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URBAN MOBILITY MODELS FOR VEHICULAR AD HOC NETWORKS

By

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To my family. You guys are the best.

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ABSTRACT

Mobility models, or the mobility patterns used to simulate the motion of participating nodes, play a vital role in the simulation of Vehicular Ad Hoc Networks (VANET). Even with recent research focusing on development of mobility models that better correspond to real-world situations, we still have a limited understanding of the level of detail required for modeling and simulating VANETs. This thesis presents a set of mobility models for VANETs and provides the capability to study the effect of simulating various levels of real-world details such as traffic lights, multi-lane roads, and vehicle acceleration/deceleration.

In contrast to earlier work in this area, this research addresses the following question: *What level of simulation detail is necessary to capture the behavior of ad-hoc routing protocols in urban contexts?*

In order to achieve this goal, this work involved creation of several new mobility models that account for varying levels of constraints on vehicular movement such as traffic lights, multi-lane roads, and acceleration/deceleration. Using physical topologies based on real maps and synthetic grids, the new mobility models and certain other mobility models were subjected to an exhaustive set of experiments to evaluate the effect of various factors such as topology, speed, wait times, and various *realistic* traffic mechanisms. The results demonstrated that the acceleration/deceleration of vehicles and the clustering effect introduced as a result of the vehicles waiting at intersections are some of the significant factors that affect the delivery ratio and packet delays in VANETs. Another important finding was that simulation of multiple lanes only marginally affected VANET routing performance in our experimental settings. These findings are an important first step toward future development of mobility models for VANET simulations.

CHAPTER 1

INTRODUCTION

There is a growing commercial and research interest in the development and deployment of Vehicular Ad-Hoc Networks (VANETs). VANETs are a special case of Mobile Ad-Hoc Networks (MANETs) and consist of a number of vehicles traveling on urban streets and capable of communicating with each other without a fixed communication infrastructure. VANETs are expected to be of great benefit for safety applications, gathering and disseminating real-time traffic congestion and routing information, sharing of wireless channel for mobile applications etc.

However, due to the high cost of deploying and testing any new VANET architecture in the real world, simulations provide a vital alternative for conducting affordable and repeatable evaluations prior to actual deployment.

1.1 Mobility Modeling for VANET Simulations

One key component of VANET simulations is the mobility pattern of vehicles, also called the *mobility model*. Mobility models are used to determine the location of nodes in the topology at any given instant, which strongly affects network connectivity and throughput. The current mobility models used in popular wireless simulators such as NS-2 [2] tend to ignore real-world constraints such as street layouts and traffic signs. Consequently, the simulation results are unlikely to reflect the protocol performance in the real world.

For example, the widely used Random-Waypoint Model (RWM) [3] assumes that nodes move in an open field without obstructions. In contrast, the layout of roads, intersections with traffic signals, buildings, and other obstacles in urban settings constrain vehicular movement. The shortcomings of RWM are widely recognized and there has been recent research interest in modeling "realistic" mobility patterns specifically targeted for VANETs [4, 1, 5, 6, 7, 8, 9, 10]. Each of these works captures different levels of simulation details and realism in various environments. However, the level of detail required to model vehicle's mobility in VANETs is still poorly understood.

1.2 Contributions

This research attempts to answer the following research question: *What level of detail in the mobility modeling is necessary and sufficient to accurately simulate the behavior of ad hoc routing protocols in urban contexts?* Specifically it attempts to identify which constraints on vehicular mobility significantly impact the performance of routing protocols in VANETs. Additionally, this evaluation also identifies certain mobility constraints that only marginally affect the routing protocol performance and hence could potentially be ignored. The specific contributions of this work are as follows:

1. This work introduces several new mobility models – the Stop Sign Model (SSM), the Probabilistic Traffic Sign Model (PTSM), and the Traffic Light Model (TLM) with four variants. These models collectively capture the vehicular mobility characteristics in urban settings with various levels of detail. Seperate models were used as a means to gain better insight into VANET mobility modeling.
2. Performance comparisons were made between the proposed mobility models and two prior models – the Random-Waypoint Model (RWM) [3] and the Rice University Model(RUM) [1], on the performance of the AODV routing protocol. These models were evaluated with the AODV routing protocol over various parameters such as topology (real maps as well as controlled grids), vehicular speed, and the wait times at intersections.
3. It was observed that one factor that significantly affects the performance of routing protocols in VANETs is a *clustering effect* of vehicles at the intersections. Increasing either the wait times at the intersections or the number of nodes leads to increased clustering. In turn, increased clustering leads to higher delivery ratios when neighboring intersections are within transmission range, and to lower delivery ratios when neighboring intersections are beyond the transmission range due.
4. The topology (block sizes and road layout)and acceleration-deceleration of vehicles were observed as the factors that had a significant effect on routing protocol performance.

5. Another conclusion of the evaluation was that adding greater complexity to the models, (e.g. simulation of multiple lanes), leads to only a marginal impact on the ad hoc routing performance in the simulation.

The remainder of this thesis is organized as follows. Chapter 2 reviews related research in the field of VANET mobility modeling Chapter 3 discusses the factors that influence mobility in VANETs. Chapter 4 presents details of the implementation of this work, including a description of the various mobility models implemented as part of this project. Chapter 5 compares the performance of AODV routing protocol using various models. Chapter 6 describes the future directions and Section 7 summarizes the research contributions of this work.

CHAPTER 2

RELATED WORK

A number of mobility models have been proposed to simulate the node mobility in a wireless ad hoc network in different scenarios. This chapter summarizes those most relevant to this work. Unlike earlier studies, the focus of this research is to understand and evaluate the performance impact and significance of various factors on VANET simulations, rather than recommending any one particular mobility model as being an ideal solution for VANET mobility modeling.

2.1 Open-Field Mobility Models

Traditional mobility models capture nodes' motion in an open area with no semblance of streets. Nodes were not constrained to move along specific paths, but could move to any point within the entire area. Such models have been referred to as Open-Field Mobility Models.

The most commonly used mobility model in the literature is the Random Waypoint (RWM) model [3]. Every node selects a random destination and speed, moves to that destination, pauses, and then moves again to another random destination. Other similar open-field models include the Random Walk Model, Random Direction Model, and the Boundless Simulation Area Model [11].

Davies [12] presented a comprehensive evaluation of existing mobility models for ad-hoc networks. The author concluded that none of the evaluated models depicted realistic mobility scenarios, and there is a need to implement mobility models appropriate for scenarios under consideration. Zheng et al. [5] reached a similar conclusion after evaluating many of the more recent mobility models. Previous studies have attempted to improve RWM's realism. Bettstetter [13] modeled vehicles' acceleration/deceleration to improve upon RWM's realism. The random trip model [14] was proposed as a generic model that contains other mobility models, including RWM. The authors attempted to increase the mobililty model's realism by producing a perfect sample of the initial state for a random trip model.

There are other group mobility models proposed for ad hoc networks. In the Reference Point Group Mobility model (RPGM) [15] every node has an individual component as well as a group component in its movement vector. Both mobility components are based on RWM, however, the former within the group scope and the latter within the entire arbitrary space. This is significantly different from vehicular motion on streets. Another group mobility model is evaluated in [16] typically for military scenarios involving movement of nodes in groups, for instance tank battalions.

2.2 Mobility Modeling for VANETs

Most of the above mentioned research targets mobility modeling in general. VANETs present a unique problem with respect to mobility modeling. The movement of communicating nodes in vehicular urban networks is along streets and is restricted by characteristics typical of vehicular motion such as stop signs, traffic lights, interdependent motion, and obstacles such as buildings.

Bai[4] argued that the choice of mobility model can affect the performance of the MANET routing protocols, and introduced the Freeway and Manhattan mobility models, which simulate nodes' mobility on roads specified by maps. The Freeway model attempted to model vehicles' movement on freeways. A map had several freeways with multiple lanes. Each vehicle's movement was restricted to its lane, and the nodes' velocity was dependent on their recent velocities. The Manhattan model captured an urban area similar to the grids used in the evaluations conducted in this study. Whenever a vehicle reached an intersection, it was determined with some fixed probability whether it would turn left or right, or continue on the same street. The vehicles were not constrained to pause, stop, or queue up at intersections.

Saha et al. [1] at Rice University modeled vehicles' mobility on real street maps, which were obtained from the TIGER database [17] maintained by the US Census Bureau, by constraining vehicles' to street boundaries. Their model, referred to as RUM in this thesis, does not enforce any traffic rules on the network, especially at intersections. They showed that results obtained from RUM are similar to those obtained from the RWM. Because RUM is a good starting point toward modeling vehicular mobility, it was included as one of the base cases for performance comparisons.

