

REALISTIC MOBILITY MODELING FOR VEHICULAR AD HOC NETWORKS

by

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REALISTIC MOBILITY MODELING FOR VEHICULAR AD HOC NETWORKS

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ABSTRACT**REALISTIC MOBILITY MODELING FOR VEHICULAR
AD HOC NETWORKS**

The validity and performance of routing protocols for Vehicular Ad Hoc Networks (VANETs) are mostly evaluated by simulations. However, simulations based on random mobility fail to consider individual and specific behaviors of nodes. A realistic mobility model that is able to reflect some features of vehicle mobility is important for a more accurate evaluation. In this thesis, a realistic mobility modeling tool, Mobility for Vehicles (MOVE), which considers the basic mobility behaviors of vehicles, is proposed. The proposed model is tested against the Random Waypoint (RWP) model using Ad Hoc On Demand Distance Vector (AODV) and Optimized Link State Routing (OLSR) protocols to show that the mobility model can affect the evaluation of a protocol significantly. Simulation results show that vehicle mobility model effects the performance of routing protocols, emphasizing the importance of the mobility models in the evaluation of VANETs.

ÖZET

TASARSIZ ARAÇ AĞLARI İÇİN GERÇEKÇİ HAREKET MODELLEME

Tasarsız araç ağları için önerilen yönlendirme protokollerinin geçerliliği ve performansı çoğunlukla benzetimlerle değerlendirilir. Fakat, rasgele hareketliliğe dayalı benzetimler araçların bireysel hareketlerini göz önüne almazlar. Bireysel araç hareketlerinin bir kısmını yansıtan gerçekçi bir hareket modeli tam ve doğru bir değerlendirme için önemlidir. Bu tezde araçların temel davranışlarını göz önüne alan gerçekçi bir hareket modelleme sistemi önerilmektedir. Hareket modelinin bir protokolün değerlendirmesini kayda değer derecede etkileyebileceğini göstermek için, önerilen model AODV ve OLSR yönlendirme protokolleri kullanılarak Random Waypoint modeline karşı test edilmiştir. Benzetim sonuçları araç hareket modelinin yönlendirme protokollerinin performansını etkilediğini göstermiş, hareket modelinin tasarsız araç ağlarının başarımlarını değerlendirmesindeki önemini vurgulamıştır.

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LIST OF SYMBOLS/ABBREVIATIONS

AODV	Ad Hoc On Demand Distance Vector Routing
DSRC	Dedicated Short Range Communication
DSDV	Destination-Sequenced Distance-Vector
DSR	Dynamic Source Routing
FSR	Fisheye State Routing
GPRS	General Packet Radio Service
GPSR	Greedy Perimeter Stateless Routing
IDM	Intelligent Driver Model
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
ITS	Intelligent Transportation System
MANET	Mobile Ad Hoc Network
MOVE	Mobility for Vehicles
MPR	Multi Point Relay
OLSR	Optimized Link State Routing
QoS	Quality of Service
RFC	Request for Comments
RWIS	Road Weather Information System
RWP	Random Waypoint
RREQ	Route Request
SMAC	Smart Medium Access Controller
TORA	Temporally-Ordered Routing Algorithm
UMTS	Universal Mobile Telecommunication System
VANET	Vehicular Ad Hoc Network
WLAN	Wireless Local Area Network
A	Total area
A_i	Attraction indicator of point i
L	Total road length

N	Number of nodes
n_{MOVE}	Number of reachable nodes in MOVE
n_{RWP}	Number of reachable nodes in RWP
P_i	Popularity of point i
R	Transmission range
V	Speed of a vehicle

1. INTRODUCTION

A variety of information and communications technology is applied to transportation infrastructure and vehicles to improve safety and efficiency of the transportation system, reduce transportation times and fuel consumption, deal with traffic congestion, and maintain security by the surveillance of roadways. Research and projects are ongoing in the US [1], Europe [2], and Japan [3] on the design and implementation of Intelligent Transportation System (ITS) supported by a variety of organizations. Incident management systems are designed to reduce the time to detect and respond to incidents, quickly eliminating the traffic congestions due to incidents. Emergency vehicle notification systems (E-MERGE, eCall) [2] detect and report the location and severity of incidents, the identification of vehicle to responsible agencies. Vehicle sensors activated by an incident can automatically generate an emergency call. Traffic signals can be controlled according to the traffic congestion obtained from the surveillance devices so the responding vehicles quickly reach the incident location. Crash prevention and safety systems detect unsafe conditions and warn the travelers providing the necessary actions to take. Driver Assistance Systems can assist the driver in operating the vehicle safely or force the driver to obey the road speed limitations and traffic rules. The queues at toll collection can be eliminated with Electronic Payment and Pricing. Road Weather Information Systems (RWIS) [4] gather information from the sensors on the roads or nearby towers and automatically report weather conditions. Important information about trip departures, routes, and traffic conditions is made accessible to travelers through user services like trip planner (EU-SPIRIT). NextMAP and ActMAP are systems for dynamic updating of on-board digital maps. Other application areas are also possible like Border information flow and multimedia service (PRETIO).

Floating car data (floating cellular data) [5] is a method used for determining traffic speed and road network. Mobile phones in cars transmit their location information to the network. This data can be analyzed and converted into accurate traffic flow information without the need for any additional hardware. However, different ap-

plications with specific needs make it indispensable to deploy specific equipments for car-to-car and infrastructure aided communication. Physical architecture [3][4] of ITS defines the major system components and ITS interfaces required between subsystems (Figure 1.1). Traffic detectors, sensors on vehicles and road surface, traffic signals, surveillance devices, and video equipments are employed to provide traffic flow information to centers. The centers are fixed locations gathering, processing, and spreading traffic data received from vehicles and roadside units through wired communication channels. Traffic is monitored for toll administration, emergency management, and traffic management while information services are provided to other subsystems. Travelers can access user services about road traffic information. Roadside subsystem includes sensors for detecting specific incidents and accidents while providing the centers and the vehicles with the necessary traffic data.

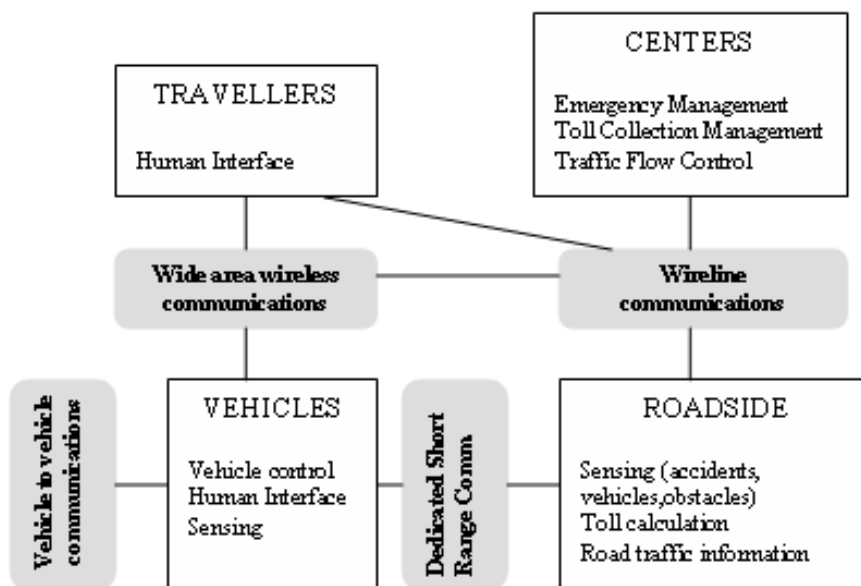


Figure 1.1. ITS architecture [3][4]

Car-to-car Communication Consortium introduces a system architecture for supporting the requirements of these heterogeneous applications (Figure 1.2) [6]. Different wireless technologies like IEEE 802.11 Wireless LAN (WLAN), Dedicated Short Range Communication (DSRC), and GPRS/ UMTS are currently considered as candidates for car-to-car communication. The standardization process of IEEE 802.11p, Wireless

Access in Vehicular Environments, is supported by the European Car-to-Car Communication Consortium. Specific network needs of vehicular environments lead many research challenges in car-to-car communication systems, like scalability, security, and QoS for high-speed real time communication [7]. Because of its complex nature, large testbed systems are not cost effective to validate new protocols and wireless transmission schemes.

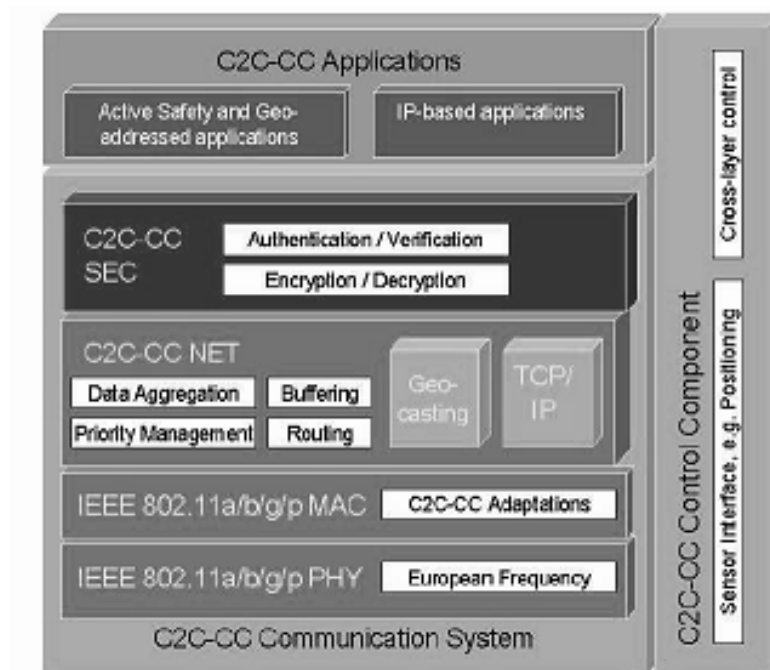


Figure 1.2. C2C-CC system components and functionality [6]

Mobile Ad-Hoc Network (MANET) is a collection of mobile nodes forming a temporary network without any fixed infrastructure. Vehicular Ad Hoc Network (VANET) is a special research area in MANETs, dealing with wireless communication between traveling vehicles and roadside units. Application data vary from sensor information from other cars to live video stream. Vehicles can exchange information about real-time traffic congestion, road condition and maintenance, car accidents, and regional weather forecast, which makes it possible to develop different safety applications such as crash avoidance, parking, automated highway systems, trip planning, and driver assistance.

The performance of routing protocols is measured by the delivery ratio and delay of packets sent between moving nodes. The delivery ratio is directly related to

the connectivity of the network and the length of the period of connectivity between nodes. The distributed and infrastructureless nature of mobile ad-hoc wireless communication and the relatively high mobility of vehicles makes connectivity essential for VANET application. Connectivity problem in wireless networks can be studied analytically according to the transmission range and distance between nodes [8]. The delay is affected by the signal propagation, collisions, and congestion at the air interface. The distribution of the nodes over the area differs according to the topology, which affects the node density in different parts of the terrain. The location of the nodes change according to their mobility patterns. Mobility model determines network connectivity and directly effects the performance of the system. Studies show that different assumptions on mobility patterns cause different results of performance evaluation [9][10]. Generally reactive protocols have better performance than proactive protocols, however, Optimized Link State Routing (OLSR) outperforms Ad Hoc On Demand Distance Vector Routing (AODV) under realistic mobility patterns [31]. Although in real traffic traces AODV is better, Greedy Perimeter Stateless Routing (GPSR) always outperforms AODV with the random waypoint model [12].

In mobile ad hoc networks, the validity and performance of different mechanisms should be evaluated considering the change in the location of the nodes. Location information can be obtained by recoding the traces of mobile nodes activity in existing networks. Yet, a large number of mobiles and long observation duration results in huge amounts of data [13]. Also, this method requires an existing system to monitor. Analytical and simulation based models are alternatives that use mathematical and computational results instead of trace data.

Analytical models describe a system or problem unit using a collection of equations. Analytical equations or numerical algorithms are developed to estimate the performance of a model or system. Simulations are the active computized model of the system and act as the operating behavior of the system or problem entity. There are also hybrid models combining the analytical and simulations models [14]. Though analytical models provide theoretical bounds, their results are generally limited and inaccurate due to assumptions. Besides, some systems cannot be represented with a

closed form analytical equation set. Simulations, on the other hand, are more appropriate for complicated systems. However, simulation models have the disadvantage of long execution times, as they must be executed until they statistically reach an absolute confidence interval.

Simulators can be divided into two classes according to the level of detail and mobile independence. Macroscopic simulators, use group behavior studies or models and attempt to predict travel behavior characteristics for an aggregate population, viewing vehicular traffic as a fluid. However, macroscopic methods fail to consider individual behavior of nodes. Microscopic simulators, on the other hand, use entity mobility modeling that bases mobile independence approach [13]. Microscopic simulators reproduce traffic conditions as they emerge from the interaction of individual vehicles with each other [15]. Macroscopic simulators consider parameters like traffic density and flow of vehicles, discarding their individual location, while microscopic simulators consider the effect of movements of individual vehicles and correlations between them.

Most of the simulators fail to model the effects of intersections, road conditions, clustering, lane changing, and different traffic control mechanisms. Also, random mobility models used for mobile ad-hoc networks do not reflect the specific behaviors of vehicle mobility, which in return affects the performance of routing protocols. In the literature, most of the routing protocols are tested with random models or with unrealistic simulation setups. In this thesis, we propose a realistic vehicular mobility model, Mobility for Vehicles (MOVE), implemented on OPNET 11.5 simulation software. Our model considers the basic mobility features of the vehicles. The results reveal the important design items to consider for appropriate routing in VANETs.

The rest of the thesis is organized as follows. In Chapter 2, previous work on mobility models for VANET is presented. In Chapter 3, routing protocols and their evaluation in the literature are summarized. The proposed mobility model is introduced in Chapter 4. In Chapter 5, simulation results are presented. Chapter 6 states the conclusions and future work.

2. MOBILITY MODELS IN THE LITERATURE

Mobility models can be classified into different categories. Random mobility models are listed as Brownian walk model, smooth mobility model, and Random Waypoint (RWP) model. In area constrained random models, random movements are restricted and based on graphs. Profile based random models consider the travel behavior of a user. Models based on real world position traces derive user trip model parameters from existing user position traces of real world observations. Aggregate models like fluid model discards the individual movement of vehicles and define a group motion. Integrated generic models can be created as a mixture of different categories ([16]).

2.1. Random mobility models

Different mobility models have been introduced by many researchers, the most commonly used of which is random walk. In the model, the speed of the user is derived from a uniform distribution over $[V_{min}, V_{max}]$, while the direction of the user is derived from a uniform distribution over $[0, 2\pi]$. The mobile travels towards to the selected direction with the selected speed for a fixed time interval. After this interval, new speed and direction values are selected with the same process. A mathematical formulation is given in [17] for systematic tracking of the random movement of a mobile station in a cellular environment.

Random Waypoint mobility model is a variation of random walk model. Points are uniformly distributed in the area and nodes move from one point to another, stop for a specific duration, and later on move towards to another point. The model cannot provide a steady state in terms of the average node speed because the speed continuously decreases over time [18]. In Sound Mobility Modeling [19], a more stationary mobility model is introduced by choosing the initial speeds from steady-state distribution, and subsequent speeds from original distribution. This prevents the impact of warm-up period. During the warm-up period, simulation runs until steady state is reached and then the initial data are deleted. The model suggests that the speed of the

initial trips selected by each node is independent of travel times, while the steady state average speed is weighted by travel times (i.e. travel time is longer for lower speed). If there are pauses between successive speeds, the movement is separated into a move process and a pause process.

In random models, nodes converge and diverge repeatedly at the center so node concentration is towards the center as simulation progresses, resulting in density waves [20]. In order to overcome this problem Random direction [21] model is introduced, in which nodes select a random direction and a destination on the boundary in this direction to travel. Then travels to that destination at a selected speed. Once it reaches the boundary, it pauses for a given pause time then selects new direction and destination. They also propose a modified version, in which the destinations can be selected anywhere in the areas.

