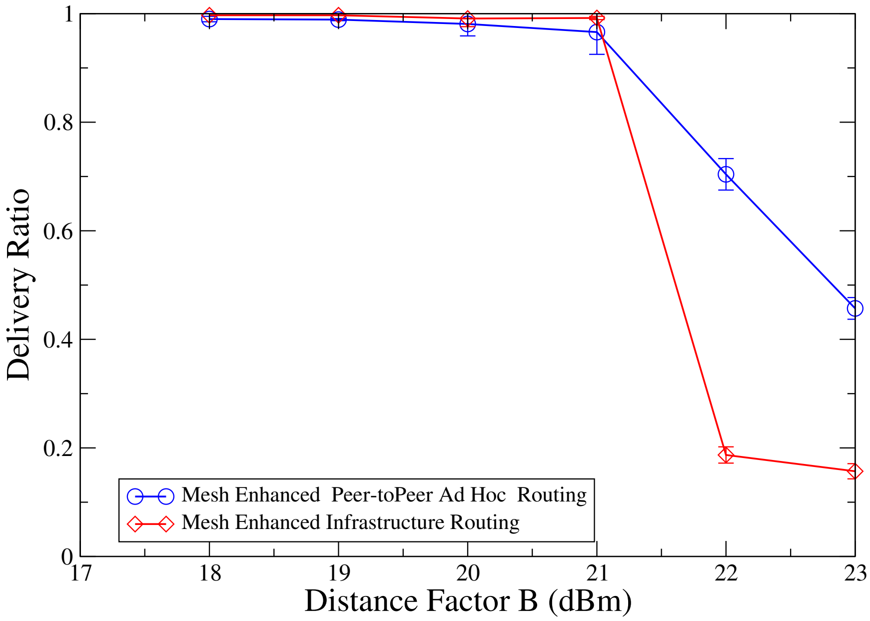

Figure 5.21. Variation of delivery ratio with distance factor B in equation (4.1). Both deployment scenarios are evaluated

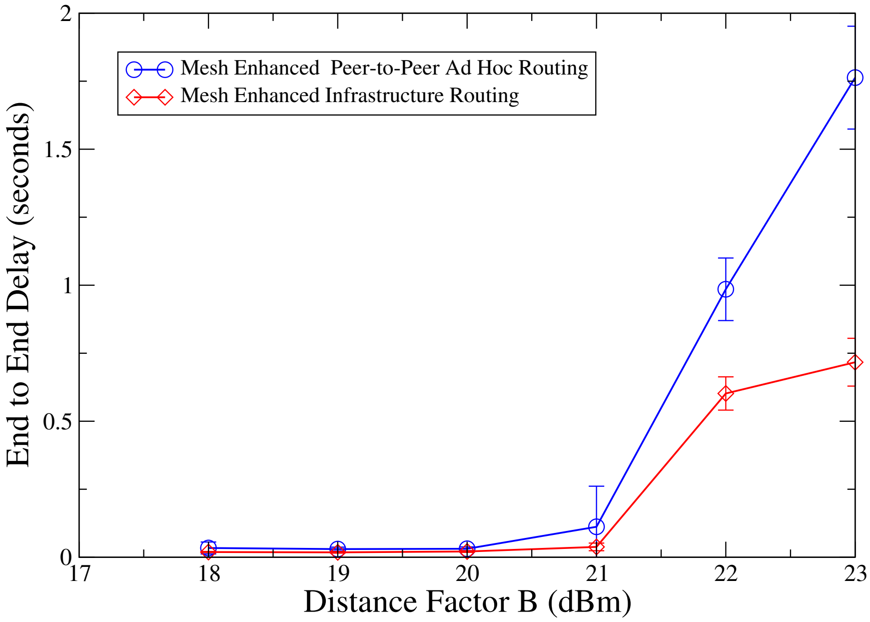

Figure 5.22. Variation of end to end delay with distance factor B in equation (4.1). Both deployment scenarios are evaluated

representation for a sample variation of these parameters. The results indicate that the use of mobile nodes to perform routing improves coverage and thus network performance in the presence of obstacles. However, mobile nodes also introduce more receiver-end interference. Since no single routing configuration can definitively excel in both the open-field and the obstacle environment, future study will explore other routing options.

CHAPTER 6

FUTURE WORK

This work provides a sound insight into the practicality of deployment of vehicular wireless networks in urban environments and discusses various deployment scenarios. Future research could take a number of directions.