Choffnes and Bustamante [7] recently introduced a vehicular mobility model for urban environments. With their simulators configured to generate delivery ratios between 0.05 and 0.3, they observed that the network performance in such a network was significantly different from the RWM. The authors also observed that the performance varied with the type of environment being simulated. The evaluations done for this thesis confirmed their findings. Additionally, our evaluations used parameter settings to generate delivery ratios over 90% that are within the usable range. Because their mobility model is written using the SWANS [18] simulator, it was difficult to evaluate their mobility models without significant porting effort to NS2.

An interesting work is [6] which presents a mobility model that captures various insightful effects of group mobility over huge geographical areas. The model simulates group based movement of people – they leave or arrive home and converge or diverge from specific points such as highway entries or popular locations in town. This work modeled mobility with the target application being cellular networks, which are inherently different from VANETs.

For modeling mobility in cities [8] proposed several theoretical models such as the city-area, area-zone and unit-street models. When combined, these models aim to create simulation environments restricting nodes' motion along orthogonal grids, with speed limits and a safe distance between nodes. As pointed out in [12], however, these models lack specific details needed to calculate nodes actual movement. They also introduce considerable computational effort and complexity when used in simulations.

Some research has focused on using mobility traces and/or proprietary software tools. In [9], a multi-tier ad-hoc wireless routing architecture is proposed based on a collection of realistic mobility traces from city buses in a metropolitan area. However, these traces need not necessarily generalize mobility for all vehicles over varied topologies. Also, they could not account for route changes due to traffic conditions, which are highly unlikely in the case of public buses. Proprietary traffic simulation tools such as Paramics [19] and CORSIM [20] are also available commercially to model modern transportation systems. For instance, [10] uses Paramics to generate nodes' movements. However, apart from some synchronization overhead involved between the traffic simulation and the wireless simulation, the use of proprietary software hinders further research and development. Also, most of these tools hide topological details from the wireless simulator, which are useful in many ways.

Interest in VANETs and in the performance of protocols at different layers has been increasing lately. For instance, [21] studies the protocols' behavior at the MAC layer and proposes a new multi-hop broadcast protocol for realistic vehicular traffic scenarios. Xu and Barth's work[10] modulates power level and transmission intervals to minimize packet collisions in inter-vehicular communication. In [22], the authors proposed a mobility centric algorithm for data dissemination in vehicular networks. Performance evaluation of safety applications in VANETS over the dedicated short range communication (DSRC) standard have been performed in [23]. All of these optimizations and evaluations depend upon an in-depth understanding of the factors that impact mobility patterns and protocol performance in VANETs, which is the focus of this work.

CHAPTER 3

FACTORS AFFECTING MOBILITY IN VANETS

The mobility pattern of nodes in a VANET influences the route discovery, maintenance, reconstruction, consistency and caching mechanisms. At any instant, a VANET can have both static (non-moving) and dynamic (moving) nodes. The static nodes tend to dampen the changes in topology and routing by acting as stable relaying points for packets to/from the neighboring nodes. On the other hand, dynamic nodes add entropy to the system and cause frequent route setups, teardowns, and packet losses. This chapter discusses the effect of various factors that influence the mobility pattern in VANETS.

3.1 Layout of streets

Streets force nodes to confine their movements to well defined paths. This constrained movement pattern determines the nodes' spatial distribution and the network's connectivity. This restricted movement highlights the significance of factors such as the nodes' transmission range, because the layout of the streets might be such that vehicles travelling on parallel streets spaced far apart might be out of communication range. Streets can have either single or multiple lanes and can allow either one-way or two-way traffic.

3.2 Block size

Urban areas are typically divided into blocks of various sizes. A city block can be considered the smallest area surrounded by streets. These blocks can be of different sizes - metropolitan areas generally have smaller city blocks than smaller towns. The block size dictates the density of the ntersections in that area, which in turn determines the frequency with which a vehicle stops. It also determines whether nodes at neighboring intersections can hear each other's radio transmissions. Larger blocks would increase the network's sensitivity to vehicles clustering at intersections and to network partitioning, and result in a degraded performance.

3.3 Traffic control mechanisms

The most common traffic control mechanisms at intersections are stop signs and traffic lights. A vehicle needs to stop at a red light until it turns green. A vehicle also needs to stop at a stop sign for a few seconds before moving onward. These mechanisms cause the formation of clusters and queues of vehicles at intersections, consequently reducing their average speed. Reduced mobility implies more static nodes and slower rates of route changes in the network. On the other hand, cluster formation can also adversely affect network performance with increased wireless channel contention and increased network partitioning.

3.4 Interdependent vehicular motion

Vehicles cannot disregard physical constraints posed by the presence of streets and nearby vehicles. Every vehicle's movement is influenced by the movement pattern of its surrounding vehicles. For example, a vehicle needs to maintain a minimum safe distance from the one in front of it, increase or decrease its speed, or change to another lane to avoid congestion.

3.5 Average speed

The speed of the vehicle determines how quickly its position changes, which in turn determines the rate of network topology change. The speed limit of each road determines the average speed of vehicles and how often the existing routes are broken or new routes are established. Additionally, vehicles' acceleration/deceleration and the map's topology also affect their average speed - if a map has fewer intersections, it implies that its roads are longer, allowing vehicles to move at higher speeds for longer periods of time.

3.6 Summary

This chapter discusses the various factors specific to VANETs that influence their mobility modeling and must be considered while analyzing the resulting network's simulation performance. The foremost constraint is the presence of streets which restrict vehicular motion to well-defined paths. This makes the area's topology crucial because the same mobility model might lead to drastically different network performance under different topologies. For example, a topology with small blocks would result in a very different performance from another topology whose blocks are so large that the nodes' transmission range becomes insufficient for reasonable network performance. Thus, these factors must be accounted for while modeling vehicular movement in a VANET, and a network simulation's performance must be considered in the context of the topology over which the simulations are conducted.

CHAPTER 4

IMPLEMENTATION

This chapter describes the approach adopted in this project's implementation, and details the three mobility models- the Stop Sign Model (SSM), the Probabilistic Traffic Sign Model (PTSM), and the Traffic Light Model (TLM). This chapter also describes other aspects of this study, including the real street maps used for this evaluation, the software's design, and the analysis of the traces produced by the network simulations.

4.1 Urban Vehicular Mobility Modeling

The three mobility models take as inputs real street maps that are extracted using the information available from the US Census Bureau's TIGER database [17]. The database also provides information about the roads' type, from which we can infer the corresponding speed limit and number of lanes on that type of road (interstate highways, residential areas, etc.). All roads are modeled as two-way streets. The SSM and PTSM assume single lanes in each direction of every road, whereas the TLM provides the option of modeling multiple lanes.

4.2 Stop Sign Model (SSM)

In the Stop Sign Model, every street at every intersection has a stop sign. Any vehicle approaching the intersection must stop at this signal for a specified time (a tunable parameter). A default value of three seconds was used in the experiments.

On the road, each vehicle's motion is constrained by the vehicle in front of it. This is quite intuitive – a vehicle moving on a road cannot move further than the vehicle that is moving in front of it, unless it is a multi-lane road and the vehicles are allowed to overtake each other. When vehicles follow each other to a stop sign, they form a per-street queue at the intersection. Each vehicle waits for at least the required wait time once it gets to the intersection. The crossing of multiple vehicles at the intersection is not coordinated among different directions. Vehicles move at random speeds within 5 MPH of the street's posted speed limit.

Although it is unlikely that an urban layout will have stop signs at every intersection, or that all vehicles move at a speed within 5 MPH of the posted limit, this model does serve as a first step toward understanding the dynamics of mobility and its effect on routing performance.

4.3 Probabilistic Traffic Sign Model (PTSM)

The next model was created as a refinement of SSM by replacing the stop signs with traffic signals at all intersections. Vehicles need to stop at red signals and drive through green signals. Although it is possible to simulate the coordination of traffic lights in an intersection's various directions, one of the goals of this work was to understand whether such a level of detailed simulation would produce routing performance significantly different from a simpler simulation.

Thus, the Probabilistic Traffic Sign Model (PTSM) was developed as an intermediate step. PTSM approximates the operation of traffic signs by adopting a probabilistic behavior rather than coordinating among different directions. When a node reaches an intersection and finds itself at the head of an empty queue, it decides whether to stop with a probability of p or to cross the intersection with a probability of $(1 - p)$. If it decides to wait, the amount of wait time is randomly chosen up to a maximum value w. While the first node is waiting in the queue, any arriving node has to wait for the first node's remaining wait time plus one second. The additional second simulates the startup delay between queued static cars. Whenever the signal turns green, the vehicles begin to cross the street until the queue becomes empty. The next vehicle that arrives at the head of an empty queue again makes a decision whether to stop with a probability p, and so on. As with SSM, there is no coordination at an intersection on the crossings of multiple vehicles from different directions. This model's advantage over SSM is that it avoids stopping at every intersection and, at the same time, approximates the behavior of traffic lights.