When the speed and direction selection of nodes are not correlated to previous values, it results in sudden speed changes and sharp turnings [22]. In Smooth random model, two stochastic processes is used to determine when to change speed and direction. The speed is changed incrementally by the current acceleration of the node also the direction change is made smooth by creating curve turnings. According to Gauss-Markov model[23] a mobile's future location and speed are likely to be correlated with its current location and speed, so equations are introduced to calculate the speed and direction considering the old values. In incremental velocity vector [24], the position and speed of the mobile node is updated periodically calculated with equations of maximal mobile velocity, maximum acceleration, and maximum angular change of the mobiles direction per unit time. Brownian motion represents the motion of molecules inside a liquid or gas and can be used to find the probability distribution of the physical location a mobile node [13].

2.2. Area constrained random models

In the mobility model by A. K. Saha and D. B. Johnson [25], random starting and ending points are assigned to each vehicle. The paths are calculated with the

Dijkstra's shortest path and are dynamically altered as the number of cars changes. The weights of the paths are calculated according to the traffic load and distance. The authors use real maps in their simulations. The effect of car following, intersections, and clustering is not mentioned in the paper.

In [26], movement paths are built using the Voronoi diagram of obstacle vertices. Destinations are chosen from the set of obstacles, influenced by the constructed pathways. Shortest path to destination is calculated for the vehicle to follow. Obstacles create signal-blocking regions, effecting the propagation of the transmission. In [10], real map is used which is represented by blocks (pixels) with different colors for different kinds of structures. The call patterns of the users are determined by the color of the block they are in. The nearby blocks are examined according to their colors and structure switching probabilities, to determine the moving direction of the user.

In city section model [27], a city is represented by a street network with different speed limits. A random destination point on a street is chosen and shortest path to that destination is calculated and assigned to the node. When the node reaches the destination, it stops for a specified time and repeats the process. The model considers minimum safety distance between two nodes but does not include intersection handling.

Instead of moving towards random destinations, users follow paths according to the activity they intend to involve in, which introduces the effect of conscious traveling. Activity-based model [28] uses an activity transition matrix and an activity duration matrix to assign destinations to users and construct paths.

2.3. Vehicle movement based models

In [29], Ahmed formulates the acceleration response of driver n at time t to the stimulus at time $(t - T^n)$ as,

$$a^n(t) = \alpha \Delta V_{front}^n(t - T^n) \quad (2.1)$$

$$\Delta V_{front}^n(t - T^n) = V_{front}^n(t - T^n) - V^n(t - T^n) \quad (2.2)$$

where, $\Delta V_{front}^n(t - T^n)$ is the stimulus, $V^n(t - T^n)$ is the subject speed at time $(t - T^n)$, $V_{front}^n(t - T^n)$ is the speed of the vehicle in the front at time $(t - T^n)$. The equation becomes a sum of all stimuli, if all the cars after the one in the front is considered. This is the car following acceleration $a_{ff}^n(t)$. If the time headway is greater than a threshold, the free-flow acceleration is used. Otherwise the car following acceleration is used.

In [20], the wait times at intersections are considered as the essential part of the model. Two different approaches are introduced. In the Stop Sign Model, the vehicles wait for a fixed stop time in the queue before crossing the intersection. In the Traffic Sign model, vehicles stop only at some intersections for a randomly chosen stop time. Also, the effect of clustering is considered. A more detailed design of obstacles, road lanes, and crossing at intersections is given as future work.

In Street Random Waypoint model (STRAW) [30], the effects of details are analyzed. A component based model is introduced, with a variable level of details for each component. The parameters of the components display the interaction between the accuracy and complexity of the system. Intra-segment component controls vehicular motion from the point at which a vehicle enters a road segment between two intersections to the point it exits the segment. Car following model of motion is issued in this component. The inter-segment component deals with the behavior of vehicles at intersections, according to the type of road segments intersecting, type of traffic control, merging scenario, and turning speed. The route management and execution component determines the path each vehicle follows during the simulation. The paths can be

determined without considering origin destination information or shortest path is calculated between a source and destination point, which dynamically changes according to traffic. Traffic flows and lane changing are given as future work in the paper.

VanetMobilSim [?] creates a realistic random topology according to obstacles in the area, different densities of city centers, lanes, and traffic signs. It generates vehicular movement traces considering both macromobility (road topology, lanes, traffic signs, point of interests, speed limit) and micromobility (car-following, acceleration) concepts. Different micromobility models can be adapted to the simulator each differs in their calculating individual vehicle speed. Among them, Intelligent Driver Model (IDM) is a follow the leader model that adjust car speed according to the front vehicle considering car following and lane change. A modular concept of mobility model is introduced with different functional blocks for specific aspects of vehicle and driver behavior (Figure 2.1).

Applications of ubiquitous computing and network layer approaches are analyzed under the assumption that they do not affect the mobility pattern of vehicles. In [32], Patwa and Dutta propose that for a more realistic model of mobility, the effect of the feedback loop of the applications on the mobility of vehicles must be analyzed. The authors verify usefulness of such a study by showing that these applications can cause oscillation waves in the traffic flow, which have not been recognized before. They study and analyze a model for the roadway congestion detection and notification application in which as congestion is detected, vehicles approaching the congestion area may choose to exit the highway (amelioration of congestion). They propose a new model enhancing the Enskog dense gas modeling of traffic model. New equations are derived from the existing ones taking into account the behavior of leaving the highway. The model is verified by both analytical solutions of the model and the microscopic simulations.

The whole traffic information of the vehicular network can be obtained with the support of Wireless Metropolitan Area Network (WMAN) infrastructure and this information can be used in routing. In [33], Chan *et al.* propose a new Heterogeneous Vehicular Network (HVN) architecture integrated with WMAN and introduces a Mo-

bility Pattern Aware Routing Protocol (MPARP) for HVN. The IEEE 802.16 base station (BS) works as a centralized location server and vehicles associated with this BS can communicate with farther vehicles. Spatial dependence, temporal dependence, and relative speed are defined as the mobility metrics that can differentiate the various mobility patterns. According to these metrics, the mobility pattern of the vehicle is determined. In routing, the mobility patterns of the vehicles are checked and Dependent Vehicular Groups (DVG) are constructed with the vehicles whose patterns may not cause path break. The BS checks the validity of route paths and DVGs. The mechanism is tested with 15 vehicles and one base station. According to their results, MPARP can maintain its connection when link breaks occur, providing a reliable connection. Increase in the relative speed causes more frequent link breaks. In this case, the BS suggests the source vehicle to forward data by the relaying BS.

In [34], authors try to enhance AODV routing protocol using three important mobility parameters of vehicles: position, direction and speed. These parameters are assumed to be obtained from GPS and used for selecting the next hop during route discovery phase. The nodes having the same direction with source and/or destination node are more likely to be selected as the next hop. The Manhattan mobility model with several horizontal and vertical streets is used in the simulations. Results show that links, which are selected with respect to nodes' directions and positions, are more stable and reliable.

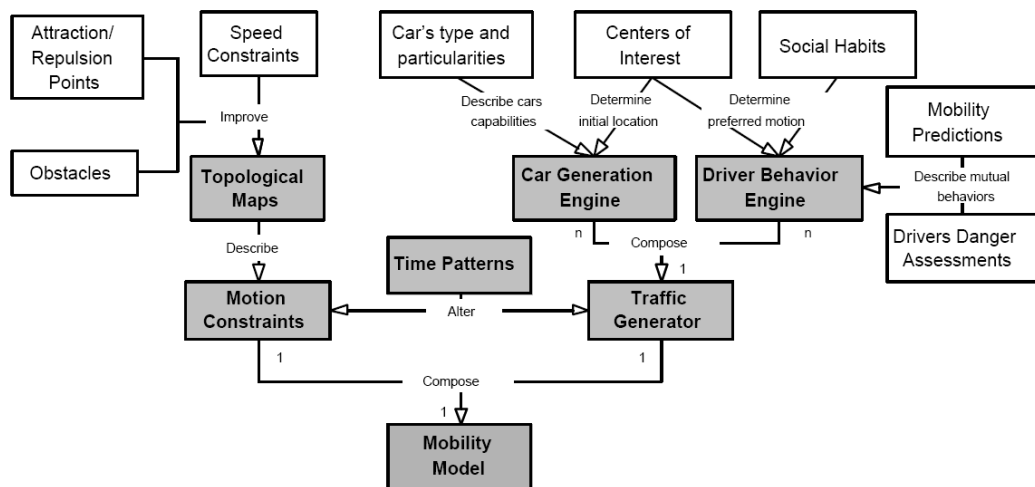


Figure 2.1. Functional blocks of vehicle mobility [?]

A multi-agent microscopic simulator is developed at ETH Zurich [12] and used to get the data about the 24-hour behavior of the vehicles in the transportation system of Switzerland using real map data. The behavior of each traveler is determined individually by sets of rules based on the area they live in, their needs, and environment *citeswiss*. Road congestion effects the travel plans, which in turn effects road congestion. The population is distributed over the cities and villages according to statistical census data. The microscopic mobility model presents lane change and turnings. Different kinds of simulators can be coupled dynamically and simulation data is exchanged during runtime among simulators to increase accuracy of simulations. In [35], Vehicle-2-X Simulation Runtime Infrastructure (VSimRTI) is presented allowing a flexible combination of time discrete simulators to be plugged onto the VSimRTI and executed together.

2.4. Aggregate mobility models

In Reference Point Group Mobility model [36], group motion is represented by a virtual center. The motion of the vehicles is calculated according to the group motion and relative motion. Check pointing is used for trajectory. Different border behavior models are considered such as wrap-around, bounce-back, delete, and replace. In Social Network Theory [37], a social network matrix of interaction indicators are created for vehicles. According to the sociability factors calculated from this matrix, vehicles follow their social groups in their movements or change direction towards another social group. This mechanism is used to determine destination points and paths.

The report in [38] summarizes the basic considerations of the traffic flow theory. Continuous flow model describes traffic in terms of fluid behavior, concerned more with the overall statistical behavior of traffic stream, leading the assumptions that traffic flow is conserved and there is a one-to-one relationship between speed and density, or between flow and density. Basic flow equations are introduced according to fluid model. It is also stated in the report that car following shows the correlation between the microscopic behavior of individual vehicles and the macroscopic characteristics of traffic stream. It also describes the human factors, perception, and reaction, unsignal-

ized/signalized intersection theory, vehicle generation, and traffic assignment model (source-destination trip demand). Acceleration distance is formulated as a function of separation distance, projected deceleration rates, and reaction time of driver in following vehicles. Average speed is given as a function of distance from central business district. Also the capacity of a single lane C is formulated as

$$C(\text{vehiclesperhour}) = (1000) * V/S \quad (2.3)$$

$$S = a + b * V + c * V^2 \quad (2.4)$$

where S is the average spacing that one vehicle would follow another at a given speed, V . Another fluid flow model [13] uses the average number of mobiles crossing the boundary of a given area. The traffic flow from one circular region to another is formulated as a function of the node density of the regions, average speed, and diameter of the region.

3. ROUTING PROTOCOLS

Common research areas in mobile ad hoc networks are medium access control, routing, resource management, power control, and security [39]. Routing is a challenging issue for dynamic multi-hop networks. One of the main problems is the node mobility, which causes topology changes frequently. Besides, the wireless links are of variable capacity. Problems like hidden terminal occur because of broadcast communication in the wireless medium. Furthermore, power, computing, and bandwidth resources of mobile nodes are limited. Thus, the routing mechanism must be effective.

In general, routing algorithms are classified in three categories: proactive, reactive, and position-based. Position-based routing, also known as geographic routing, improves the topology based ones, because additional information about the nodes' geographical position is used to find suitable routes. This simplifies packet forwarding [40]. To maintain location information about other nodes in the network, each mobile node maintains a location table. Location table contains an entry for every node in the network whose location information is known. In position-based routing, route request messages are directional, so route requests received by a vehicle that is moving towards the opposite direction of the destination can be dropped.

Reactive protocols discover routes only when needed [41]. In contrast to proactive methods, no periodical link state updates are needed. However, the initial packet delay may be higher. Proactive protocols maintain routes to all possible destination nodes in its routing table. The tables are updated continuously so a route request is answered immediately. Generally reactive protocols have better performance than proactive protocols [42]. However, studies show that proactive protocols outperform reactive protocols under specific traffic conditions [43]. Table 3.1 lists the commonly

Table 3.1. Routing protocols

Abbreviation	Protocol Name	Protocol Type
AODV	Ad Hoc On Demand Distance Vector	reactive, non-geographic
OLSR	Optimized Link State Routing	proactive, non-geographic
DSDV	Destination-Sequenced Distance-Vector	proactive, non-geographic
GPSR	Greedy Perimeter Stateless Routing	reactive, geographic
FSR	Fisheye State Routing	proactive, non-geographic
TORA	Temporally-Ordered Routing Algorithm	reactive, non-geographic
DSR	Dynamic Source Routing	reactive, non-geographic

used mobile ad hoc routing protocols.

3.1. OLSR Protocol

OLSR [44], is a proactive table-driven non-uniform link state routing protocol. In link state routing, topology information is exchanged between nodes regularly. OLSR improves the original link state algorithm, in which each node broadcasts its link state information to all other nodes in the network [39]. The overhead for message flooding is reduced by the use of Multi Point Relays (MPR).

Each node constructs and maintains the set of multipoint relays from its one hop neighbors. A MPR algorithm is used to determine a minimum number of active relay nodes to cover all two hops neighbors. Only a MPR node forwards the packet that it receives to its relay nodes, reducing the message overhead. Also MPR nodes are responsible for generating and forwarding link state information, so the control traffic is reduced as well. An active route is created at each node to reach any destination in the network. Nodes periodically update link state information over the MPR backbone.

3.2. AODV Protocol

In AODV [45], routes are obtained as needed, when the node is to communicate to another one. A node does not have to involve in periodic routing table exchanges to maintain information about active paths, unless it is serving as an intermediate forwarding station. The overload of periodic update messages is low, which decreases the demand on the total bandwidth [46]. Whereas, delay of the first packet (e.g. latency) to a specific destination is high.

When a source wants to transmit, it broadcasts a route request (RREQ) packet. Neighbor nodes receiving the message forward the packet to their neighbors if they do not know an active route to the destination. Otherwise, a reply is sent back to source node. When the source node gets the reply, it discovers the route. In contrast to source routing, route table entries are dynamically established at intermediate nodes. As a result, a route to a destination may be returned by any intermediate node. Nodes may become aware of other neighbor nodes using the local broadcasts called hello messages. However, the local connectivity management and general topology maintenance is considered different from each other [46].

In evaluating the effect of mobility model a reactive protocol AODV and a proactive routing protocol OLSR is considered to show the effect of mobility on different mechanism. Also AODV and OLSR reached the IETF RFC stage and are commonly used by many researches for VANETS [31, 12].

3.3. Performance Evaluation of Routing Protocols

Certain applications may have specific concerns on what should be analyzed. The metrics used for evaluation may change depending on the application requirements. Most commonly used evaluation metrics for routing protocols are as follows:

- *Packet delivery ratio with/without retransmission (PDR)*: The fraction of data packets that are successfully transmitted from source to destination. The per-

centage of dropped packets can also be used.

- *Routing overhead (RO)*: The number of routing packets required by the protocol to construct and maintain the routes. Also, *normalized routing load* can be used, which is the ratio of routing control packets to the data packets delivered.
- *Delay*: Average end-to-end transmission delay of the successfully transferred packets.
- *Number of hops*: A measure of expected route length per source-destination.
- *Average delay of the first packet (Latency)*: Average time difference between the first data packet originated and received by its destination.
- *Connectivity*: Number of reachable/unreachable node pairs.
- *Average queue length*: Average MAC buffer length.