6.1 Enhancements to the Deployment Scenarios

Further enhancements or optimizations could be applied to the deployment scenarios in addition to the mesh-enhanced VANET peer-to-peer routing and infrastructural routing scenarios. The former network configuration is more suitable for a sparse network with fewer nodes, while the latter performs better in a dense network. A natural extension is to explore dynamic switching between the two deployment strategies based on the density of nodes in a particular area. When density of nodes in a given area exceeds a threshold, infrastructural routing is automatically deployed to reduce channel contention and boost performance. On the other hand, in an area with fewer nodes, mobile nodes could also participate in routing and relaying packets to improve network coverage and performance. Hypothetically, this approach can lead to the best of both worlds.

6.2 Enhancements to Obstacle Modeling

This work proposes a method to incorporate the effect of obstacles in wireless network simulations. However, this model could be refined to obtain more accurate evaluations. In particular, this thesis represents obstacles through tunable parameters that can be set through empirical experiments. Once set, these parameters remain constant throughout the simulations. Alternatively, these parameters can be adjusted dynamically based on information like presence or absence of obstacle in between sender and receiver, nature and type of obstacle etc. We have already developed a separate tool that extracts obstacle position information from any given topology. This tool could be used in conjunction with our current obstacle model and the parameters could be varied to simulate the presence or absence of the obstacle in between the sender and receiver. This enhancement would lead to increased accuracy in evaluations, and the resulting model would be widely applicable well beyond this thesis.

6.3 Enhancements to Multi Radio Deployment

This thesis evaluated deployment scenarios where the static infrastructure nodes had the ability to communicate over multiple wireless channels. However, even the mobile nodes can be provided with similar capabilities. This deployment model is realistic since many vehicles carry multiple communicating devices. For instance, consider a vehicle with a GPS display, a laptop with Internet access in the rear seat, and a traffic monitoring device on the driver's side. These devices can communicate through different wireless channels to reduce channel contention. In addition, with this capability, mobile nodes could relay packets more efficiently. Also, vehicles could communicate over a different channel than that used for communication between infrastructure nodes. Such types of deployment scenarios could be easily extended with the current evaluation framework.

6.4 Summary

This chapter identifies future directions to further this thesis. The two evaluated deployment approaches can be combined to gain the best of both worlds. The obstacle model can be enhanced to account for the relative positions of obstacles in the path of communication. Along with the static infrastructure nodes, the mobile nodes can be given the ability to communicate over multiple channels. These enhancements could lead to increased accuracy in evaluation of various deployment scenarios and allow the exploration of better deployment alternatives for VANETs.

CHAPTER 7

CONCLUSIONS

This work evaluates the practicality of various deployment scenarios for vehicular wireless networks. The deployment scenarios comprised of static wireless base stations positioned at intersections and mobile vehicles. Three deployment scenarios were studied - (1) a mesh-enhanced peer-to-peer ad hoc routing deployment where base stations as well as mobile nodes relay packets in the network, (2) a mesh-enhanced infrastructural routing deployment scenario where only the base stations relay packets, and (3) a multi-radio deployment scenario where the base stations have the ability to communicate over multiple wireless channels.

The results show that various deployment scenarios provide benefits over each other under different conditions. The infrastructural routing deployment has a positive impact on network performance and scalability as it dedicates nodes for routing. The mesh-enhanced peer-to-peer ad hoc routing deployment is beneficial in a sparse network with a small number of nodes. The multi-radio deployment reduces channel contention to a significant extent for both types of deployment. This work also proposes a method to incorporate the effect of obstacles into wireless network simulations. It was shown that obstacles could be represented in simulations through tunable parameters that can be set through empirical experiments. All the deployment scenarios are evaluated with a traffic-rule based mobility model for vehicular movement.

Deployment of vehicular wireless networks has not been studied in detail until recently. This thesis brings into focus issues central to vehicular wireless network deployment. To the best of our knowledge, this works is the first one to perform a comprehensive study of vehicular wireless networks, with focus on recent advances in wireless technologies like mesh routing and multi-radio networks. While studies in the fields of mesh networks, obstacle effects on wireless communication, mobility modeling, and multi-radio networks are largely performed in isolation, this thesis synthesizes these technologies so that the practicality of

VANET deployment can be evaluated systematically. The results demonstrate the promise of VANET being deployable in an urban setting. Adjusting the routing policies and exploiting multiple wireless channels can overcome the node density factor and the presence of obstacles. The thesis also demonstrates that such complex network environment with traffic rules and obstacles can be captured in a single evaluation framework, which is a major step forward toward understanding the behavior of VANET in urban settings.

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BIOGRAPHICAL SKETCH

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