4.4 Traffic Light Model (TLM)

SSM and PTSM approximate the behavior of vehicular traffic. Because this work aims to understand what levels of mobility details are needed, PTSM was refined gradually by adding incremental mobility details. The resulting model is called the Traffic Light Model.

4.4.1 Coordinated Traffic Lights

The primary feature of the TLM is that traffic lights at each intersection are coordinated. First, consider the case in which all roads have single lanes in each direction. The lights turn green in such a manner that only opposing traffic crosses the intersection simultaneously. Nodes that need to turn left or right follow the free turn rule once they reach the head of the queue. The nodes facing each other on the same road have the green signal, while the others have a red signal. After a fixed period, the traffic lights switch and give the green signals to the another set of opposing roads. A T-intersection is treated by permitting one of the roads to periodically have a green light by itself. For intersections with more than four incoming direction, it was hard to come up with a generic rule, so a simple token passing mechanism was used. At a given time only one road has access to the intersection, cycled periodically across all incoming roads. By implementing these traffic lights, we replaced PTSM's probabilistic behavior with a more deterministic model.

4.4.2 Acceleration and Deceleration

The next level of detail added to TLM was vehicles' acceleration and deceleration. In this feature, vehicles at rest do not change their state to peak speeds instantaneously, unlike other models such as RWM. Instead, they accelerate from rest up to the maximum possible speed. Similarly, when approaching a stopping point (e.g. stop signs and red lights), they decelerate gradually to a stop.

4.4.3 Multiple Lanes

Another feature of the TLM was the introduction of multiple lanes on roads. Each road can have more than one lanes. For real maps, the number of lanes can be determined by

Table 4.1. Variants of the Traffic Light Model

Mobility Model	Multiple Lanes	Acceleration-Deceleration
TLM 1	No	No
TLM 2	No	Yes
TLM 3	Yes	No
TLM 4 (TLM)	Yes	Yes

the type of the road as specified in the TIGER database. When a vehicle enters a road, it selects the lane with the least number of vehicles (both moving and stopped).

4.4.4 Variants of TLM

An important goal of this study is to understand which simulation features significantly affect the ad hoc routing protocols' performance and hence merit inclusion in the mobility model. For this purpose, various features in the TLM can be enabled independently to obtain different variants of TLM. In particular, four variants of TLM can be obtained by enabling or disabling the acceleration-deceleration and multi-lane features. Hence, the basic TLM with neither of these two features has one additional feature over PTSM, namely coordinated traffic lights. Table 4.1 summarizes the differences between the variants.

4.5 Implementation Details

This section discusses the implementation details of this thesis, including the input street maps used, the proposed mobility models' operation, and the analyses of the traces produced by the network simulations.

4.5.1 Real Maps - The *TIGER* Database

The TIGER [17] database contains topographical information for each county in the United States, one file per county. Different landmarks are represented in specific types, along with their coordinates. A tool proposed in [1] was used to extract topographical maps from a specific file, given the coordinates of the area being considered.

The resulting map file for the specified area is in ASCII format, and represents each road as a datum entry. Each entry contains the following fields - road identifier, road type, and the coordinates of both of the road's end points. The road type is used to determine the number of lanes on the road, as well as its speed limit.

4.5.2 Software Design

These mobility models were implemented in C++ as independent programs that generate mobility files. These mobility files serve as input to the wireless simulations in NS2. These mobility models were developed using the Object Oriented programming paradigm.

The software consisted of the following classes:

1. Road
2. Vehicle
3. Intersection

As the first step in the mobility simulation, the input map file is read. For each entry in the file, a set of bi-directional *Roads* is created between the specified coordinates. Each point where a road can terminate is modeled as being an *Intersection*. By this definition, each intersection has one or more roads coming into it. However traffic signs were modeled only at intersections with more than two incoming roads. The specified number of nodes are then created as objects of the *Vehicle* class. The vehicles' initial positions and destinations are chosen randomly. Each vehicle is placed on a randomly selected road, and is assigned a random destination. It is ensured that the vehicle's start position and destination are not the same. Each node follows the shortest path to its destination computed using the Dijkstra's algorithm. On reaching its destination, the node first pauses for a specified duration, then is assigned another random destination with a different speed, and starts moving toward it. This process repeats throughout the simulation for each vehicle. Each vehicle is sampled every second of the simulation and is moved based on its state at that time.

Each mobility model takes a time parameter (in seconds). For SSM, the time parameter denotes the duration for which the vehicle must stop at each intersection. For PTSM, this parameter denotes the maximum duration for which a vehicle may have to stop at an intersection, in case it arrives at the head of an empty queue. For TLM, it represents the duration for which light stays green for each road on an intersection. The street topology is specified in the form of a map file described earlier.

4.5.3 NS2 Trace Analysis

NS2 [2] simulator was used for conducting the wireless simulations. The output produced by NS2 was a trace of the entire network simulation. NS2 provides support for two different trace formats in its wireless simulations – the *Old* format and the *New* trace format. We used the *New* format since it provided more information including the specific reasons for packet drops which helped in validating the various hypotheses concerning the dynamics involved in the simulation.

A software was developed to analyze these traces and to summarize the simulated network's performance. This program provided information regarding the delivery ratio, average end-to-end delay, hop count, and the number of packet losses categorized by their cause. To account for transient behavior during the simulation's warm-up period, the results for the initial 450 seconds were dropped. The simulation's duration was 1,350 seconds.

4.6 Summary

This project involved the development of three distinct urban mobility models, with four variants within the Traffic Light Model. The next chapter will present detailed analysis of the experiments. This chapter describes each of our mobility models' salient features. The Stop Sign Model captures the presence of stop signs at each intersection. The Probabilistic Traffic Sign Model adopts a probabilistic approach to approximate the operation of traffic lights.

The Traffic Light Model presents the highest level of detail and models coordinated traffic lights at intersections. It also simulates the acceleration and deceleration of vehicles on the road, as well as providing the option of simulating multiple lanes. Thus, each model essentially incorporates a level of detail greater than the preceding one. The experimental results will help us to determine the effect of these mobility models' incremental refinement on the network's performance.

CHAPTER 5

PERFORMANCE

A detailed evaluation of the impact of various mobility models on the AODV routing protocol was conducted using the NS2 [2] network simulator. The mobility models compared included SSM, PTSM and TLM, the Random Waypoint Model (RWM) [3] and the Rice University Model (RUM) [1]. RWM captures mobility in an open field with no obstacles, roads or intersections. RUM simulates roads in a real map, but vehicles do not stop at intersections.

For controlled experiments, the block sizes were varied in a grid topology over a $1200m \times 1200m$ area. Several real-world street maps with information retrieved from the US Census Bureau TIGER [17] database were also used. Though real-world maps are useful in understanding the combined effects of various modeling details, a controlled grid topology with different city block sizes was also used to understand the performance impact of each individual factor affecting mobility. Each simulation was repeated with at least five mobility patterns to attain a 95% confidence interval. Table 5.1 presents a summary of the default values of the various parameters used.

5.1 Varying Number of Nodes

The performance of different mobility models was compared as the number of nodes was varied in a $1200m \times 1200m$ grid topology with a block size of $200m \times 50m$. Figures 5.1 and 5.2 compare the delivery ratio and end-to-end delay among all mobility models. SSM had a wait time of 3 seconds. PTSM had a maximum wait time of 30 seconds. TLM switched the traffic signals with a periodicity of 30 seconds and used two lanes in each direction with acceleration/deceleration of vehicles enabled.

The results indicate that the RWM yields the lowest delivery ratio and the maximum end-to-end delay, for this particular topology. The range of performance variation across

Table 5.1. NS2 Wireless Simulation Default Parameters

Parameter	Default Value(s)
Simulation Time	900s (plus 450s warmup)
Routing Protocol	AODV
NS2 Version	ns 2.28
Transmission Range	250m
Number of Nodes	100
CBR Sources	15 sources and sinks at 4 pkts/sec and 64 byte pkt
Mobility Models	RWM, RUM, SSM, PTSM, TLM
Topologies	1200 × 1200m Grid, Real Map
Max. Wait Time	SSM–3 sec PTSM–30 sec ($p = 0.5$) TLM – 30 sec
Max. Node Speed	35 mph
Accel./Decel. Rate	3 meters/sec^2 for TLM
Performance Metrics	Delivery Ratio End to End delay Mobility, Clustering

various mobility models highlights the point regarding the importance of the fidelity of mobility models in VANET simulations.

The common trend is that the delivery ratio increases with the number of nodes, up to 100 nodes, as the connectivity of the communication graph increases. Then the delivery ratio starts decreasing as the number of nodes increases further. This behavior is due to the increased channel contention as the large number of nodes lead to a flood of control messages in the network. The end-to-end delay in Figure 5.2 displays a similar trend: it first improves (decreases) as the number of nodes increases, and then there is a sharp degradation thereafter.