Obtained results change depending on the network parameters used in the simulations. Common parameters effecting these metrics are as follows:

- *Topology*: Grid, block size, roads, real map, and partial roads (if starting or ending points of a street are not in the simulation area).
- *Number of nodes*: The number of nodes can be fixed or varied. There may be arrivals and/or departures to/from the area.
- *Density of nodes*: The number of nodes per area (nodes/ m^2) or per road.
- *Mobility pattern parameters*: Distance between cars, lane change, waiting time at an intersection, average node speed, speed distribution, and step size (direction change, speed update).
- *Heterogeneity*: Percentage of vehicles in the network that are not equipped with a radio, such as all vehicles transmitting, some vehicles transmitting.
- *Wireless transmission range*: Transmission range determines the number of reachable nodes.
- *Duration of simulation*
- *Routing protocol*
- *Call pattern parameters* (e.g., call duration distribution) may depend on location, speed, and time.
- *Data traffic rates*

3.4. Evaluation of VANET Protocols in Literature

In [47], authors evaluate the performance of their position-based routing protocol, GVGrid, under real time live stream data traffic. GVGrid constructs and maintains a route from a fixed, stationary source to a specific destination, considering vehicles with similar speeds and directions. Traffic simulator NETSTREAM is used to model and simulate realistic mobility. According to the simulation results, distribution of packets dropped in grids shows that road segments and intersections have a big impact on the stability of route and delay. Delay of packets is mainly because of broken routes, which take two seconds to recover. The protocol is tested only for fixed, stationary source and destinations. The effect of speed of vehicles is not considered. No comparison with other protocols is included.

In [31], the performance of AODV and OLSR are compared under realistic mobility patterns. The simulations are made on a 1000m x 1000m square area with different clusters of roads: downtown, residential, suburban. Results show that clustering at intersections has the major effect on the performance metrics. Authors also claim that, although generally reactive protocols have better performance than proactive, OLSR outperforms AODV. Their results imply that average velocity does not effect delivery ratio although previous results showed both protocols are sensitive to speed. This is because of the micro-model behavior in intersections and speed limitations of roads. For low data rates, OLSR performs better due to the fact that all routes are computed previously, before a send request is initiated. However, AODV has to go through route discovery procedures. When the data rate increases, AODV performance gets better than OLSR. Data traffic rate does not effect OLSR, while the control traffic of AODV increases, and after a certain point OLSR performance gets better than AODV. OLSR has lowest delay as a proactive protocol. The extra number of nodes improves connectivity and results in good performance. However, as the number of nodes increases, MAC layer get saturated and packet delivery ratio drops down. This situation is worse in VANET because of the clustering effect at the intersections. Impact of shorter radio transmission range, heterogeneous vehicles, and geographical forwarding protocols are given as future work.

In [12], authors test the performance of GPSR and AODV. Realistic mobility traces of 260,000 in Switzerland for 24 hours are obtained from their Multi-agent Microscopic Traffic Simulator (MMTS) and used as the input of *ns-2* simulator. However, they point out that this file is too big for *ns-2* to process so smaller sub regions are selected. In this simulation, an area of 3 km x 2 km is simulated for 0.5 hours with high (50 vehicles/km of road), medium (30-40 vehicles/km of road), and low (15 vehicles/km of road) densities. The number of nodes is nearly 550, with their speed varying from 15km/h to 55 km/h. Probabilistic Shadowing found in *ns-2* is used for radio propagation model. The transmission range is 400 m for the city and 500 meter for highways. Traffic sources are used with a rate of 4 packets/sec where data rate is 2Mbps. All nodes stay inside the simulation area for the duration of their communications. According to the results of the tests, authors propose two techniques to improve the performance of the protocols on realistic traffic. AODV performance mostly suffers from the routing packet overhead, while GPSR performance is affected by the consistency of routing tables. A Preferred Group Broadcasting (PGB) strategy with the ability to split and merge hops is introduced for AODV. A more fault tolerant Advanced Greedy Forwarding (AGF) method is used for GPSR. Effect of mobility model is tested against random mobility. Although in real traces, AODV performance is better, GPSR always outperforms AODV with the random waypoint model. The results show that AODV+ PGB shows better performance than GPSR.

In [48], a reactive location routing algorithm with cluster-based flooding (LORA-CBF) is developed. A new broadcast strategy is introduced using clustering. Cluster heads control the broadcasting of packets, resulting in improved routing overhead. The algorithm is tested against two non-positional algorithms; AODV and DSR. Short term predictive algorithm is integrated into the protocol to predict the next position of every neighbor node. In simulations, a microscopic mobility model with car following and lane change is used. 250 nodes travel on 6283 m circular and square roadways without leaving the system. Vehicle speed is 42m/s in circular scenario and 8 m/s in square scenario, which represents urban traffic. Transmission range is 300 meters. Their results show that position-based routing protocol provides the best end-to-end delay and packet delivery ratio among others.

A new realistic mobility model for urban traffic scenarios is proposed in [9]. A macroscopic car-following model, IDM and traffic flow at crossings are adapted into the model. Traffic signs and lights are not part of the model. The model is used for the evaluation of routing protocols AODV, DSR, FSR, and TORA. Performance of mobility model is tested with simulated area of 1500m x1500 m with 8 roads. Although high density is considered as 30 vehicle/km (per lane), not all the vehicles are equipped with necessary hardware. Thus traffic density is between 2 and 25 vehicles/km. Radio transmission range is 100 meters. AODV exhibits lower routing overhead. DSR has the highest delay because route discovery process takes more time. AODV has the best performance, followed by FSR. Results show that when density is between 2 to 5 vehicle/km, throughput increases as the network connectivity gets better. However, after that point, the throughput of all routing protocols clearly decline as more vehicles are communicating in the shared common wireless channel.

In [49], authors use non-random mobility patterns of users to foresee the future state of network topology. With the help of this prediction, topology changes are observed and possible connection breaks are prevented before they actually happen. By performing rerouting prior to route breaks, a seamless network access is maintained regardless of topology changes. Besides, the predicted information is used to reduce the number of control packets needed to reconfigure routes. Proposed scheme is tested using the Global Mobile Simulation (GloMoSim) library, modeling a network of 50 mobile nodes within a 1000 m^2 area.

In [50], the authors claim that adaptivity and scalability can be maintained using position-based forwarding. A greedy forwarding method is used by choosing the next hop according to the geographic direction of the destination, with the help of GPS. By this way, cars can communicate one-to-one. Also data can be transferred to all the cars located in a geographical area. Despite the topology-based routing protocols, in position-based routing there is no need to keep a global route from source to destination. Reactive Location Service is tested against DSR. Although greedy position-based routing outperforms DSR in highway scenarios, it fails in city scenarios due to uncorrelated position information with available paths and streets to the destination.

Implemented software prototype is integrated into a real network of cars to gain real world measurements.

4. REALISTIC MOBILITY IN VANET

Mobility model determines the location of nodes in the topology at any given instant after the initial distribution of the nodes. It constructs the movement paths of the mobile users over the terrain. In mobile ad hoc networks, node movement generally occurs in an open field. In contrast, vehicular movements in VANETS are restricted by traffic patterns, obstacles, and street layouts. The main properties of user motion can be listed as moving-in-groups, conscious traveling, inertial behavior, non-pass through feature of structures [10]. Since [10] is not a specific model for VANETs, traffic control mechanisms are not considered. A mobility model for VANET should reflect the specific behaviors of vehicle movement shaped by the mobility parameters as well as the effect of mobility of individual nodes on each other.

4.1. Mobility Parameters

Mobility parameters are the main factors that characterize mobility of vehicles and distinguish it from random or pedestrian movement. Mobility parameters are determined according to the physical characteristics of roads and vehicles (layout of roads, traffic signs) as well as the driving behaviors and interests of drivers (conscious traveling). These are the basic set of requirements that should be implemented in a realistic mobility model.

Layout of Roads: Streets defined by map data for real cities constrain node movement patterns. For example, a car traveling on a road is likely to follow the path of the road. Nodes bound their movements to well-defined paths separated by non-pass through structures like buildings, trees, or other obstructions. These constraints result in some degree of regularity in mobility patterns and also determine the average distance between nodes, distribution of nodes, and connectivity of the network. The effect of other road features like curvature, lanes, and obstacles that restrict wireless transmission range should also be reflected in the model.

Speed Limit: The speed limit depends on the type of road; highway, un-separated city streets, one-way/bi-directional. Speed limit determines the position change rate of a vehicle, which in turn determines the network topology changes.

Traffic Control Mechanisms: Real world artifacts specific to urban settings must be considered such as stop signs, traffic lights, and queuing of vehicles at intersections. These artifacts result in formation of clusters and limit mobility.

Interdependent Vehicular Motion: The movement of a vehicle is directed by the movement of other nearby vehicles, according to the minimum distance from the vehicle in front and increase or decrease in its speed. Although each independent node chooses its direction individually, its speed should be arranged according to the distance from the vehicle in front. This causes the formation of clusters and reflects the *moving-in-groups behavior*. Therefore, lane change and car following scenarios must be included into the system.

Block Size: A city block can be considered as the smallest area containing several buildings and surrounded by streets. Block size determines the number of intersections in a specific area.

Conscious traveling: Conscious traveling deals with the determination of paths for vehicles to follow. Vehicles are inclined to keep their directions towards a destination. This destination is mostly close to some hot spots like city center (point of interest-POI). Reversely, blind spots like lakes and seas, do not shelter humans and attract any vehicle traffic. Traffic patterns are affected by population density, number of cars in the road at the time of congestion and rush hours. The mobile user controls travel decisions about the selection of paths. A static shortest path algorithm can be used for route management as well as a dynamic one that alters the path according to traffic load.

User movement dynamics: Traffic can be a heterogeneous mixture of different types of vehicles and pedestrian, each exhibiting different mobility characteristics.

These behaviors of vehicles produce the number of mobiles per area/road, clustering and neighbor change in a particular time interval which in turn effects the connectivity of the network. The proposed model, MOVE, is based on the above listed mobility parameters, considering the individual movements of cars, car following, target based movement, and takeover.

4.2. Significant features of the model

The speed of the vehicles is determined according to other vehicles and type of the road. A graph of roads and intersections is used to determine the movement limits and to calculate destinations and shortest paths for the vehicles. Partial roads and boundary conditions are ignored.

Intersection Handling: When a car approaches an intersection, it slows down and stops if a queue of cars exists at the intersection. It waits until the cars in front of the queue leave and then changes its direction to the intended road according to its previously determined destination. It waits for a gap in the new road to form. After entering the new road, it accelerates according to the speed limit and car density on the road. Intersections are main cause of clustering in roads. When number of cars in a road segment (vehicles per unit length) reaches a threshold, a cluster occurs. Intersections are modeled using a black box approach. They are abstracted as gray areas with a waiting queue for each lane. When a car approaches an intersection, it slows down and stops if the waiting queue of the intersection is full, and waits until the queue has an empty room. The cars behind the waiting one slow down and stop as well because of car following. Using this method, the queuing effect of intersections are simulated. When the car finds an empty place and gets into the queue, it is assigned a random wait time which is the time to cross that intersection. The car stays in the queue for that time period. When wait time is up, the car approaches to its intended lane and starts moving according to its current lane, accelerating or decelerating.

Conscious Traveling: Mobile nodes are assigned random starting and destination points which correspond to coordinates on the road. After reaching one destination,

a new destination is assigned and after a configurable stop time, the mobile starts moving towards that destination again. The destinations are chosen according to the popularity indices of the places. Points of interest array holds the popularity indices for specific places. These hot spots are taken into account while choosing a random destination for a vehicle. The shortest path from the source to the destination is found and set as the route of the vehicle. The time to cross a road segment is simply considered proportional to the length of the road. The route does not change during the trip of the vehicle.

Acceleration Model: A mobile node can be in one of three conditions: free flow, car following, or stopped. If the distance between two vehicles is long enough, the nodes can move in free flow, which means they can accelerate to a maximum speed for the segment. Otherwise the car adjusts its speed according to the car in front and moves with a similar speed. This is called *car following*. The vehicle accelerates on the way to the destination and after some point decelerates when it approaches the destination point. It stops at the destination point for a configured amount of time. Cars start with zero velocity for the warm-up period and accelerate according to road dynamics.

Lane Change: Lane change can occur for two reasons; speed consideration and being destination driven. The route of the vehicle may require it to change its lane. If lane change is occurs according to a speed consideration, then a probabilistic approach is needed. We define a probability for a vehicle to change lane. Drivers change lane when average speed is faster in the other lane, with a probabilistic willingness to arrive earlier.

Mobility Updates: OPNET interrupts are used to update the speed/ position/ movement of every node in each update interval, which is set from the property settings. The system is updated in a configurable period called update interval. In each update interval speed of each mobile is calculated and new positions are set. The speed of the mobile depends on the acceleration or deceleration calculated according to the speed limit of the road, distance to the car in front, intersection, turning point, or traffic sign.

The mobile makes some controls in particular sequence before updating its speed for the next time interval. The driver first checks the distance between the car in front and adjusts its speed according to the car following concept. Then he checks if lane change is possible and necessary. If the distance to the intersection is smaller than the intersection intercept distance, the mobile adjusts its speed according to intersection queue. If no cars and intersections are in front, the mobile accelerates up to the road speed limit in free flow mode.

4.3. Design Issues

In order to strict vehicle movement by roads and determine destinations, a road graph is used, which is a full representation of the roads, their types, speed limits, lanes, and intersections in a particular area. Each link in the graph represents a road segment with a weight of the length of the road, while nodes of the graph represent intersections between road segments. Road segments are indicated by their starting and ending coordinates and the number of lanes in each direction. Default traffic flow direction of the road is from the starting coordinates to ending coordinates. Positive lane numbers indicate the default direction while negative numbers indicate the opposite direction. A queue exists for both directions of the road for intersection handling. Each road segment is assigned a road type identifier that determines the maximum speed allowed on that road segment. When a new road is added to the graph, the line equations are created from the starting and ending points (Appendix-A). Line equations are used to examine if a vehicle is on that road segment and to calculate the movement of the vehicle along the road.

A point of interest (POI) array is created for the hot spots on the terrain. Each POI consists of the coordinates of the place and its popularity index. It is not necessary for POI to be on any road, just a point within the simulation area. Destination points are calculated according to POI array. Firstly, the center of the attraction is calculated according to the POIs and the current location of the vehicle. The attraction of a hot spot decreases as the distance to this point increases. The attraction indicator for each POI is calculated as in Eq. 4.1 and the resulting (X, Y) coordinates for the center of

attraction are calculated as in Eq. 4.2. In the equations, A_i is the attraction indicator of the i th POI in the array, P_i is the popularity of this point, d_i is the distance between the mobile's current location and the coordinates of POI, (X_c, Y_c) is the coordinates of the current location of the mobile.

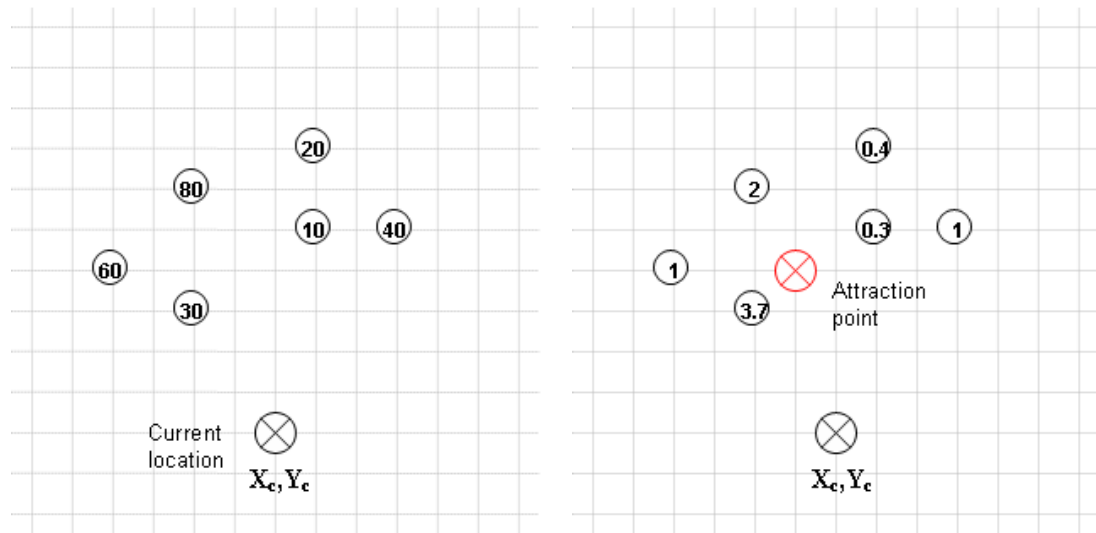
$$A_i = \frac{P_i}{d_i^2} \quad (4.1)$$

$$X = \frac{\Sigma(A_i * (X_i - X_c))}{\Sigma A_i} + X_c \quad (4.2)$$

$$Y = \frac{\Sigma(A_i * (Y_i - Y_c))}{\Sigma A_i} + Y_c \quad (4.3)$$

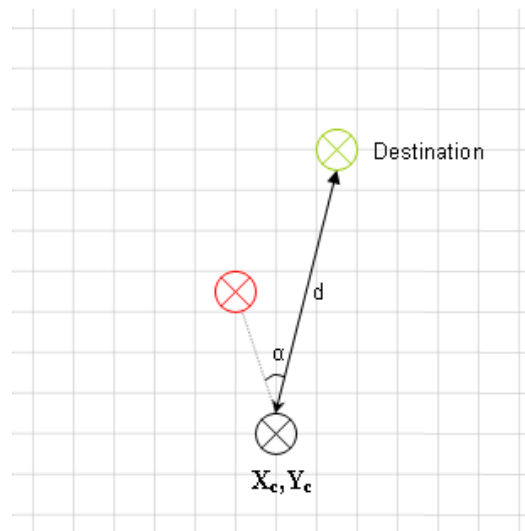
Choosing the center of attraction as a destination results in gathering of all nodes at these hot spots. Instead of moving towards that point, the destination point is slid with a random angle and distance. This calculated coordinate may not necessarily be on any of the roads so it has to be projected to a point on the nearest road in the road graph. The distance of the calculated coordinates to each road is calculated to find the nearest road and the steep projection of the coordinate on that road is calculated. The resulting coordinate after the sliding and projection is assigned to the vehicle as the destination.

Initial coordinates are determined with the same method as determining the destination coordinates. The process of calculating a coordinate using the POI array is invoked by processing a randomly selected coordinate as the current coordinate. The resulting coordinate is set to the mobile as the initial coordinate. When determining initial locations, the distance between vehicles is checked in order to make sure that the safety distance is preserved between any two vehicles. For just the initial placement, if



(a) Points of interest with weights

(b) Calculated popularity indices



(c) Destination point

Figure 4.1. Point of interest

the chosen coordinates violate the safety distance, a new initial coordinate is selected for that vehicle. The vehicles have zero velocity initially.

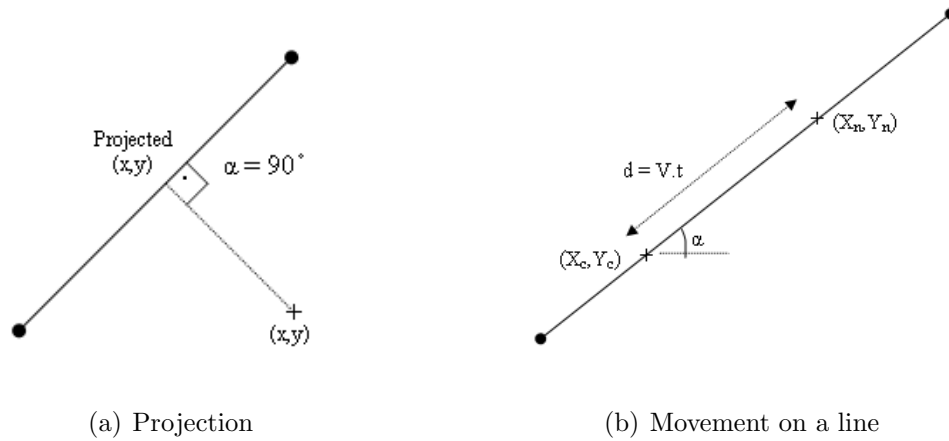


Figure 4.2. Road line

After determining a destination, the shortest path is constructed leading to that destination using the road graph and the starting points of the roads are recorded as the intermediate destinations of the vehicle. During its movement, the vehicle must travel on the roads from one intermediate destination to another, which are the intersections. If the speed of the vehicle is V and the current location is (X_c, Y_c) then the new coordinates (X_n, Y_n) of the vehicle after t seconds is

$$X_n = X_c + \sin(\alpha) * V * t \quad (4.4)$$

$$Y_n = Y_c + \cos(\alpha) * V * t \quad (4.5)$$

where α is the angle that representing the gradient of the line.

Vehicles always resides on the roads so the coordinates of a vehicle always confirm the line equation of the road. This means all the vehicles on different lanes of the same road complies with the same line equation. There can be two vehicles with same

coordinates which corresponds to the same road, but their lanes must be different. When the real location of the vehicle is requested, the real coordinates are computed according to its lane. Figure 4.3 depicts representation of a road with two lanes in each direction. The default direction of the road is from starting point of the road to ending point. A positive lane number indicates that the direction of the lane is the same as the default direction, while a negative lane number indicates the reverse direction. The width of each lane is assumed to be the same, so the real coordinates of a vehicle that is in the third lane of the road is the point that is $(LANEWIDTH * 3)$ meters distant from that point in the road. Within the simulation, the real coordinates are never used, but it is calculated when the coordinate of the vehicle is updated within the OPNET framework.

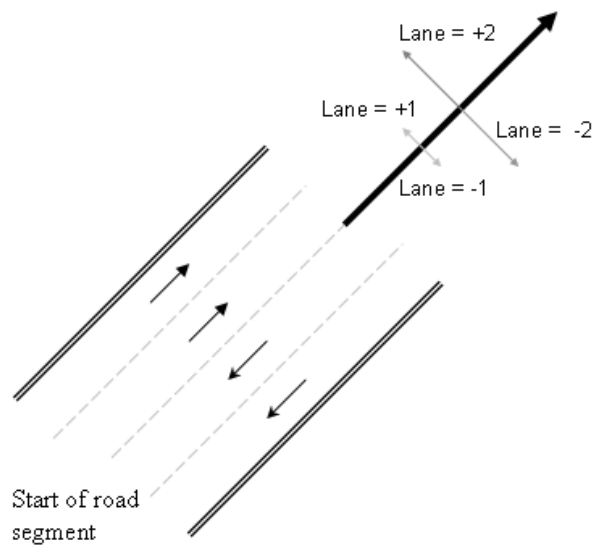


Figure 4.3. Road and lane representation

When the vehicle reaches its destination, it leaves the road and stops for a specified duration. The location that it stops is calculated as lane width long from the outermost lane of the road. Before it starts moving again, it waits for a gap in the road to reenter. It checks for the safety distance with the vehicles near that coordinate of the road. Then it reenters the road with a velocity of zero.

The simulation time consists of small time slices called update intervals. In each update interval, new vehicle speed and positions are calculated and assigned. The simulation is updated with an interval of 0.5 seconds. If a longer update interval is chosen, the position updates of vehicles with high speeds may cause crashes. In order to be predictable about the future locations of vehicles and detect crashes on time, the update interval must be chosen small enough.

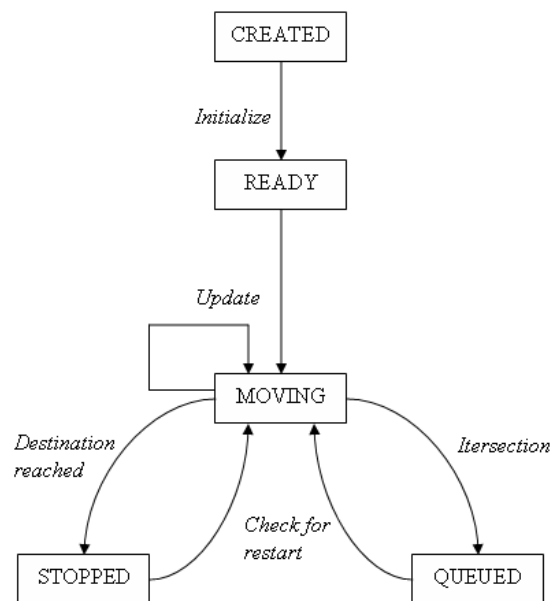


Figure 4.4. Vehicle states

For any given time during the simulation, a vehicle can be in one of four states: Ready, moving, queued, and stopped. Ready is the initial status. The mobile is initiated, initial coordinates are assigned and ready to move. In the moving state, vehicle is moving towards its destination. In the queued state, vehicle is waiting in a queue at an intersection. When its turn to leave the queue comes, it checks for a gap to enter the new road to which its queued to turn for. It stays in the queue until it finds a gap in the road, blocking all the other vehicles in the queue. After leaving the queue, its velocity is set to the assigned value. When vehicle reaches its destination, it passes to the stopped state. It waits for a fixed waiting time nearby the road and then checks for a gap in the road to reenter. It stays in stopped state until it detects a gap to enter the road. After stopped state, it starts movement with zero velocity and

accelerates.

In order to prevent crashes a safety distance must be preserved between the vehicles. *SPACING* is the minimum distance allowed between mobiles (Table 4.1). In car following, the distance between mobiles, *AllowedDistance*, must be long enough that one of the cars can make an instant brake without crashing the one in the back. Allowed distance is calculated with the Eq. 4.6, where V_c is the current speed of the vehicle, *BRAKERATE* is the maximum deceleration of the vehicle (Table 4.1).

$$AllowedDistance > FullBrakeDistance + SPACING \quad (4.6)$$

$$FullBrakeDistance = \frac{TimeToStop * V_c}{2} \quad (4.7)$$

$$TimeToStop = \frac{V_c}{BRAKERATE} \quad (4.8)$$

The vehicles can accelerate unless this distance is not violated. The maximum allowed speed that a vehicle can accelerate is calculated as

$$d = \frac{(V_{MAX} + V_c).t}{2} + \frac{V_{MAX}^2}{2 * BRAKERATE} \quad (4.9)$$

where d is the distance between a car and the one it follows.

In each update interval, the mobiles speed and location is checked one by one for intersection queuing, car following, and lane change, new speed is determined. Next location is calculated according to the speed and mobile is moved to that coordinate.

Firstly, mobiles distance to intersection against the queuing distance, which is a constant value equal to the queue length. The area around the intersection is called the gray area (Figure 4.5). If the mobile is close enough to enter the gray area, it is added to the queue, a queuing time and a random queue leaving speed is assigned according to the other mobiles in the queue. When queuing time finishes, the mobile leaves the intersection and the gray area with the assigned speed value. In this gray area, no car following and speed checks are done. The gray area approach brings an approximation and simplifies the complexity of intersection handling. Otherwise, all the roads connected to that intersection and the mobiles on these roads must be accounted for car following, gap acceptance, etc.

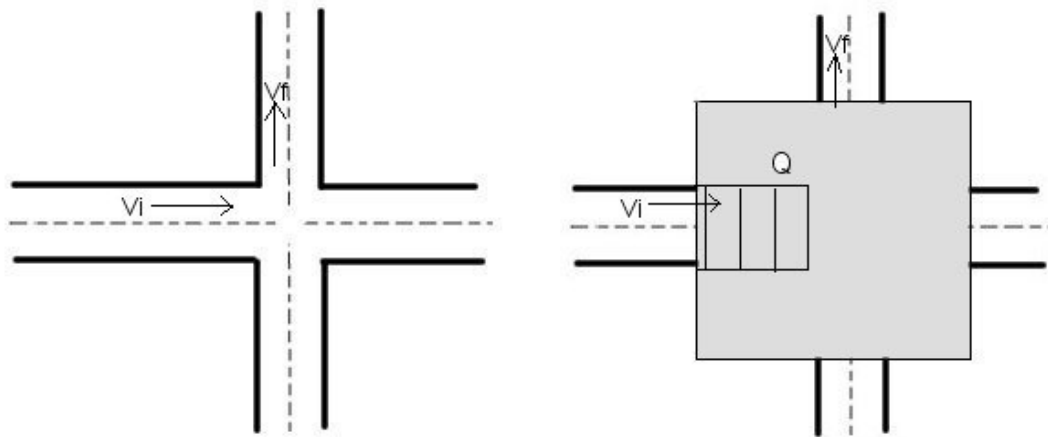


Figure 4.5. Intersection queue

If the mobile does not enter an intersection in that update interval, car following check is done. If there is no other mobile in front of it, then car following phase is passed. Otherwise, a maximum speed is calculated according to the distance between the cars and their brake distance. Maximum speed is calculated as Eq. 4.9. After calculating the maximum speed possible according to car following, the lane change decision is taken. The lanes in the same direction as the mobile is checked according to the speeds of cars in that lane and if a gap exists to pass to that lane. The possible speed in other lanes is calculated and compared to current speed to decide to change lanes.

The simulation constructs a file representing the movements of all the nodes,

indicating their positions with geographical x, y, and z coordinates. When the nodes are initialized, a method is called for each mobile node to record the starting (X,Y) coordinates to a file in a format that OPNET can understand. The z coordinates are all set to zero. After constructing a destination point and a path to follow for the mobile, the node starts following this path. After each update interval, a method is called to record the current position of the node into a file. This is done until the simulation time expires. Some constants and parameters used in the simulation are given in Table 4.1.

Table 4.1. Basic mobility parameters assumed

Vehicle Length	5 m
Spacing	1 m
Minimum Road Length	Spacing + Vehicle Length
Lane Width	3 m
Maximum Acceleration	2.31 m/sec ²
Maximum Deceleration	7.0 m/sec ²
Intersection Queue Size	3
Queue Length	Vehicle Length * (Queue Size - 1)
Grayed area distance	Queue Length + 0.9
Speed Limit	90 km/h
Maximum Queue Leave Speed	21 km/h
Minimum Queue Leave Speed	36 km/h
Update Interval	0.1 sec

Spacing is the minimum distance between any two cars. If spacing is violated, then it is supposed that a car crash occurred. In all the movements of vehicles this distance is always preserved to avoid crashes. A road must be long enough to include at least one vehicle. Lane width parameter gives the width of a lane of a road. In is used to calculate the real coordinates of a mobile according to its lane (Figure 4.3). The acceleration of a car is limited to maximum acceleration parameter. Maximum acceleration is calculated under the assumption that a car accelerates from zero speed to 100 km/h in 12 seconds. The maximum deceleration is the deceleration resulted

when a full brake is issued. It is calculated under the assumption that a vehicle with a speed of 100 km/h can stop in 3.8 seconds if it makes a sudden brake. This parameter is used to calculate the safety distance and speed between moving vehicles. Intersection queue size and vehicle length together determines the length of queue and the gray area around the intersection. The grayed area distance determine the intersection safety distance, which is the minimum distance to detect an intersection is approached and calculate its move according to queue intensity. Two types of roads with speed limits 54, 72, and 90 km/h are considered. When a vehicle is leaving the intersection queue it is assigned a random speed, between 21 km/h and 36 km/h which is the maximum speed allowed at turnings.

5. SIMULATION RESULTS

Mobility patterns of the mobile nodes directly affect the performance of routing protocols for mobile ad hoc networks. Unrealistic assumptions about mobility produces misleading results about the behavior of routing protocols in real deployments. In the simulations, the performance of two commonly used routing protocols, AODV and OLSR, are compared under the RWP and MOVE mobility models to show the effects of mobility model on routing. In the RWP model, a node picks a random destination and velocity, then moves towards the destination. When it reaches the destination, stops for a specific duration and picks another destination. This results in the jumpy behavior depicted in Figure 5.1. Here, two nodes make random movements while all points in the terrain can be selected as the next destination equally likely. On the other hand, MOVE calculates the movement of each node according to traffic conditions and intersections.