NS2 scalability constraints became apparent as the number of nodes became large. The simulation time became a concern because of the need to explore a large parameter space. Also, the resource requirements of memory and storage (for output traces) became prohibitive. Additionally, with a large number of nodes, the confidence intervals of performance numbers widen significantly, further requiring more repetitions to reduce the

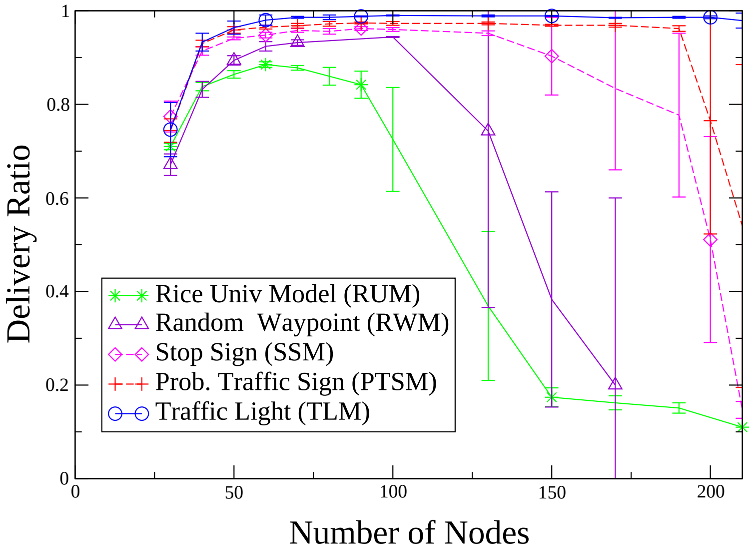

Figure 5.1. Variation of delivery ratio with number of simulated nodes. This graph presents the relative performance of all the evaluated mobility models.

variance of the results. Unless otherwise specified, 100 nodes were simulated in the remaining evaluations.

To analyze the performance effects of various mobility features (e.g., multi-lane roads and acceleration/deceleration of vehicles), this experiment was performed with all four variants of TLM mentioned in Table 4.1. Figures 5.3 and 5.4 compare the performance of the resulting models. The results indicated that the acceleration/deceleration feature led to a significant increase in the delivery ratio. This is because acceleration/deceleration reduces the average speed of vehicles, which provides greater stability to network routes. Additionally, the performance difference between the single-lane and multi-lane models is not noticeable below 100 nodes. However, with acceleration/deceleration disabled, the performance difference becomes noticeable beyond 100 nodes as the channel contention begins to rise. It is interesting to note that, once the acceleration/deceleration is enabled, the difference between the single-lane and multi-lane models becomes negligible.

This analysis leads to the conclusion that with fewer than 200 vehicles in a 1200m x 1200m area, the additional complexity of modeling multiple lanes does not significantly

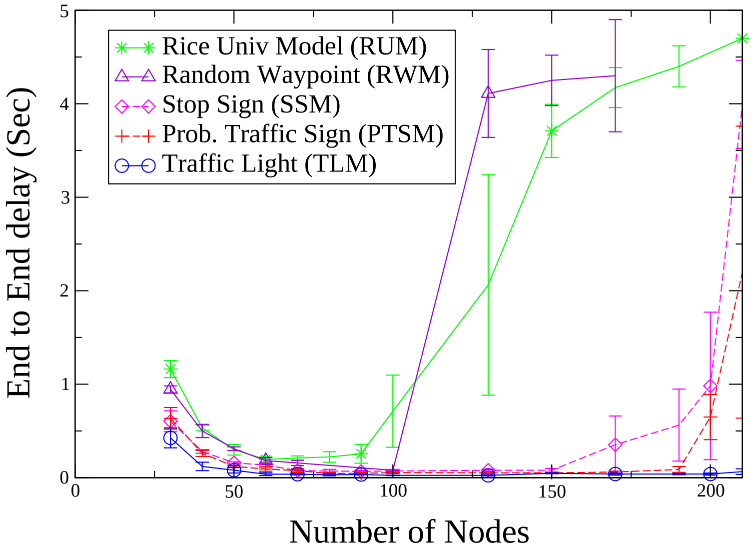

Figure 5.2. Variation of end to end delay with number of simulated nodes. Across all models, the delay decreases initially with increase in the number of nodes, but rises sharply as the number of nodes is increased further.

affect the performance of ad hoc routing protocols in VANETs, compared to the effects of vehicle acceleration and deceleration.

5.2 Varying number of Constant Bit Rate Sources

This section presents the variation in delivery ratio and packet delay with the number of Constant Bit Rate (CBR) sources. A $1200m \times 1200m$ grid topology with a block size of $200m \times 50m$ was used, and the number of nodes was fixed to 100.

Figures 5.5 and 5.6 show that as the number of sources increases beyond 15, there is a significant drop in the delivery ratio and an increase in the end-to-end delay by an order of magnitude. The deviation in the results obtained is also quite large beyond 15 sources, as indicated by the error bars in the graphs. As the number of CBR sources increases, there is an increase in the number of packets contending for a common wireless channel, which leads to more collisions and packet drops. For the remaining experiments, 15 CBR sources among a total of 100 simulated nodes were used.

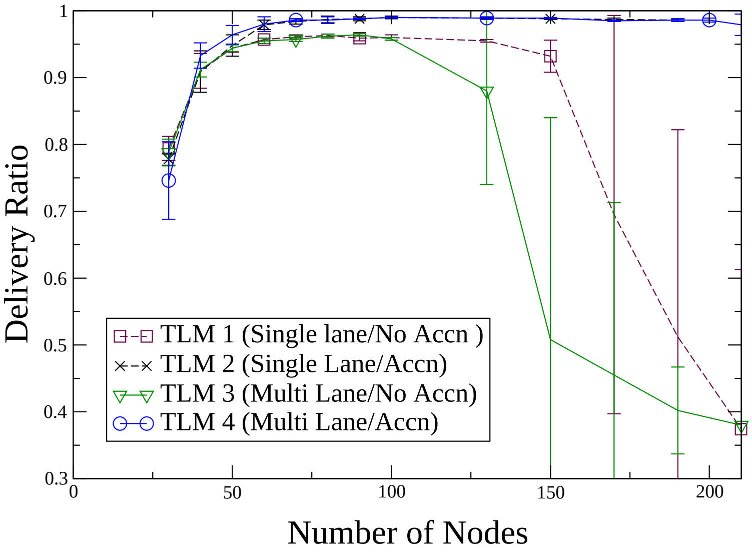

Figure 5.3. Comparison of single/double lane, acceleration/deceleration models under different numbers of nodes and their delivery ratios.

5.3 Varying Vehicle Speeds

The maximum speed of the vehicles was varied and the resulting performance of various mobility models was analyzed. Figure 5.7 shows the results of this experiment. Note that the maximum speed by default is based on the type of road, as defined by the US Census Bureau. The speed limit on the roads was varied from its default value to study how this parameter affects the resulting mobility pattern. The results show a significant drop in the value of the delivery ratio for RUM as speed is increased. RUM represents a network with highly dynamic topology in which vehicles constantly move through the streets without stopping at any intersection. This results in a continuous churn in routes between different sources and destinations. The delivery ratio of SSM (with a fixed wait time of 3 seconds) also decreases with increasing maximum speed, but not to the extent it does with RUM. The performance of PTSM and TLM (with maximum wait times of 30 seconds) does not vary much with the increasing maximum speed. The results for SSM, PTSM, and TLM are explained by the fact that the vehicles spend a significant amount of time waiting at intersections. Consequently,

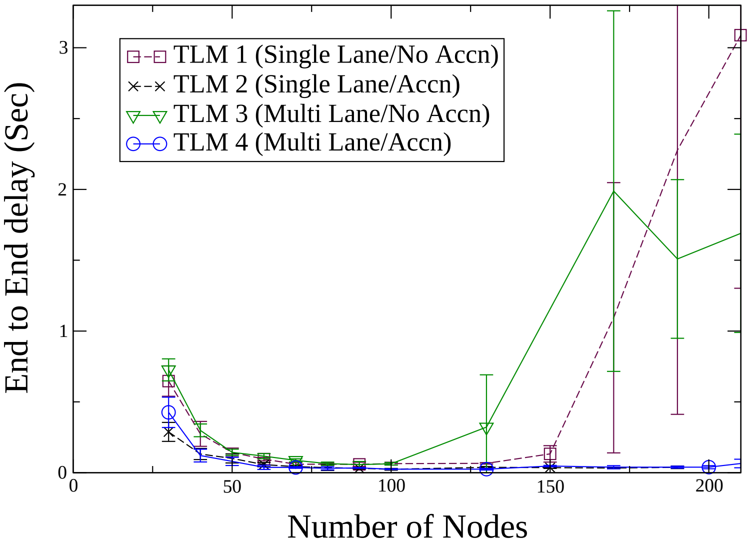

Figure 5.4. Comparison of single/double lane, acceleration/deceleration models under different numbers of nodes and their end-to-end delays

higher speed plays a smaller role in changing the network topology as rapidly as with RUM, and routes have a higher degree of stability and lower churn rate.