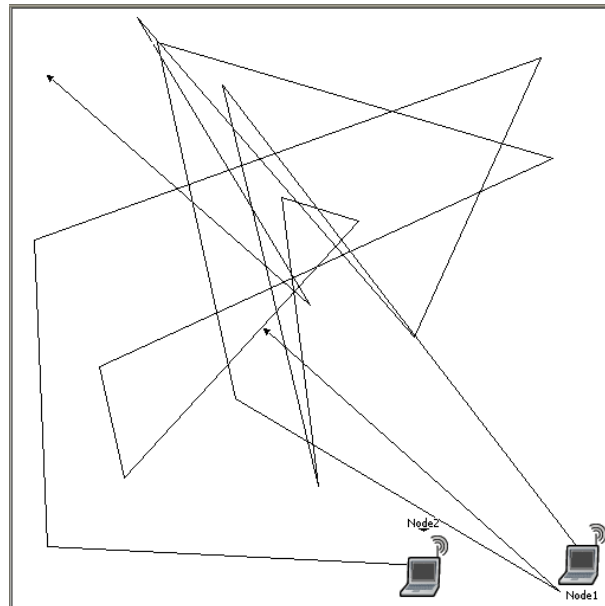


Figure 5.1. Trajectory of two nodes with RWP

OPNET modeler is a tool that provides an environment for designing and testing networks. It includes the implementation of a protocol suite for wireless communications and necessary modules to run simulations and collect statistics. The wireless module, traffic generator node, AODV and OLSR implementations in the OPNET

modeler are used in the simulations. A mobile ad-hoc node can be simulated using the built-in IEEE 802.11 MAC layer module. As this module is a full representation of the physical layer, actual simulation runtimes are very long. For example, a simulation of one hour with 220 nodes takes 37 hours to finish. On the other hand, OPNET Smart MAC (SMAC) model provides an abstraction of physical layer of IEEE 802.11 in a probabilistic way. A look up table is used for the delay and dropping probabilities of packages instead of modeling different transiver-receiver pairs, simplifying calculations and decreasing the simulation time. SMAC mobile nodes can be configured to move according to the built-in random waypoint model. The realistic VANET mobility model, MOVE, is added to be used with mobile nodes of OPNET modeler instead of random waypoint model.

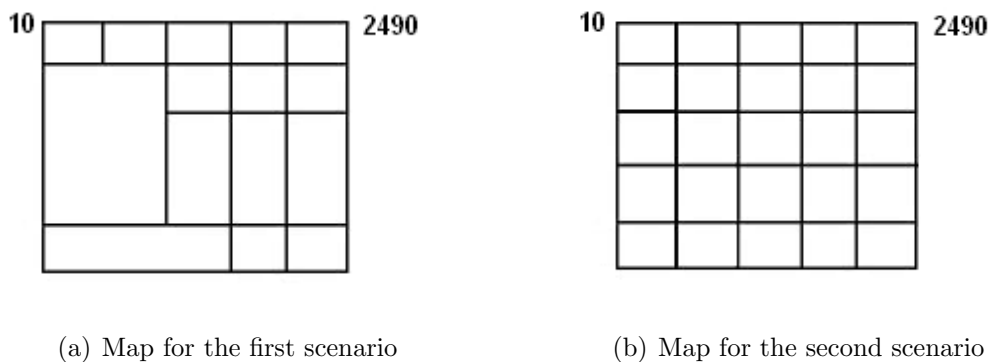


Figure 5.2. Maps used in MOVE scenarios

A proactive (OLSR) and a reactive (AODV) routing protocol are used in the simulations to study the effects of mobility model on routing algorithms. Two different scenarios, which differ in the number of source nodes, are tested. In the first scenario, there are fixed number of traffic generating nodes and test data are obtained by increasing the number of relay nodes. Therefore, the generated traffic does not change although connectivity increases as the number of nodes increases. In the second scenario, each node acts as a traffic source, so generated traffic increases proportional to the number of nodes. The traffic generation is the same for different test cases. In the beginning of the simulation each source node chooses a random destination and sends its packets to that destination throughout the simulation. Two different topologies are used to test MOVE mobility model. The maps of the topologies are given in Figure 5.2. The difference between these two topologies is the number of roads. This difference

directly effects the connectivity and number of nodes in the transmission range of a node.

The number of reachable nodes, n , is calculated as in Eq. 5.1 for the RWP model and as in Eq. 5.2 for the MOVE, where R is the transmission range of a node, A is the total area, N is the total number of nodes in the system, and x is a constant bigger than two. L is the total road length, $\sum(\text{roadsegmentlength})$.

$$n_{RWP} = \frac{\pi * R^2 * N}{A} \quad (5.1)$$

$$n_{MOVE} = \frac{x * R * N}{L} \quad (5.2)$$

The variable x represents the real effect of transmission range in line shaped roads. If we consider only linear behavior of nodes on roads, then nodes can communicate over a range of $2R$, assuming the length between roads is more than this transmission range. However, x is mostly more than two because at the intersections the effect of transmission range changes from linear to circular shape. As the number of roads in the graph connected to an intersection increases, the value of x also increases, because the transmission range contains more roads at the intersection. Also, the distance between road segments at intersections are important. If the distance between road segments is smaller than the transmission range, the value of x increases. To test the values x gets, an additional third map is used with different road lengths and intersections (Figure 5.3). The values of x obtained from the tests using these three maps are given in Table 5.1.

The number of nodes that are within the transmission range of transmitter nodes is given in Figure 5.4. In the MOVE model, road segments separate nodes, but in the RWP model, mobiles are distributed over the area without any limitation. Reachable

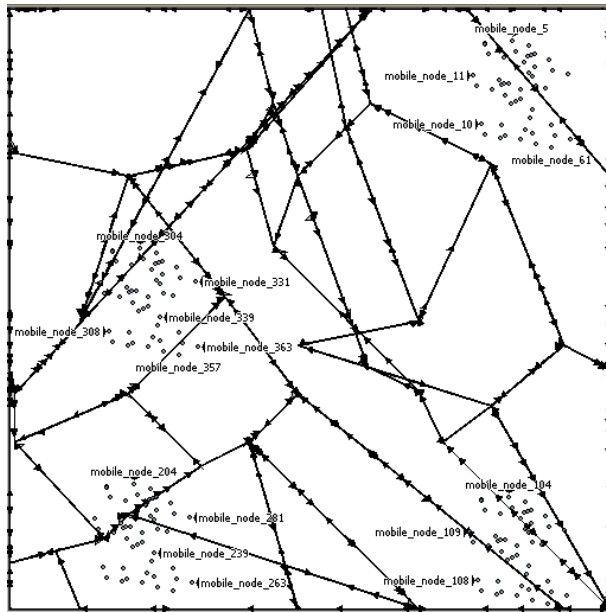
Figure 5.3. Map for testing x values

Table 5.1. Ratio of number of reachable nodes

Topology	$A (m^2)$	$L (m)$	n_{RWP}/n_{MOVE}	$R (m)$	x
Map1	6150400	23909	1.6	300	2.28
Map2	6150400	39100	2	300	2.99
Map3	6150400	77879	1.6	300	7.69

nodes are also related to the transmission range. In MOVE, transmission range is limited by intersections and road segments. According to the calculations and the results obtained from simulations, it is observed that the number of reachable nodes is higher in the RWP mobility model, although node density is lower. This is because of the intersections in maps and the fact that the grid size is larger than the transmission range.

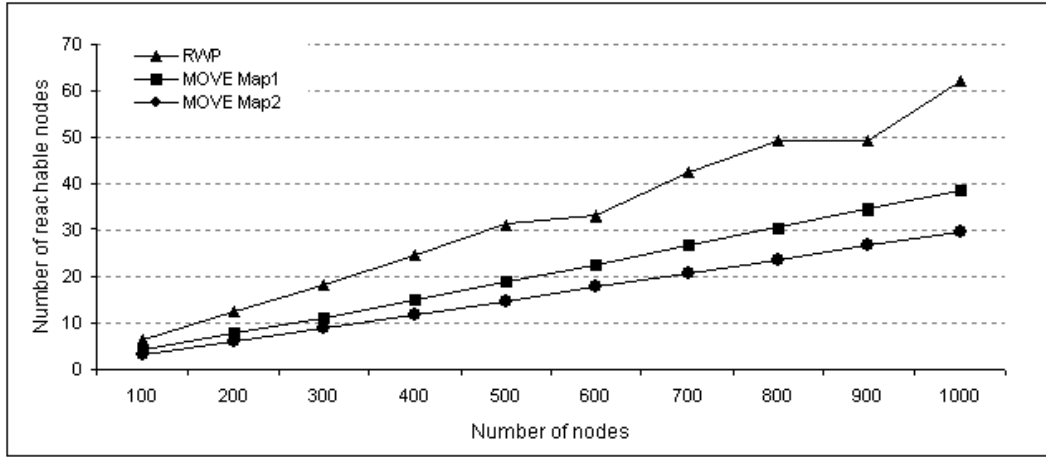


Figure 5.4. Number of reachable nodes

The density of nodes are also calculated in different ways for RWP and MOVE as given in Eq. 5.3 and Eq. 5.4. In Table 5.2, the node densities are given.

$$density_{RWP} = \frac{N}{A} nodes/km^2 \quad (5.3)$$

$$density_{MOVE} = \frac{N}{L} nodes/km \quad (5.4)$$

The average speed of all nodes in the network throughout the simulation is given in Figure 5.5. The graph shows the limiting effect of car following and traffic congestion on speed of nodes in the MOVE model. In the second topology used with MOVE, the number of intersections is more than the first one. For 100 nodes, the average speed is

Table 5.2. Node density

Node Number	RWP(<i>nodes/km²</i>)	MOVE1(<i>nodes/km</i>)	MOVE2(<i>nodes/km</i>)
100	16.3	4.2	2.6
200	32.5	8.4	5.1
300	48.8	12.5	7.7
400	65.0	16.7	10.2
500	81.3	20.9	12.8
600	97.6	25.1	15.3
700	113.8	29.3	17.9
800	130.1	33.5	20.5
900	146.3	37.6	23.0
1000	162.6	41.8	25.6

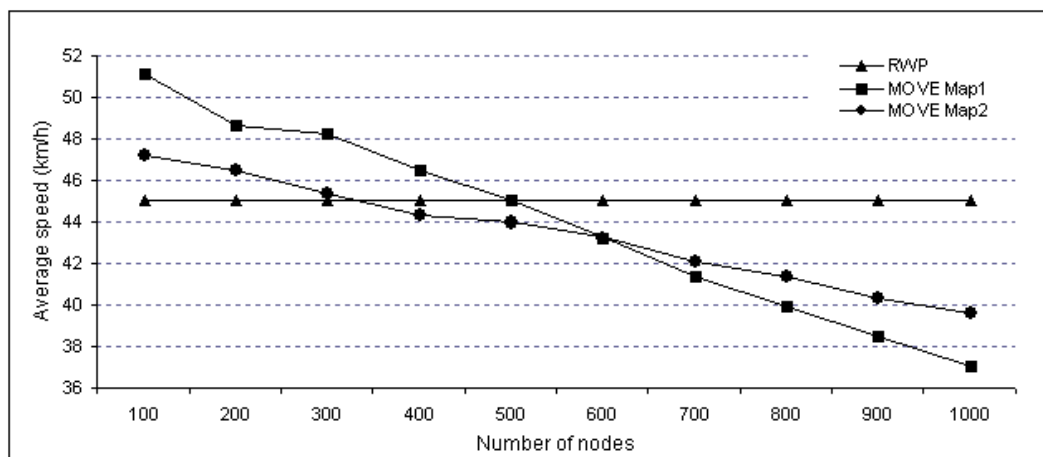


Figure 5.5. Average speed of nodes

less because of slowing down at the intersections. However, for 1000 nodes, the effects of congestion suppresses the effect of intersection. In the second topology, total road length is higher resulting in less congestion. When the number of nodes is less than 600, the effect of intersections on average node speed is more significant than the effect of traffic density.

Table 5.3. Simulation parameters

Wireless transmission range	300m
Topology	2.48km x 2.48km $A = 6.1km^2$ Grid size for maps used in MOVE=500m Total road length, L , for Map1 = 2.3km for Map2 = 3.9km
Number of nodes	100-1000 (no arrival-departure)
Density of nodes	$\frac{N}{A} nodes/km^2$ for RWP $\frac{N}{L} nodes/km$ for MOVE (see Table 5.2)
Nodes within transmission range	$\frac{\pi * R^2 * N}{A}$ for RWP $\frac{x * R * N}{L}$ for MOVE (see Figure 5.4)
Duration of simulation	1 hour
Routing protocols	AODV, OLSR (All mobiles capable of routing)
Average node speed	uniform(45km/h) for RWP Max 90km/h for MOVE (see Figure 5.5)
Traffic generation parameters	Packet Interarrival Time distribution=exponential(0.1 sec) Packet Size distribution=exponential(3500bits)
Physical channel data rate	11 Mbps
Heterogeneity	Some vehicles transmitting All vehicles transmitting All vehicles equipped with radio
AODV parameters	Route Request Retries 5 Active Route Timeout 3 sec

5.1. Fixed Number of Sources, Varying Number of Nodes

In order to analyze the effect of the number of nodes on connectivity, the number of traffic generating nodes is fixed at 100 nodes while the number of relay nodes is increased. Total traffic generated by 100 source nodes is 994 packets/sec, which is equivalent of 3.5 Mbits/sec. The simulations are run with the AODV routing protocol. RWP model and MOVE model with two different topologies (Figure 5.2) are compared.

The total number of data traffic received by all MANET traffic destinations in the entire network is given in Figure 5.6. Only 7 per cent of the traffic sent reaches the destination in RWP and 3.5 per cent in MOVE. The major reason for this excessive loss is routing. When no route is found to the destination, a node drops the packets queued for the destination. The total number of application packets discarded by all nodes in the network is given in Figure 5.7. When node number is less than 600, the network is not connected so it is harder to find routes. There are more dropped packets in the MOVE model because the number of reachable nodes effects the connectivity of the network as MOVE causes more separated clusters because of its grid and intersections. Although the number of reachable nodes is higher in the second map used in MOVE, the delivery ratio is even lower, because the number of intersections are more in the second map. The intersections cause connectivity breaks in MOVE model.

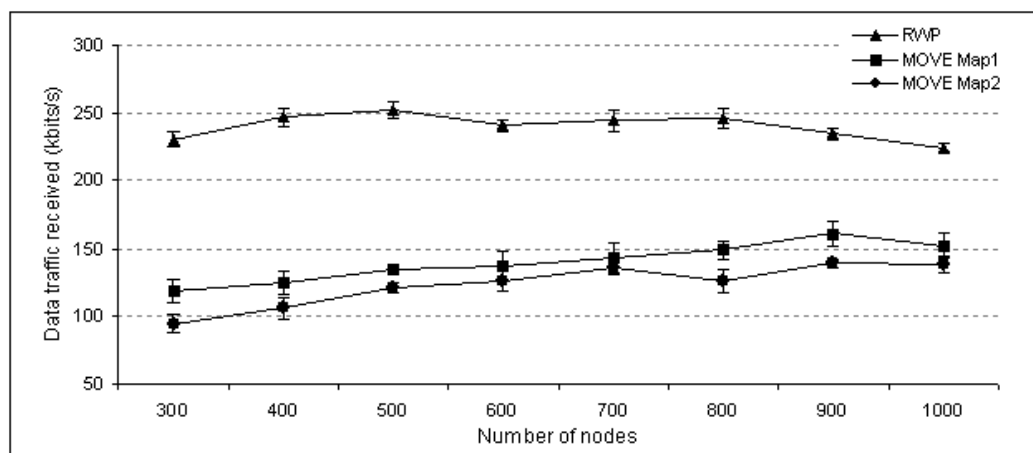


Figure 5.6. Data traffic received

Although the number of dropped packets decreases as the number of nodes in-

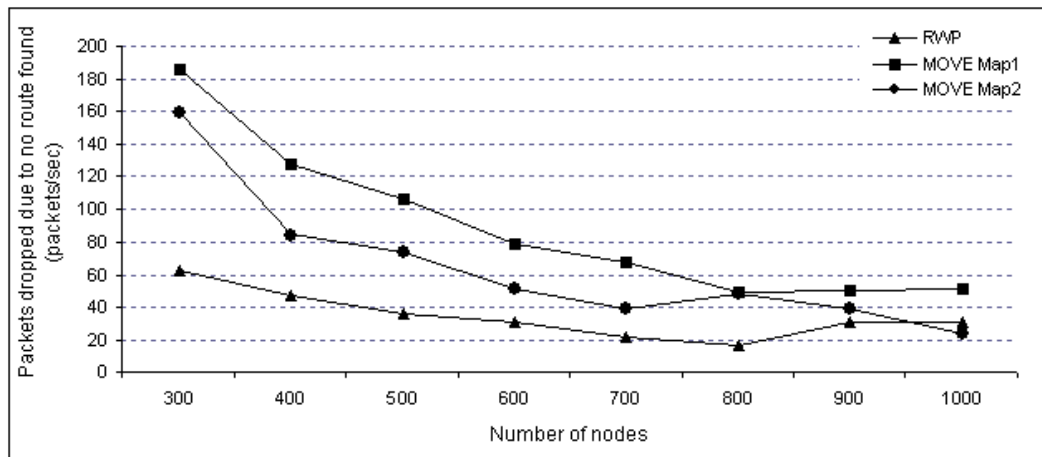


Figure 5.7. Total packets dropped due to no route found

creases, the delivery ratio is still low. The ratio of the routed packets to the packets successfully received by the destination nodes is given in Figure 5.8. This is the measure of the successfully routed packets over the number of packets for which we can find a route. The figure indicates that although we find routes for specific destinations, the packets are not received successfully by the destination. The reason for low throughput can be explained with routing errors caused by route changes. A node may send Hello messages to its neighbor to confirm next hop reachability. If next hop reachability cannot be confirmed, the node sends back a route error message to all nodes that use that hop to reach various destinations. The total number of route error packets sent by all nodes in the network is given in Figure 5.9. The number of route errors increases with increasing number of nodes because the number of neighbor nodes creating routing traffic increases. Route changes are more frequent in the MOVE model because of the grid size and intersections. However in RWP, nodes follow long direct lines as their routes and maintain their direction till the destination. In MOVE, nodes change direction at the intersections so connectivity of a route is broken more frequently. This situation is worse when second topology is used because it has more intersections than the first topology.

When a node receives a route request and is not the target of the route request, it looks up its route table to determine if it has any route to the target of the request. If so, the node sends back a "Cached Route Reply" and does not re-broadcast the request

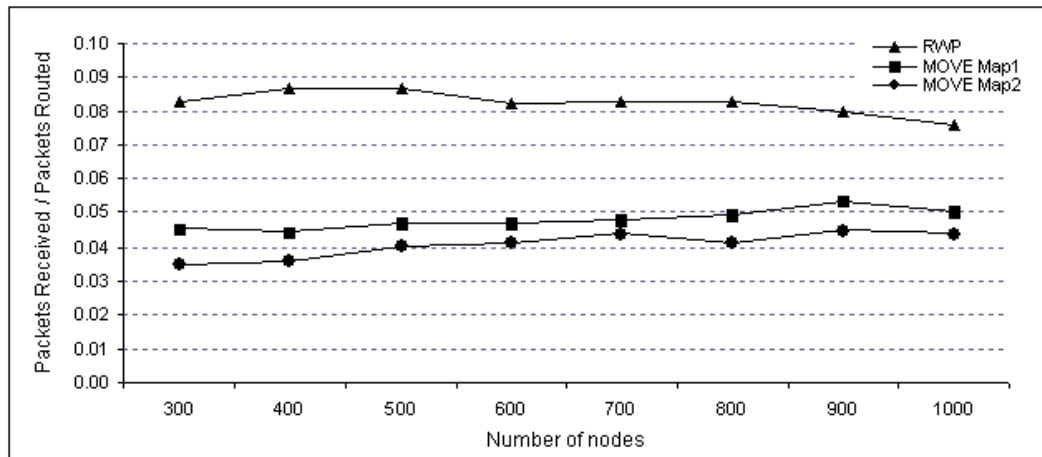


Figure 5.8. Proportion of successfully received packets over routed packets

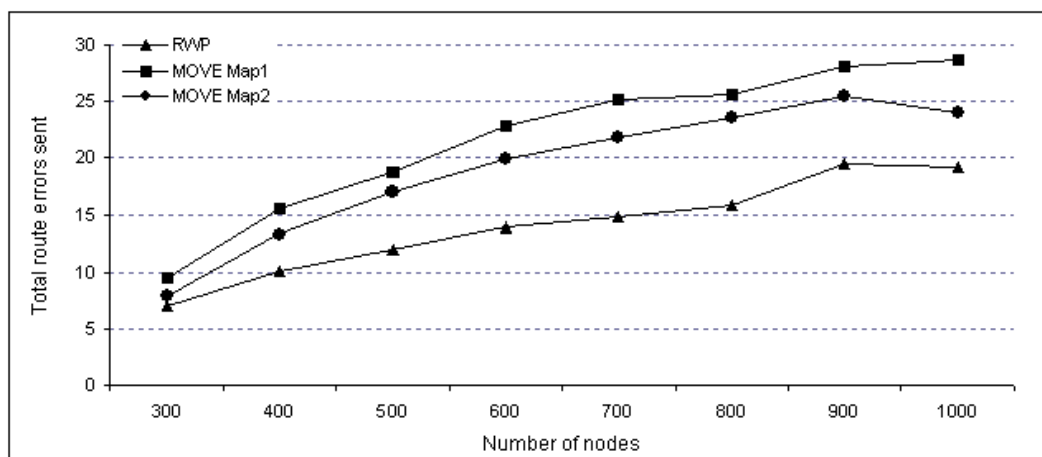


Figure 5.9. Total route errors sent.

packet. The total number of cached replies over all route replies sent by all nodes in the network is given in Figure 5.10. Above 600 nodes, the network is not connected, route requests are generated for some destinations continuously. However, when the network becomes connected there is no need for excessive route requests because routes are found and cached for further use. As network becomes denser and mobility decreases, route changes are less frequent so route requests are replied from the cache. In MOVE, route changes are more frequent because of intersections and grids.

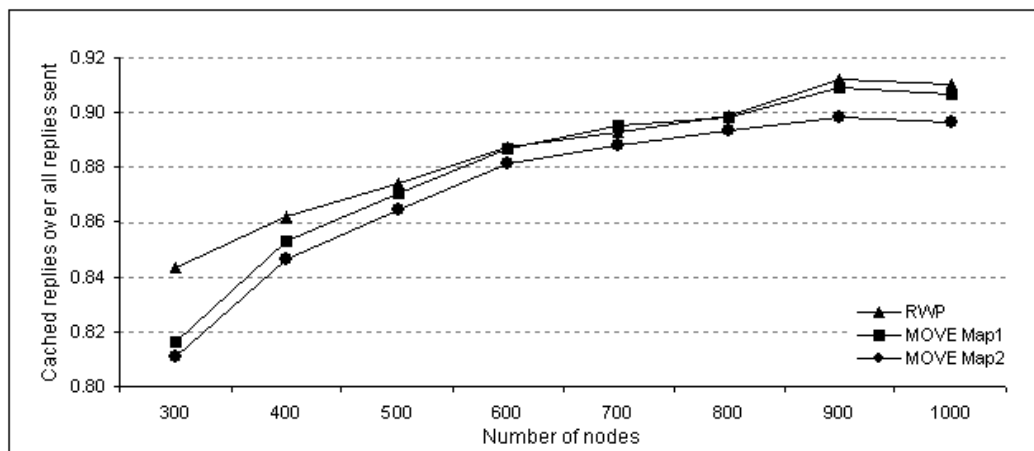


Figure 5.10. Cached replies over all route replies sent

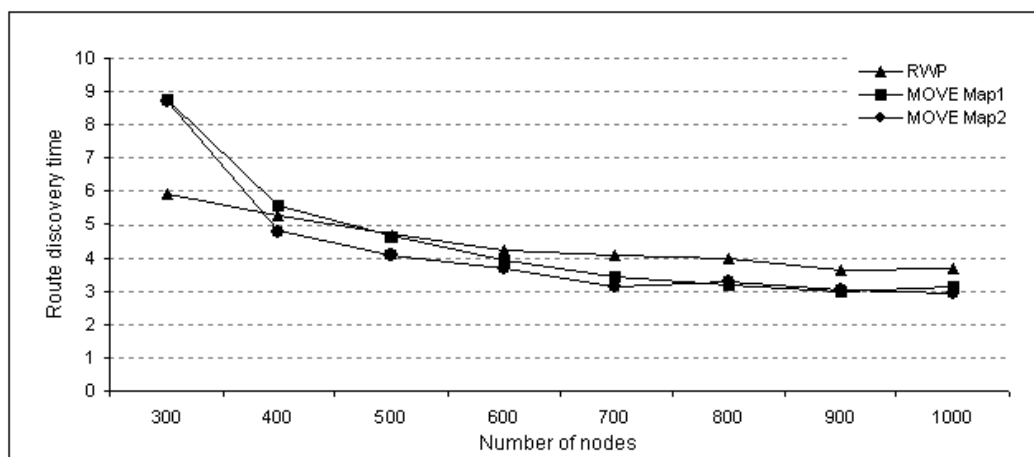


Figure 5.11. Route discovery time

The time to discover a route to a specific destination is the time when a route request was sent out to discover a route to that destination until the time a route reply is received (Figure 5.11). AODV is a reactive routing protocol. Routes are calculated on demand, and once constructed, they are cached for further use. As network gets

more connected and the routes are cached, the route discovery time decreases. As the number of nodes increases, the network gets more connected and routes with less hops are found (Figure 5.12). With the MOVE model, the connectivity is less because of the intersections and the grid size being longer than the transmission range of a node. Therefore, the routes in MOVE are longer than those in RWP.

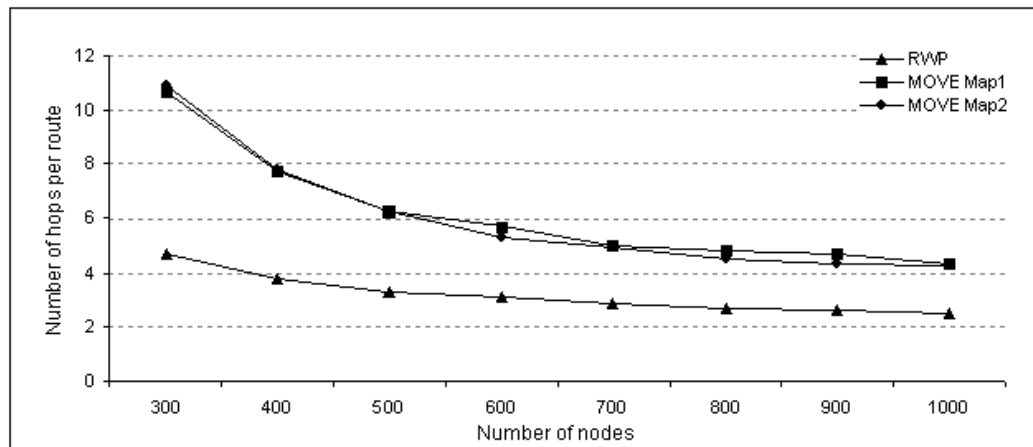


Figure 5.12. Number of hops per route.

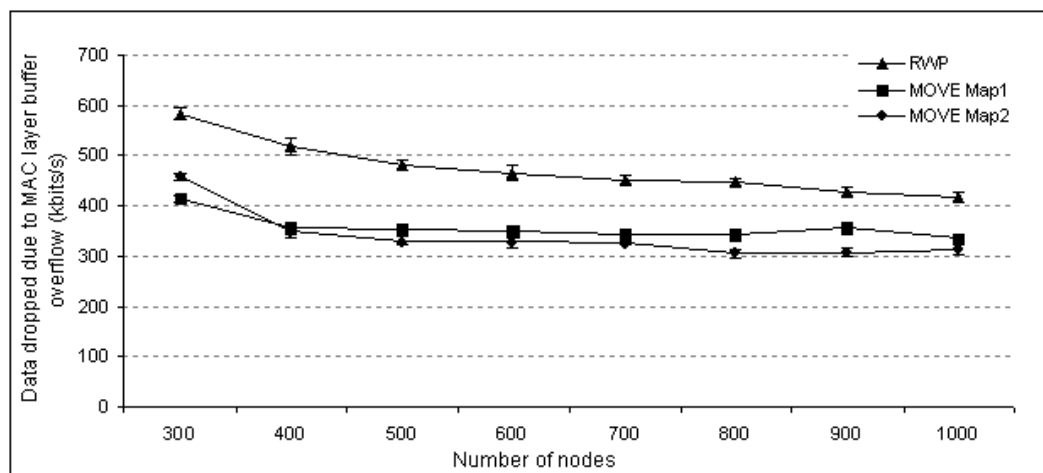


Figure 5.13. Data dropped due to MAC buffer overflow

The packets dropped by the SMAC due to the overflow of the transmission buffer is given in Figure 5.13. This is the number of the higher layer packets that are dropped upon arrival and not considered for transmission due to insufficient space left in the higher layer packet buffer. Due to high mobility and loose connectivity, finding route process and transmitting a packet takes longer, so buffer gets full. In the MOVE model, fewer packets are routed, so buffer overflow is lower as well.

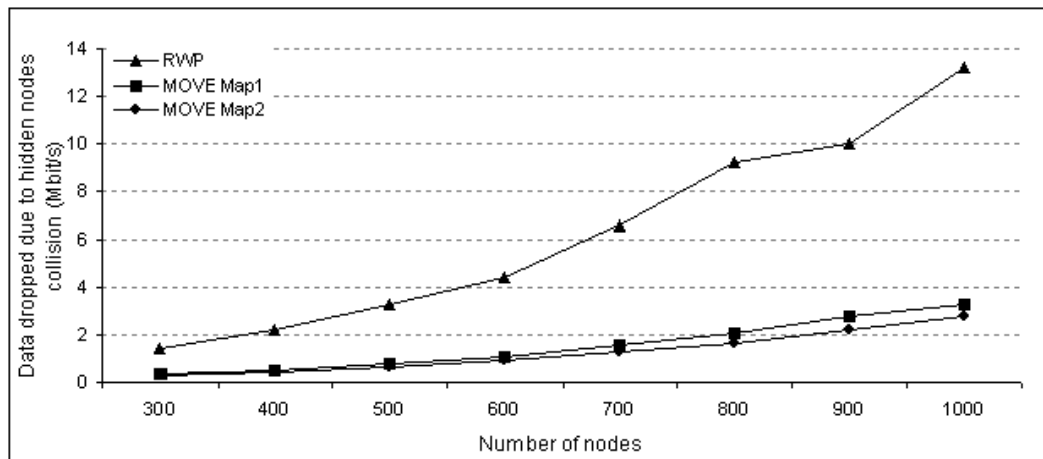


Figure 5.14. Data dropped due to hidden nodes collision

Data traffic sent by the transmitter that is dropped due to collisions with hidden nodes' traffic is given in Figure 5.14. As the number of nodes increases, broadcast traffic increases as well due to the number of nodes trying to transmit simultaneously. Therefore, collisions occur. As the number of reachable nodes is smaller in MOVE (Figure 5.4) due to intersections, broadcast traffic is also lower resulting in fewer collisions.

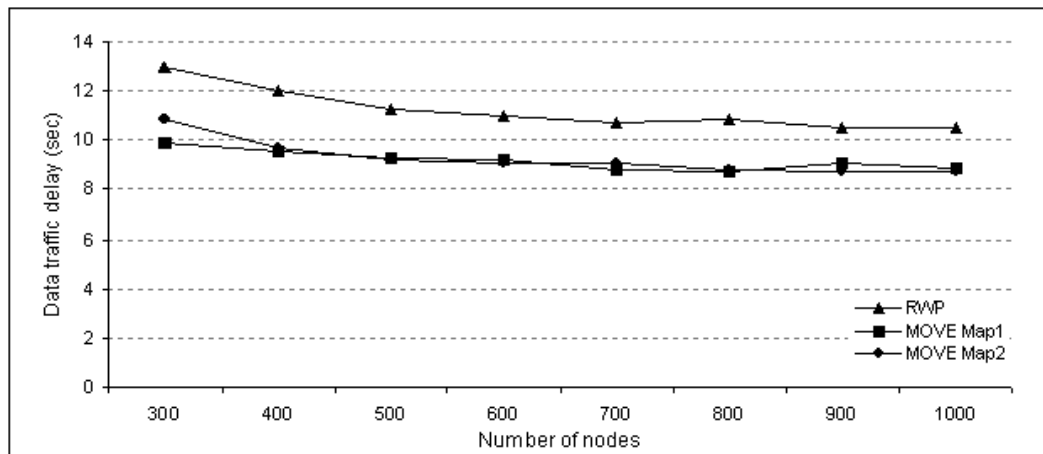


Figure 5.15. Data packet delay

End-to-end delay of data packets for the entire network is the time elapsed between the creation of the packet at its source and its destruction at its destination node (Figure 5.15). With MOVE, less traffic is received in destination nodes so the delay is lower than RWP.