5.4 Varying Maximum Wait Times at Intersections

To further understand the effect introduced by making vehicles stop at intersections, another important parameter was varied – the nodes' maximum wait time at intersections. Figure 5.8 plots the packet delivery ratio as the value of maximum wait times at intersections was varied. The results brought out an interesting aspect of this study. As expected, the RUM model yields the lowest delivery ratio due to its highly dynamic mobility pattern. In contrast to earlier experiments, however, SSM yields a higher delivery ratio than that of PTSM for the same values of wait times. The reason is that the SSM models a more static network than PTSM, whose nodes are forced to stop at each intersection. On the other hand, nodes at the head of the queue in PTSM decide with a 50% probability whether or not to wait, and how long to wait. Thus PTSM represents a more dynamic network than SSM for

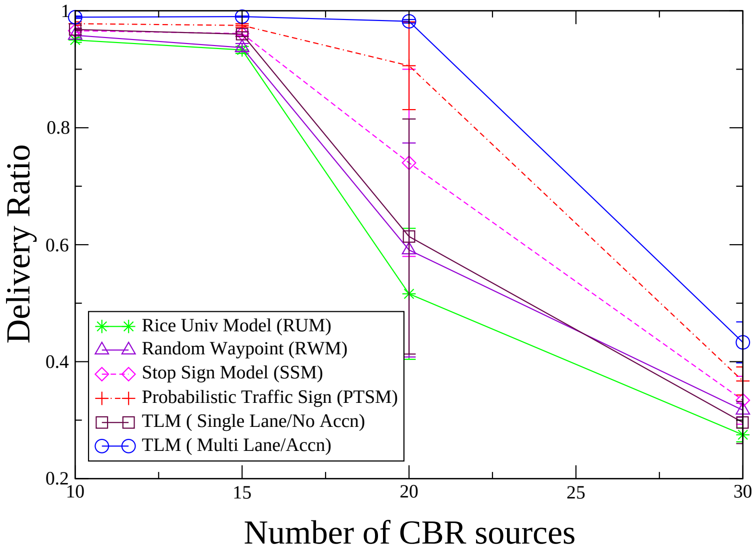

Figure 5.5. Variation of delivery ratio with number of CBR sources. The delivery ratio increases as the number of sources is increased to 15, but any further increase leads to a rapid drop as the channel contention in the network dominates.

the same value of the wait time parameter. The single-lane, no-acceleration/deceleration TLM displays a marginally lower delivery ratio than PTSM for the same wait time because the network has a slightly higher rate of churn with PTSM. The addition of multiple lanes and acceleration/deceleration to TLM results in a mobility model that displays the highest delivery ratio among these models. This result, combined with the earlier observation in Section 5.1 about negligible impact of modeling multiple lanes, suggests that the introduction of acceleration/deceleration effectively slows down the vehicle speeds most significantly and dampens the changes in the network topology. However, these results are also dependent upon other factors, such as block sizes, which would be considered next.

5.5 Effect of Block Sizes

The block sizes in the topology play an important role in determining the performance of the routing protocol. Given larger block sizes, vehicles spend a relatively longer time in traversing the distance between intersections; thus they are mobile for a longer time. This

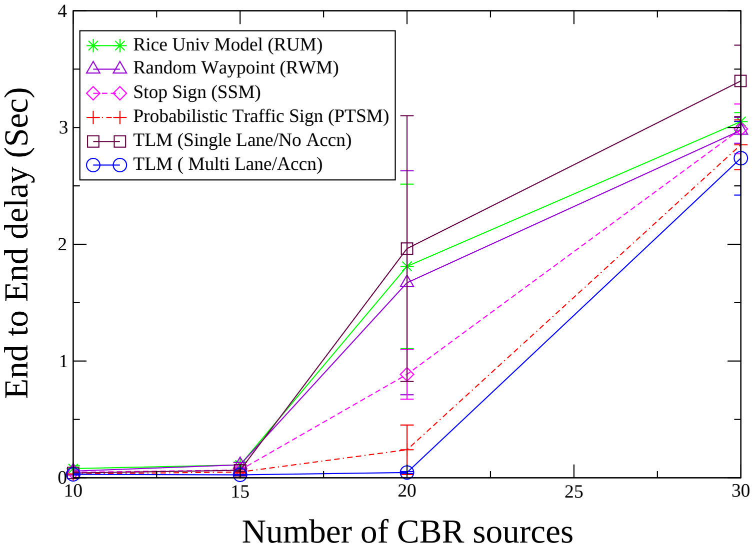

Figure 5.6. Variation of end to end delay with number of CBR sources. The trend seen here is similar to the results for delivery ratio, with a rapid increase in end to end delay as the number of sources is increased beyond 15.

increased mobility would lead to a weakened connectivity in the network, and a corresponding drop in the delivery ratio. To validate this, experiments were conducted with varying block sizes in a 1200m × 1200m area. The results in Figure 5.9 largely confirmed the hypothesis - as the block size increases, the delivery ratio is indeed found to decrease. Note that over the largest evaluated block, SSM outperforms PTSM due to a lower churn rate of routes, illustrating the interplay between block sizes and wait times in VANET simulations.

5.6 Analysis of Increased Mobility

The results of the experiments described so far have shown a distinct trend between the performance of various mobility models – the TLM resulted in the highest delivery ratios, and the performance did not degrade considerably with an increase in the number of simulated nodes; PTSM showed a higher delivery ratio than SSM, and the throughput obtained through use of each of these models was considerably higher than RUM. This brings into context the hypothesis that the varying degree of mobility (node speed) within these

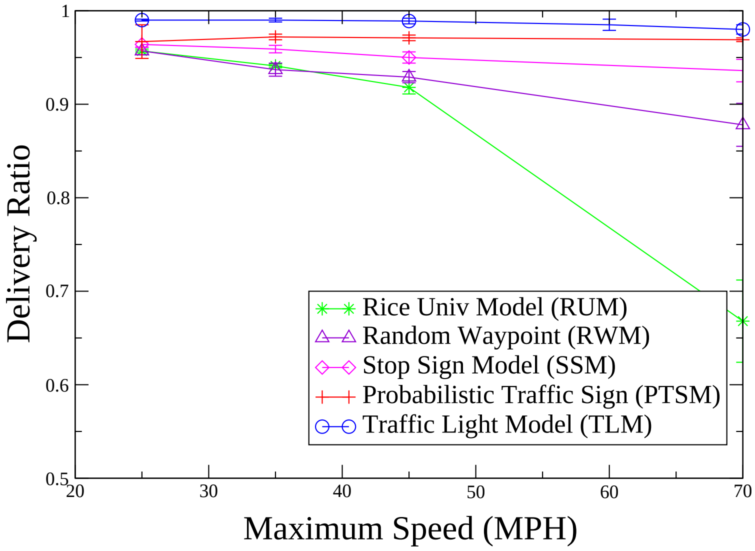

Figure 5.7. Variation of delivery ratio with the maximum speed of vehicles. As the speed increases the delivery ratio drops. This decrease is most significant for the RUM model, as compared to the SSM, PTSM, and TLM in which the communication topology does not change as rapidly.

networks is the reason for differing performance. In SSM, each node is forced to stop at each intersection. On the other hand, in PTSM, they stop only at some of the intersections and queued nodes cross an intersection one behind another analogous to the manner in which traffic proceeds when a traffic signal turns green. However, the default wait times for PTSM are higher as compared to SSM. This leads to a network that is effectively more static when compared to SSM, with better connectivity and corresponding performance improvements. TLM eliminates the probabilistic behavior of traffic lights and introduces acceleration and deceleration of vehicles, which leads to an even more stable network.

A detailed understanding of the underlying behavior requires identification of metrics that measure the nodes' mobility and the vehicles' clustering at intersections. The first metric measures the fraction of nodes that are moving at any given instant. The second metric is the extent of clustering at intersections. The number of vehicle clusters can be

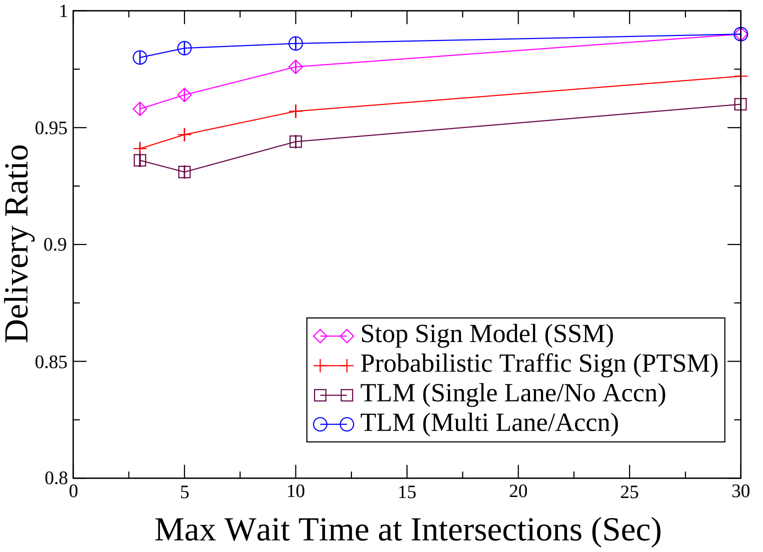

Figure 5.8. Variation of delivery ratio with maximum wait time at intersections. Mobility models that reduce the churn in network connectivity display a higher delivery ratio.

viewed as an effective number of nodes because clustering reduces the network's coverage. The third metric measures the average speed of the vehicles.

5.6.1 Average Number of Mobile Nodes

Computing this metric required determining the number of nodes not waiting in a queue at any intersection. The number of static nodes was sampled each second, and the results were averaged over the entire simulated time; the result is presented in terms of the percentage of total nodes expected to be mobile at a given time.

An interesting observation from the experiments is that, for the same wait time, increasing the number of nodes does not appear to significantly affect the percentage of mobile nodes. This implies that the topology and wait time largely regulate the mobility patterns for all nodes, unless there are enough vehicles to congest the traffic.

Under similar wait times and topological conditions, the SSM is less mobile than PTSM. Figure 5.10 presents the comparisons between the various mobility models. SSM and PTSM

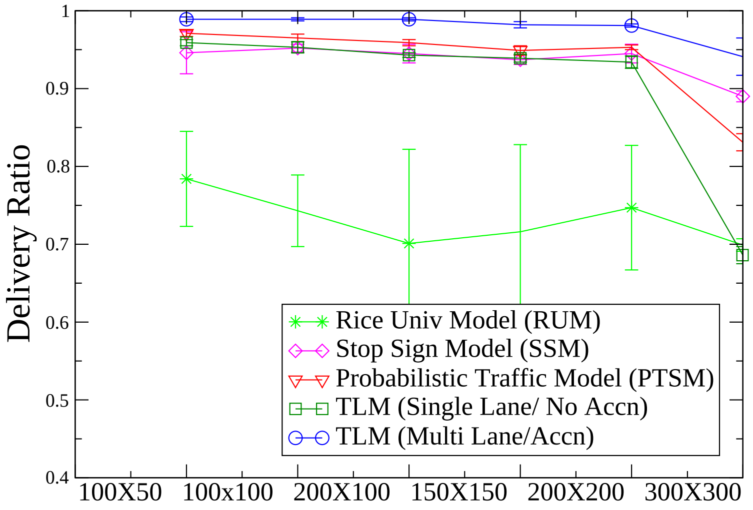

Figure 5.9. Variation of delivery ratio with block size, in a 1200m × 1200m area.

were evaluated with varying wait times, while TLM and its variants were evaluated with wait times set to 30 sec. Introducing vehicles' acceleration/deceleration to the TLM significantly increased the network's mobility, as seen from the nearly coincident plots for TLM 2 and TLM 4. To illustrate the effect of wait time, both PTSM and TLM were evaluated with a similar wait time value of 10 seconds. The plots indicate that PTSM is more mobile than SSM, with about 85% of PTSM's nodes moving at any given time as compared to about 68% of SSM's nodes.

5.6.2 Average Number of Clusters

Nodes stopping at intersections effectively created many clusters all over the network. Connectivity among the nodes within a cluster is strong (minus the channel contention effects). On the other hand, if one node in the cluster is unreachable by a certain node outside the cluster, then most likely all nodes in the cluster are unreachable by that node. The number of such clusters can be treated as the effective number of (logical) nodes in the

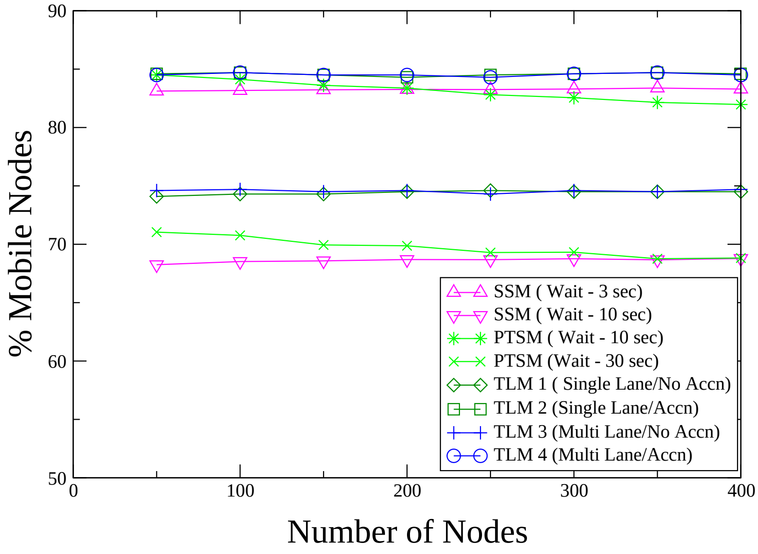

Figure 5.10. Variation in the percentage of mobile nodes at a given time versus the total number of nodes.

VANET at any time. Thus, clustering appears to have an effect equivalent to decreasing the number of nodes in the network.

To estimate the number of these effective nodes, the simulated area was divided into 60m × 60m regions. The number of nodes in each of these regions was sampled each simulated second, and an average was computed. Figure 5.11 presents the results of this analysis for all the models. The figures show that as the total number of nodes increases the number of effective nodes grows sub-linearly, i.e., at an increasingly slower rate. This indicates that more nodes are clustered together at intersections waiting for their turn to move. TLM resulted in a marginally greater number of effective nodes as compared to PTSM, for similar wait duration of 30 seconds. This indicates a reduced clustering effect in TLM – a consequence of the reduced average speeds of the vehicles. The variation of this effect with the maximum wait time at intersections was also studied, and it was observed that the SSM with a wait time of 3 seconds resulted in a similar plot as the PTSM with a wait time of 10 sec. The earlier analysis of mobility of the nodes in Figure 5.10 displayed this behavior as well. Interestingly, Figure 5.12 shows that acceleration/deceleration and multiple lanes

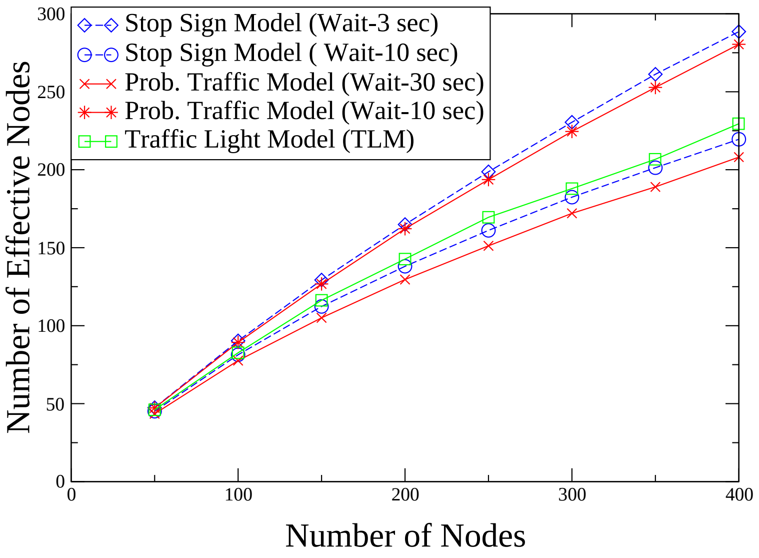

Figure 5.11. Variation of the number of effective nodes as the number of nodes increases. An increased clustering is evident from the decreasing slope of the plots. Also observed here is the variation in clustering caused by the wait time at intersections.

do not significantly impact the difference in clustering level between the various versions of TLM. This indicates that the performance difference across TLM variants is mainly due to differences in average speed.

5.6.3 Average Speed of Vehicles

Another useful indicator of the mobility pattern is the average vehicle speed. The average speed was computed for each vehicle as the ratio of the entire distance it travels during the simulation and the simulated time. Figure 5.13 shows the variation of average speed of vehicles with the number of nodes, across all mobility models. PTSM resulted in reduced average speeds as compared to SSM, because of the longer wait times involved at intersections. For TLM, the addition of acceleration/deceleration lead to a significant decrease in average speed, and the effect of this change was reflected as a higher delivery ratio. Another observation was that TLM with multiple lanes did not noticeably modify the average speed compared to single lane.