There are many reasons for data drops in mobile ad hoc networks. If the node density and the number of reachable nodes is low, a route cannot be formed from source to destination. If the network topology changes occur frequently, routes break and must be reconstructed dynamically. Moreover, nodes transmitting at the same time cause collisions. Dense data traffic and excessive routing overhead result in buffer overflow and collisions. Beyond 600 nodes, the network becomes connected and AODV can find routes. However, it is not possible to maintain the routes, which is the major reason for data drops. Most of the data drops are due to changes in routing, mobility, and topology. When MOVE is used for mobility, the network gets less connected because of the intersections. The grid size is larger than the transmission range of a node, which blocks the connectivity of the nodes and breaks the routes. On the other hand with RWP, the number of reachable nodes is higher.

5.2. All nodes transmitting

When all nodes in the system generate data packets, the total load increases with the increase in the number of nodes, and the MAC layer gets saturated. In this test set, all nodes act as traffic sources to examine the effect of the load on the AODV routing protocol using the RWP and MOVE mobility models. Each node generates an overall traffic of 35 kbits/sec, so the total traffic generated by all nodes in the network is $35 * N$ kbits/sec, where N is the number of nodes (Figure 5.16). The topology in Figure 5.2(a) is used.

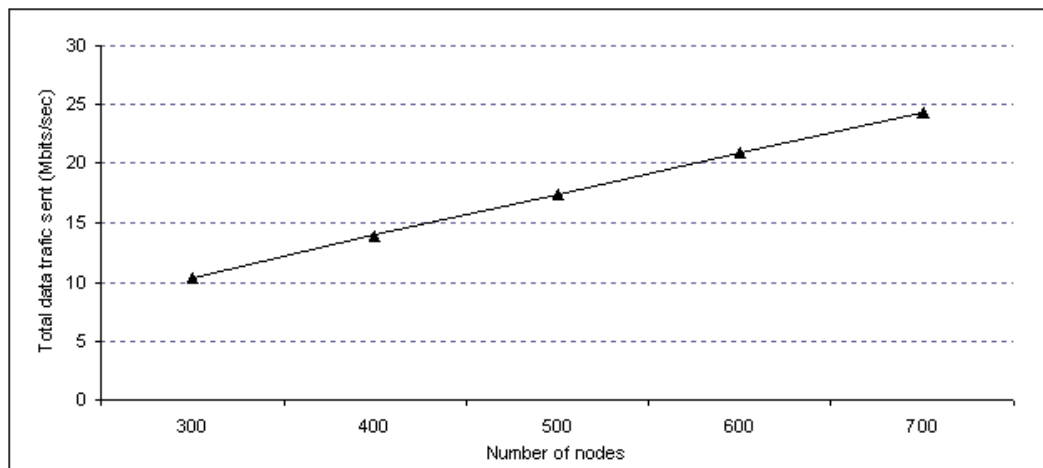


Figure 5.16. Total data traffic sent

The ratio of routing control traffic over data traffic is depicted in Figure 5.17. Routing overhead increases as the number of nodes increases in the system, because more packets are broadcasted for routing. The increase in routing traffic is more than the increase in data traffic because data packets are routed to one destination through a path while routing packets are broadcasted from every possible node. The packet overhead is higher in RWP because number of reachable nodes is higher than MOVE, so broadcast traffic causes more routing overhead.

Data and control traffic load causes most of the packets to drop due to buffer overflow (Figure 5.18). Buffer overflow increases as the number of nodes increases because routing packets add to the traffic load. The percentage of dropped packets is higher in RWP because the number of reachable nodes is higher, which causes more

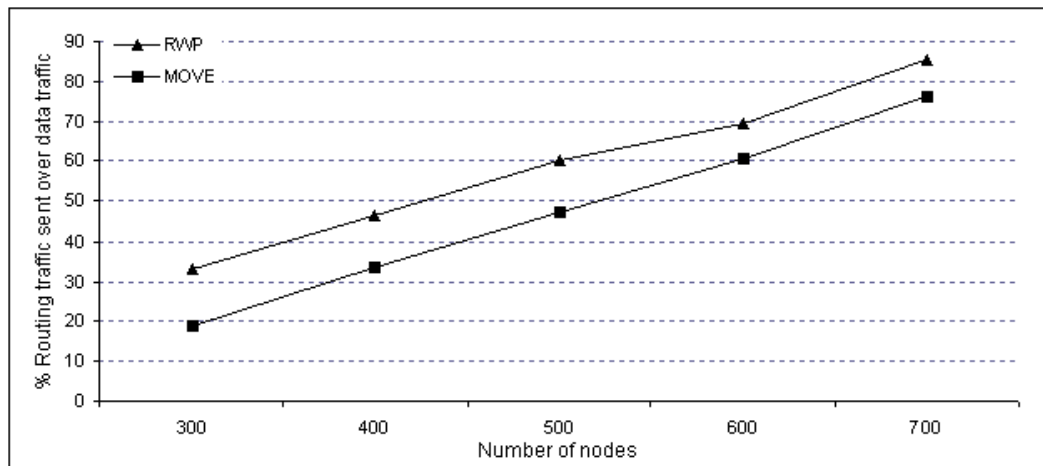


Figure 5.17. Routing traffic ratio

routing traffic load.

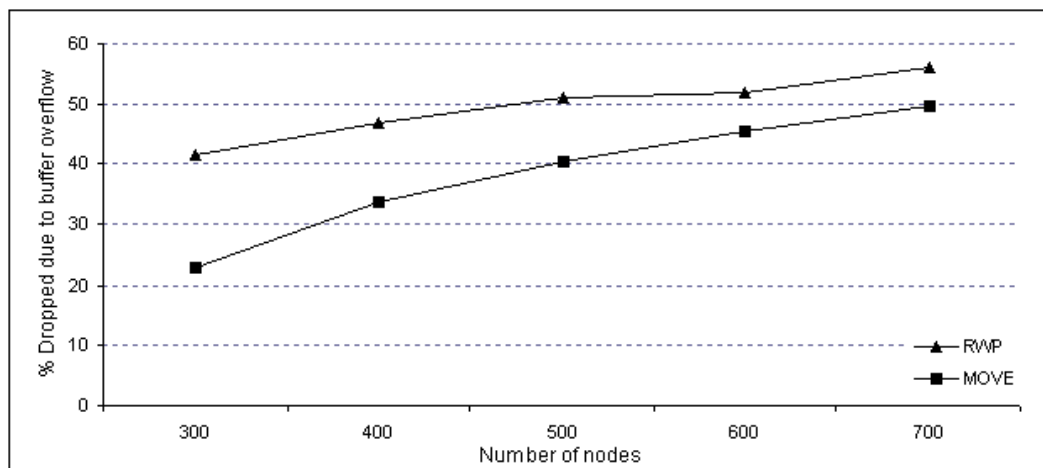


Figure 5.18. Buffer overflow

The percentage of the dropped traffic because of the collisions is given in Figure 5.19. Collisions occur because of high data and routing traffic. As the number of nodes increases, the total data and control traffic generated increases as well, so buffer overflows and collisions occur. Routing traffic is broadcasted to all nodes within the transmission range. In RWP, there are more nodes in the transmission range, so the load is higher. This causes more frequent collisions.

As the number of nodes increases, connectivity increases and data drop due to routing decreases (Figure 5.20). Connectivity is less in MOVE since the number of

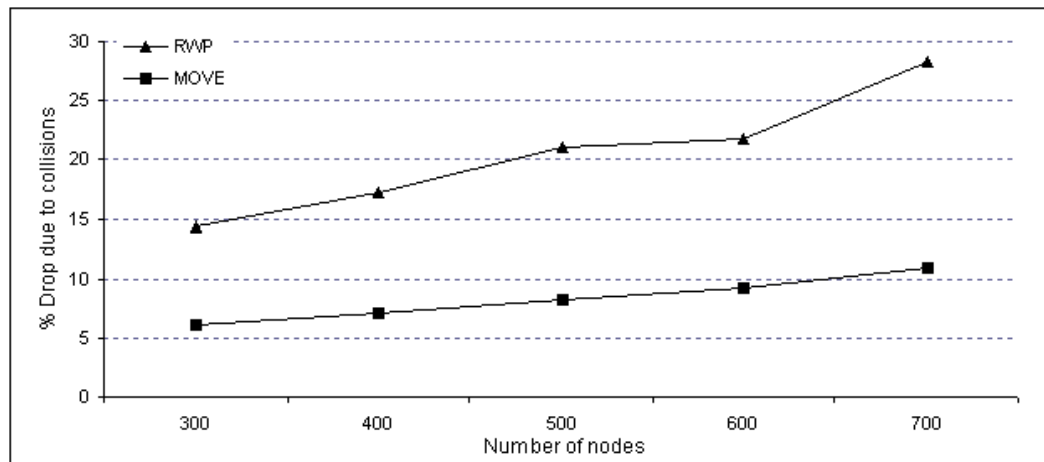


Figure 5.19. Collisions due to hidden nodes

nodes in the transmission range is less than RWP. Also, intersections cause more separated clusters of nodes and breaks connectivity.

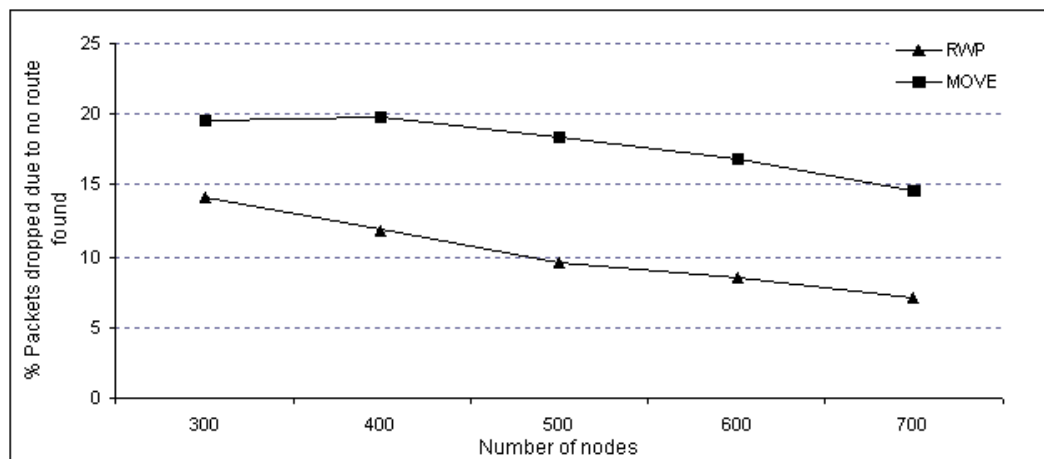


Figure 5.20. Data dropped due to routing

Although connectivity increases as the number of nodes increases, data traffic received by a node decreases. Routed packets do not reach the destination because of route breakdowns and collisions. The proportion of the successfully received traffic over the packets routed is given in Figure 5.21. Only a small proportion of the routed packets are successfully received from the destinations. The low delivery ratio is due to route break downs and collisions in the MAC layer. Figure 5.18 and Figure 5.19 show that data loss because of buffer overflow, and collisions is higher in RWP, especially beyond 500 nodes (Figures 5.21). As a result, packet delivery ratio decreases in RWP

faster than MOVE.

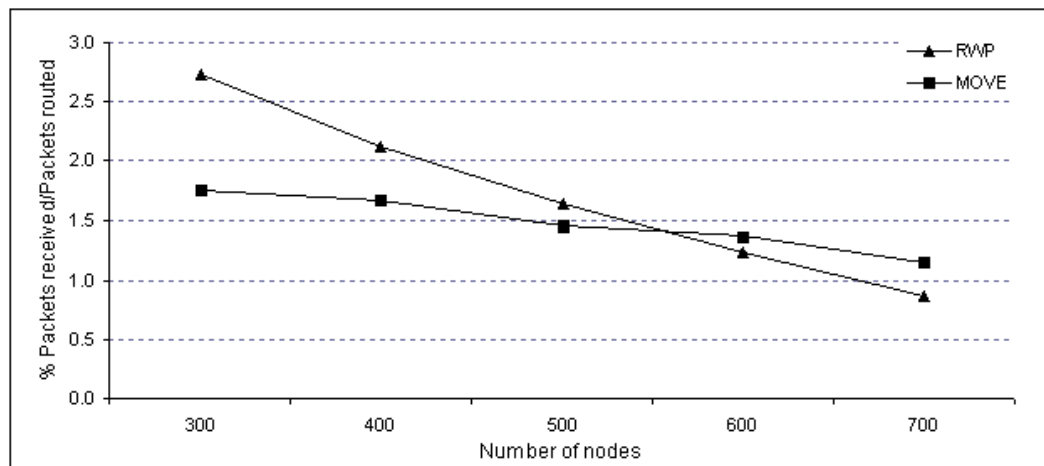


Figure 5.21. Delivery ratio

In RWP, number of reachable nodes is more, as well as connectivity. In MOVE, more packets are dropped because routes cannot be established or maintained due to intersections and loose connectivity. However, beyond 500 nodes, packet delivery ratio is higher with MOVE. As the number of nodes increases, the total data and control traffic generated increase as well, so buffer overflows and collisions occur. Routing traffic is broadcasted to all nodes within transmission range. In RWP, there are more nodes in the transmission range, so load is higher. This causes more frequent collisions. As a result, although routes cannot be maintained with MOVE due to the intersections, the drawback of collisions causes RWP to behave worse. This results in misleading conclusions about the performance of the routing algorithm just because of the mobility model selected.

5.3. OLSR and AODV Comparison Tests

In the previous subsection, it was shown that the selection of the mobility model has a significant effect on the performance of a routing algorithm. In this subsection, we analyze how different algorithms may be affected. In this test case, the comparison of a proactive protocol, OLSR, and a reactive protocol, AODV, is given using RWP and MOVE. The topology used is given in Figure 5.2(a). The number of nodes is 400 but only 100 nodes act as traffic source. Other nodes act as relay nodes. The total data traffic generated by 100 nodes is approximately 3.5 Mbits/secs.

Comparison of routing overhead for AODV and OLSR protocols is given in Figure 5.22. Routing overhead is higher in the proactive routing protocol, OLSR, because of the frequent link state packets broadcasted. On the contrary, AODV finds routes on demand, so no state packets are sent. The effect of mobility model is more significant in OLSR routing protocol. The big difference is due to the sensitivity to the number of reachable nodes and routing packets. The number of reachable nodes in RWP is more than MOVE, so routing traffic sent to neighbor nodes is higher.

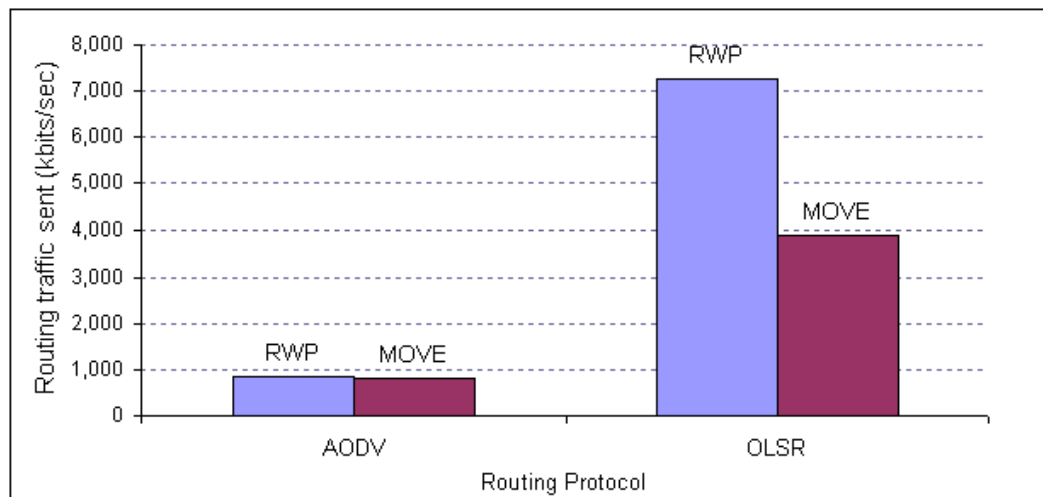


Figure 5.22. Routing traffic sent

The routing overhead in OLSR causes most of the traffic to drop due to collisions (Figure 5.23). Routing traffic is higher in OLSR, so collisions occur more frequently. The huge difference between RWP and MOVE in OLSR is because the number of

nodes in transmission range is higher in RWP, so most of the traffic collides. Similarly more packets are dropped with RWP in OLSR due to buffer overflow (Figure 5.24). The main cause of data drop in AODV is broken routes, while OLSR also suffers from collisions and buffer overflow.