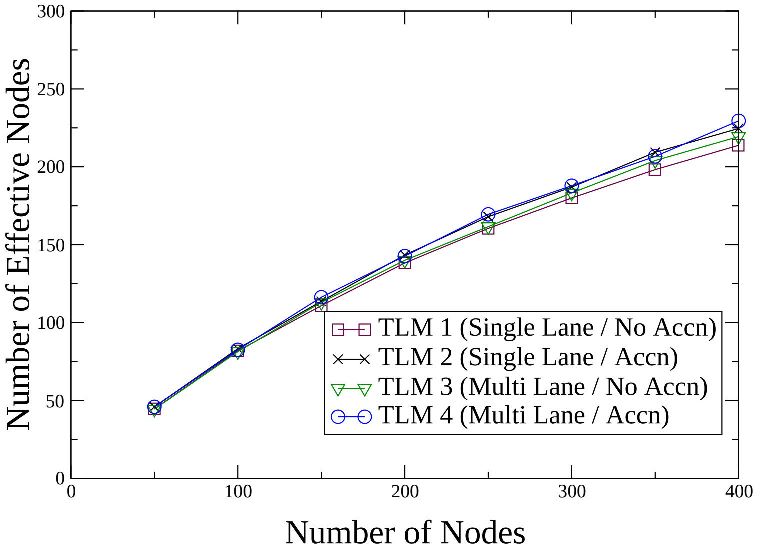

Figure 5.12. Variation in the effective number of nodes for different variants of the Traffic Light Model.

5.7 Real Map Results

Having obtained an insight into the various factors affecting the VANET in a uniform grid topology, simulations were conducted using real maps obtained from the TIGER database.

5.7.1 Real Map 1 - Houston, TX

A set of experiments was performed using a smaller section of the map used for the evaluation of RUM[1]. The original map was 2400m × 2400m, but the NS2 simulations at this size require too many nodes (or conversely unrealistic transmission ranges) to achieve meaningful network coverage and delivery ratios. To address this problem, RUM [1] had used a transmission range of 500 meters. However, 500 meters seems to be too large a transmission range for the typical vehicular nodes considered for VANET applications. Hence a lower value of 250 meters was used as the transmission range, and to maintain manageable simulations, the map size was truncated to 1200m × 1200m.

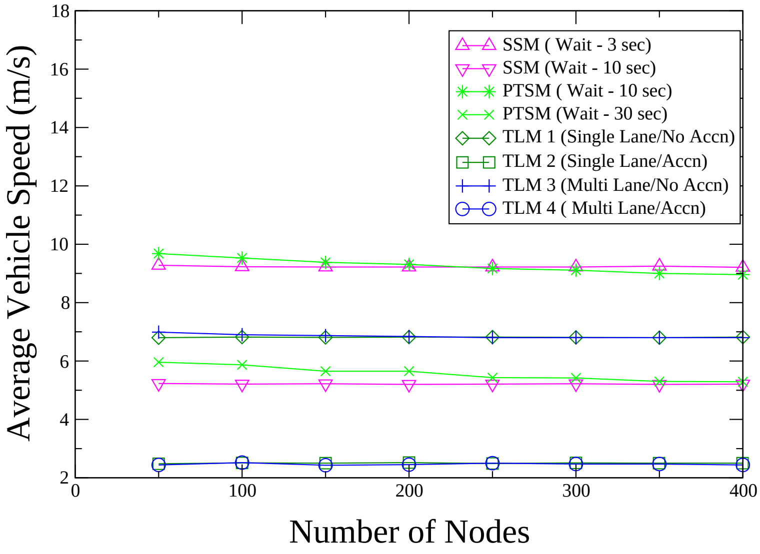

Figure 5.13. Variation in the average speed of mobile nodes for the proposed mobility models.

Figure 5.14 displays the layout of the map used for these experiments. The results of these experiments are summarized in Figure 5.15. The delivery ratio for each of the analyzed models increased with an increase in nodes up to 100, and performance rapidly degraded beyond that. The performance using TLM remained constant up to almost 200 nodes, and some degradation was observed beyond that point. These results validate the hypothesis in earlier sections regarding the correlation between topology and mobility, and between the simulated VANET's mobility and performance.

5.7.2 Real Map 2 - Tallahassee, FL

As another experiment, a map of Tallahassee over an area of 2000m × 2000m was used to conduct a complete set of experiments over the map. The results in this case were different from what had been seen so far, owing to the fact that this map represented a much larger area as compared to the first map. Figures 5.16 and 5.17 present the actual map and the graph showing the variation in delivery ratio as the number of nodes was increased.

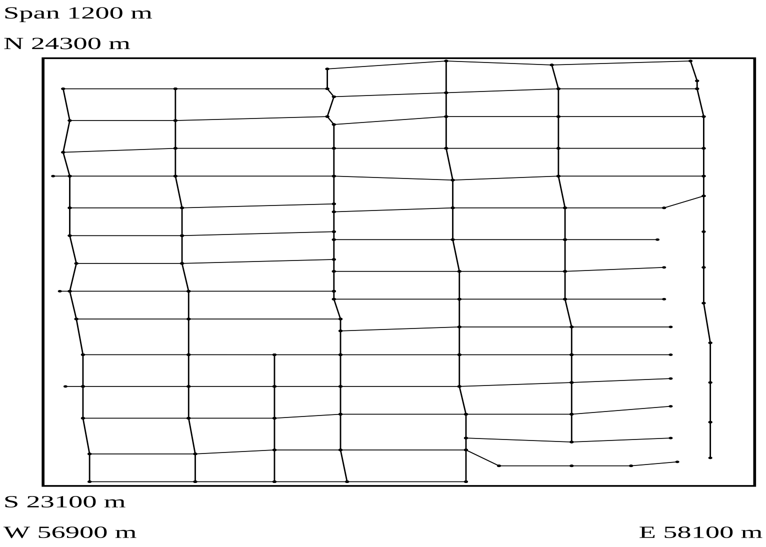

Figure 5.14. Real world map - 1200 × 1200m, Houston, Texas. Map extracted using information from the TIGER database. All lines represent actual roads within the plotted area. This map is a section of the map used in[1]

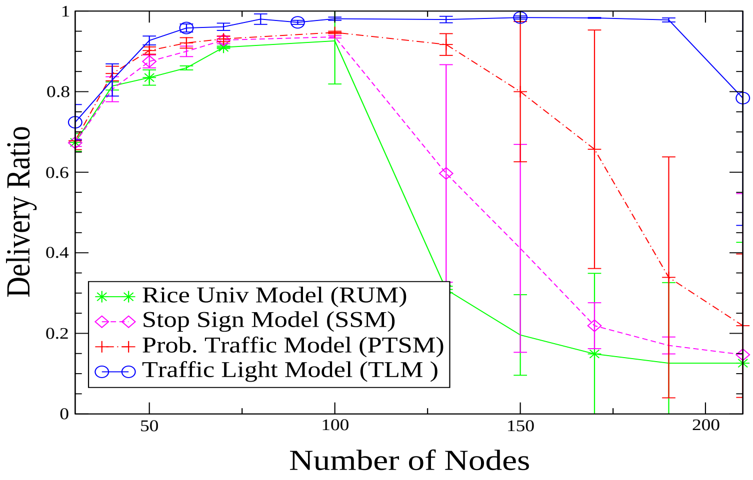

Figure 5.15. Variation of delivery ratio with total number of nodes over a 1200m × 1200m residential area shown in Figure 5.14.

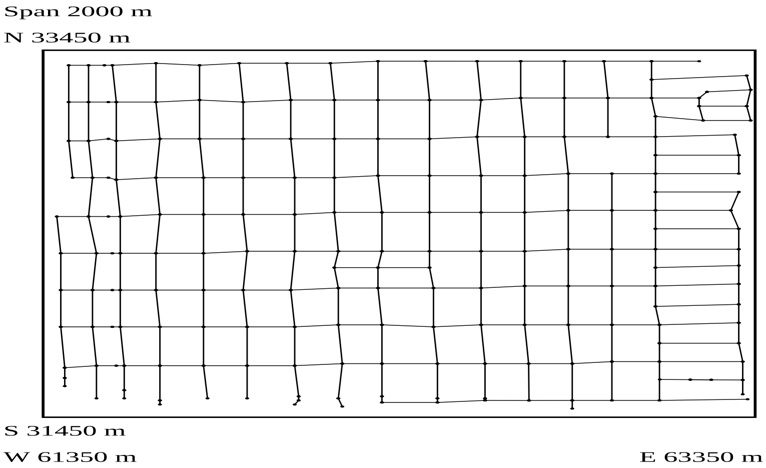

Figure 5.16. Real world map - 2000m × 2000m, Tallahassee, Florida.

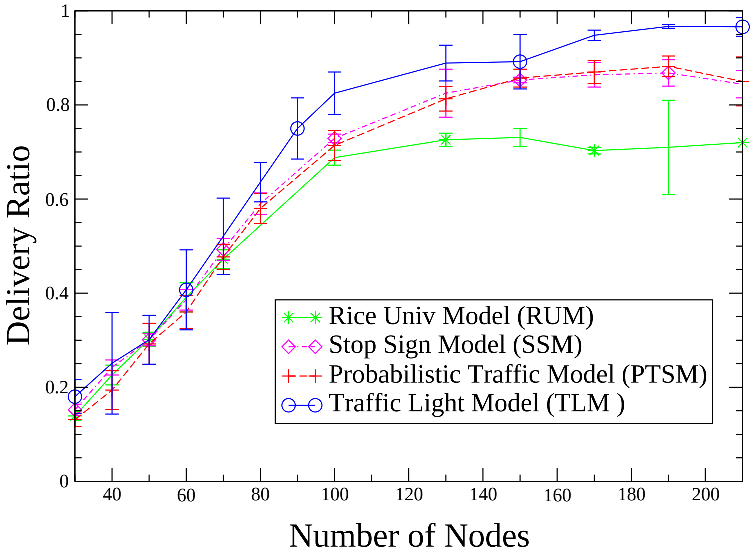

Figure 5.17. Variation of delivery ratio with total number of nodes, for map displayed in Fig 5.16.

This experiment displayed the effect of network partitioning due to the large area and small number of nodes initially. This effect was also strengthened due to the pauses enforced by these mobility models – once a node is in the waiting state at an intersection, it is highly likely that it would not be able to communicate with other nodes waiting on other intersections due to the large size of the map. The delivery ratios were initially very low with a small number of nodes, and the performance improved as the number of nodes increased upto 200. This was in contrast to the results obtained with the smaller map, where the performance fell with an increasing number of nodes, perceivably due to network saturation. This again brings into perspective the observation that the results obtained in these simulations must always be analyzed in the context of the topology. However, the basic findings remain valid. As is apparant, the delivery ratio obtained with TLM still remains higher than that with PTSM, SSM, and RUM due to a lower churn of network routes.

5.8 Summary

This chapter presented a detailed analysis of the various factors that affect the mobility of vehicles in the urban network. An increase in the number of transmitting nodes displayed a degradation of performance beyond a certain threshold, caused due to saturation of the network channel. A similar effect was observed as the total number of nodes was increased. The effect of topology was studied by conducting experiments on grids with varying block sizes, as well as real road maps. Topology was found to be a significant factor that determined the performance of the simulated VANET. The maximum node speed and wait times at intersections were also varied, and they also led to variations in the performance of the VANET. Mobility of nodes was analyzed in terms of clustering, static-ness of the nodes, and average speed. These metrics were computed and used to validate the hypothesis regarding the effect of different mobility patterns towards the performance of the network.

CHAPTER 6

FUTURE WORK

This work has provided significant insights into mobility modeling for VANETs. However there are certain other aspects of VANET simulations that we would like to study, and finally come up with a framework through which VANETs could be reliably tested before deployment. This chapter discusses certain other directions into which further research could be pursued, in order to achieve this vision.

6.1 Results on Actual Roads

Our understanding of VANET mobility modeling would be improved significantly if these results could be compared to real life traces of vehicular motion in urban networks. However, such real life traces are not available, at least not as per our requirements. In the absence of this information, another way of achieving this goal could be an experimental deployment of a VANET within an urban situation. This could consist of multiple vehicles equipped with wireless devices such as P.D.A.s or notebook computers. Through such an experiment, the vehicles' movement pattern and the resultant network performance could be compared to the performance of an ns2 simulation using mobility patterns generated through the proposed mobility models. Such an analysis would be an important step towards validation of the results and our hypotheses concerning mobility of vehicles in a VANET.

6.2 Modeling Temporal and Spatial Locality

It has been observed that the movement of nodes in a physical situation is governed by constraints of temporal and spatial locality. Spatial locality arises from the fact that certain locations are more popular than others, and temporal locality occurs due to the fact that people perform certain tasks at similar times of the day, such as taking lunch. Within an urban area there are certain locations or roads that are more congested during certain times of the day. In the morning, roads leading to the city downtown are packed, but there is significantly less traffic going in the other direction. The converse holds during the evening when offices close for the day. In a university campus, students arrive at their departments before start of classes, leave for the food court at lunch time, and so on.

The proposed mobility models do not model these constraints. In order to model these situations, certain locations could be designated as *anchor points* and the vehicular movement could be biased towards these points.

6.3 Obstacle Modeling

The wireless communication between vehicles running in an urban network suffers a degradation due to the presence of buildings and other physical obstacles along the roads. This aspect of VANET modeling has not been explored sufficiently. Jardosh [24] presented an obstacle modeling mechanism that allows users to specify obstacles within the simulated area, and the effect of the obstacles towards signal propogation is determined through a table lookup based on the type of obstacle.

This thesis did not consider the effect of the presence of obstacles. However, one of our major goals is presenting an integrated solution that incorporates the effect of mobility as well as presence of obstacles along the path. The idea is to extract obstacle information from the map, and then devise a radio propogation model that modifies the signal strength based on the presence, type, and orientation of the obstacles in the path of communication. This obstacle model would be created based on real world experiments to measure the signal degradation caused due to buildings.

6.4 An Integrated Model

The major observation in this work has been that different situations require different mobility modeling. For example, the constraints of temporal/spatial locality are more relevant in certain cases such as university campuses or city business districts. Similarly, clustering of vehicles is not a significant concern in a sparsely populated area.

Considering that different situations require to be handled differently, we would like to present an integrated solution that provides the user a complete control of the traffic situation being modeled. The resulting urban mobility model will aid the user in determining the behavior of the simulated network for certain values of factors such as the number of communicating nodes, their transmission ranges, and the durations of traffic lights. Essentially the user would be able to determine the optimal set of parameters for a successful deployment of the proposed network.

6.5 Summary

This thesis evaluated the various factors that must be taken into account while analyzing the results of a mobility model, and also attempted to determine the redundant features in such a mobility model. Future work in this study pertains to enhancement of the mobility models to account for temporal and spatial locatity of nodes, and incorporating the degradation introduced in the wireless communication due to the presence of obstacles along the roads. Finally we would like to present a complete solution to the problem of VANET simulation that would allow users to modify various settings/features and use the corresponding results to essentially design the VANET specific to the urban area being considered for deployment.

CHAPTER 7

CONCLUSIONS

Mobility models play a critical role in simulating routing protocol performance in Vehicular Ad Hoc Networks (VANETs). This work identifies the levels of detail in mobility models that are necessary to simulate VANETs in a variety of urban contexts.

This thesis introduces three related vehicular mobility models – the Stop Sign Model (SSM), the Traffic Sign Model (TSM), and the Traffic Light Model (TLM) – that represent the movement pattern of vehicles in urban environments to varying levels of simulation details. It also evaluates the usefulness of various details in capturing the major factors affecting the performance of routing protocols in VANETs.

Evaluation results indicated that the clustering effect among vehicles waiting at intersections and acceleration/deceleration of vehicles are some of the significant factors that affect the performance of the simulated VANET. Another observation was that simulating certain features might have only a marginal impact on the VANET performance. This effect was illustrated by the simulation of multiple lanes - a feature that was found to have limited effect on the simulated network's performance, when compared against other features such as the acceleration and deceleration of vehicles.

The results also illustrate the importance of topology in analyzing the simulated VANET's performance. Given the same experimental setup, different topologies can lead to dramatic variations in network performance. A larger block size could lead to nodes being out of each other's transmission range; thus resulting in network partitioning and a consequent degradation in network performance. Due to this reason, the performance of a simulation must be considered keeping in perspective the topology over which the simulation was conducted. The value of the wait times at intersections was also observed to significantly affect the behavior of the resulting network.

This work brings into focus the varying requirements for modeling different types of situations. Unlike the existing state of the art, we require mobility models to simulate a vehicular situation specific to the topology being modeled. This should take into account the presence and behavior of the traffic controlling mechanisms being employed, and locality constraints specific to the location. This work is a step towards achieving that goal.

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BIOGRAPHICAL SKETCH

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Atulya Mahajan was born in Delhi, India in 1980 on August 15th, India's independence day. In 2002 he completed his Bahelors of Engineering in Electrical Engineering from Delhi College of Engineering. During the next two years he worked as a software engineer for CMC Ltd and Oracle India. In the Fall of 2004 he started his Masters of Science course in Computer Science at Florida State University, which he completed in May 2006.

He is a member of academic honor societies Phi Kappa Phi and the Computer Science honor society Upsilon Pi Epsilon.