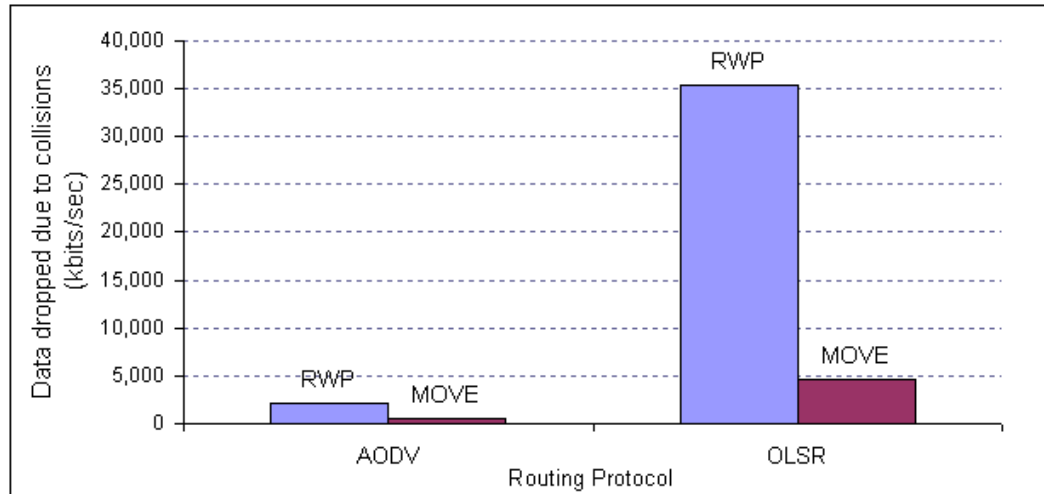


Figure 5.23. Collisions due to hidden nodes

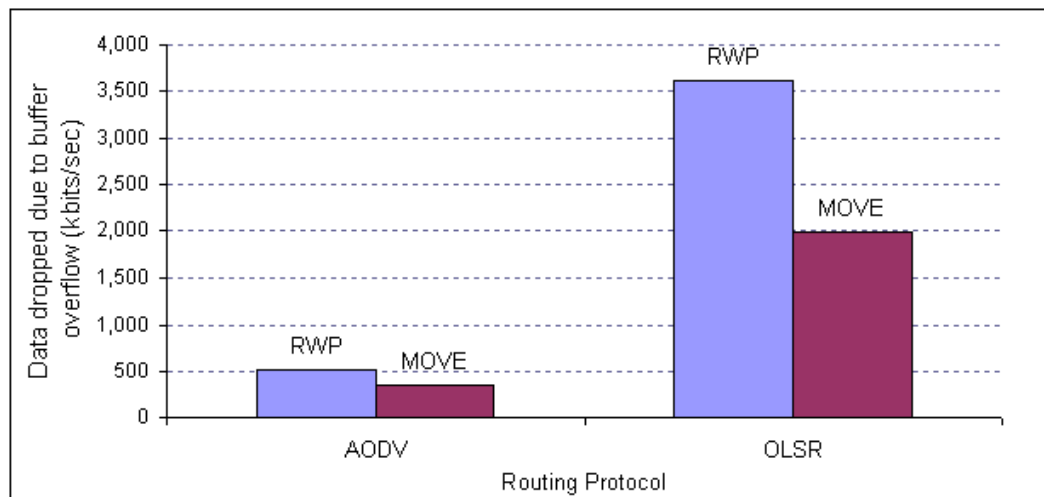


Figure 5.24. Buffer overflow

The comparison of successfully received data traffic with AODV and OLSR is given in Figure 5.25. MOVE model causes less throughput than RWP model when used with AODV. However, OLSR achieves slightly better performance with MOVE. This result can be explained considering the difference of the causes of packet drops in AODV and OLSR. AODV suffers from route changes caused by intersections. The frequent

route changes occur when MOVE model is used, so AODV exhibits lower performance when used with MOVE. However in OLSR, packet drops are due to collisions and buffer overflow resulting from the extreme routing overhead. The packets that do not overflow or collide will find the way to the destination since the routes are still valid. As the number of reachable nodes is more in RWP model than in MOVE model, broadcast traffic is higher and collisions are more frequent. Thus, we conclude that the effect of the mobility model in performance heavily depends on the algorithm.

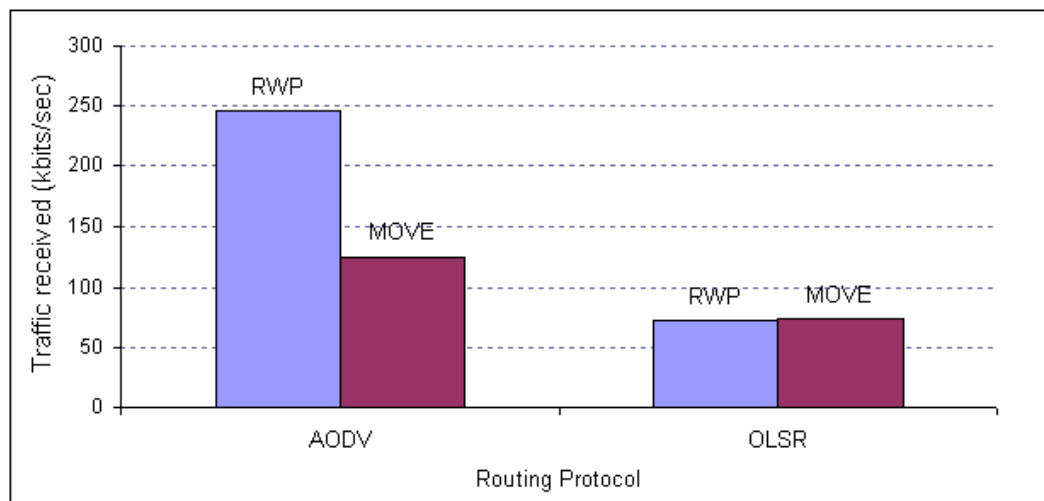


Figure 5.25. Data traffic received successfully

5.4. Topology Tests

In this test set, the effect of the grid size on the performance of routing is analyzed. AODV routing protocol is used with 100 source nodes. When the grid size is chosen larger than the transmission range, it is seen that connectivity breaks occur at the intersections. When the grid size is 250 meters, the number of reachable nodes increases because connectivity breaks at the intersections decrease (Figure 5.26). Still, the number of reachable nodes is higher in RWP model. As a result, data traffic successfully received by the destinations nodes is higher when grid size is smaller than transmission range, as route breaks are less frequent (Figure 5.27).

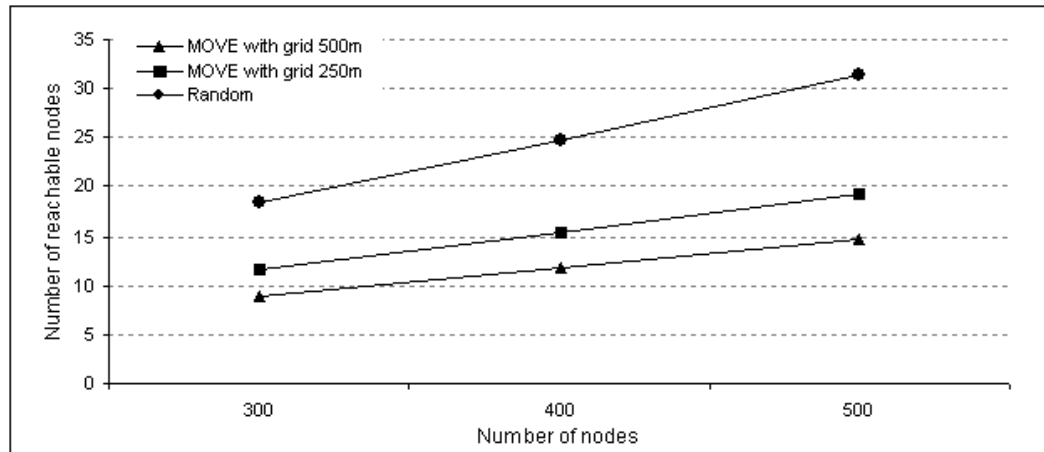


Figure 5.26. Number of reachable nodes

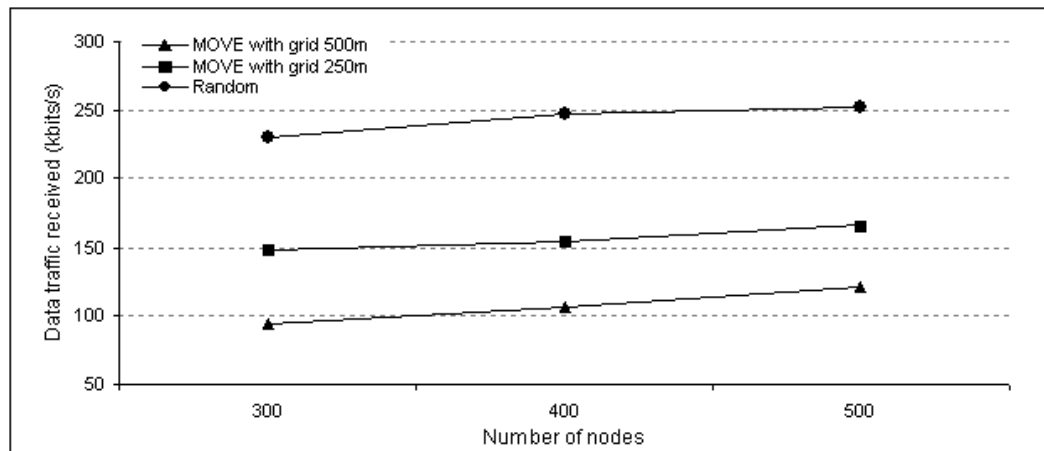


Figure 5.27. Data received

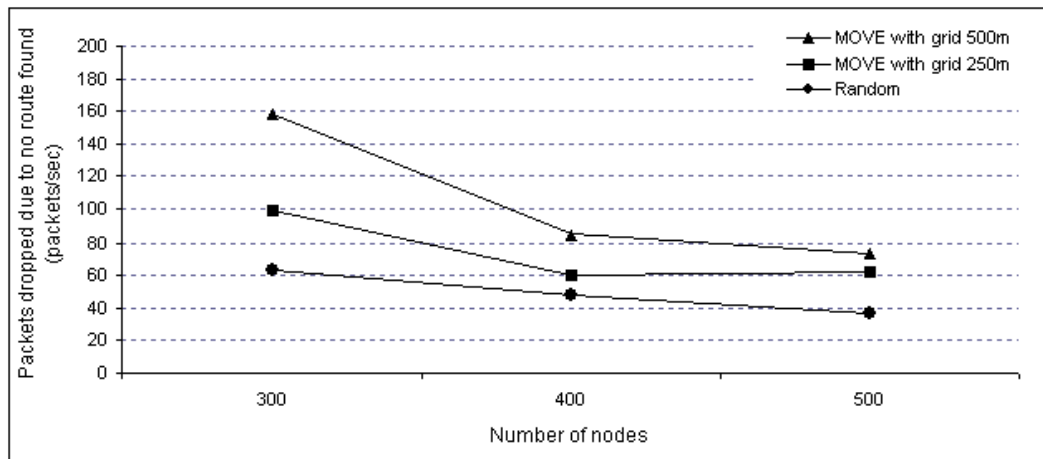


Figure 5.28. Packets dropped

5.5. Simple MOVE

In this test set, the effect of mobility parameters on the performance of routing is analyzed. AODV routing protocol is used and all nodes act as traffic sources. A simpler MOVE model is compared with the original complex MOVE mobility. The simpler mobility model is created removing the safety space, car following, lane change, intersection handling, and POI functionalities. This simpler model is closer to random model although the vehicles still follow the roads. As there is no functionality to restrict speed of vehicles like car following and intersection handling, the average speed of nodes is higher in simple MOVE. Also, average speed does not change significantly with the increase in number of nodes because the limiting effect of car following on speed is not observed in simple MOVE (Figure 5.29). The connectivity blocking effect of intersections still exists in simple MOVE because vehicles move on the roads. As average speed is higher in simple MOVE, packets are dropped more frequently because routes cannot be re-established (Figure 5.30). Also, routed packets are not successfully received by the destinations because high speed of vehicles break routes in simple MOVE (Figure 5.31). Because of the difference in average speed, the delivery ratio is higher in MOVE (Figure 5.32).

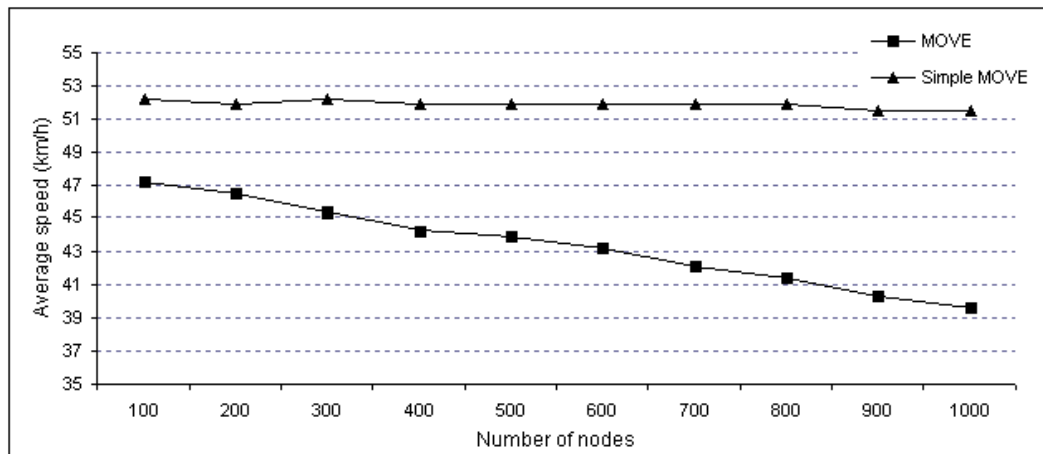


Figure 5.29. Average speed

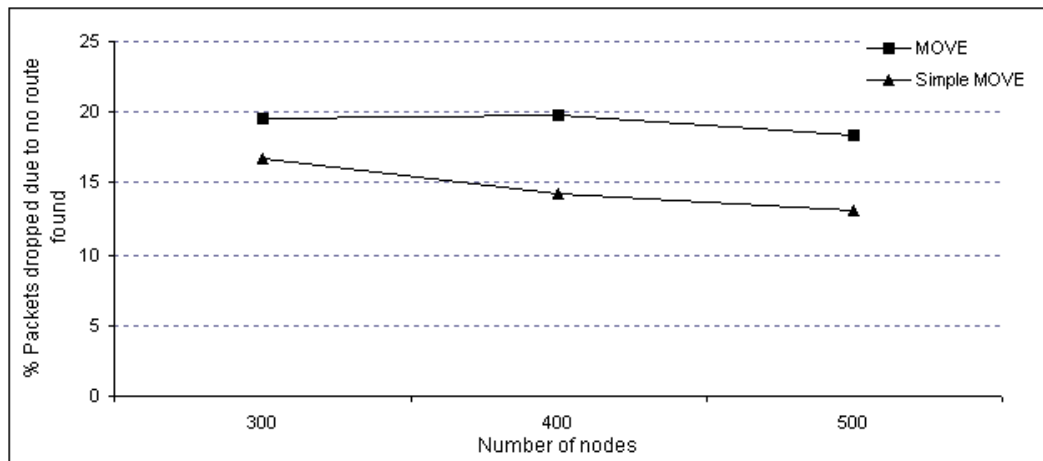


Figure 5.30. Data dropped

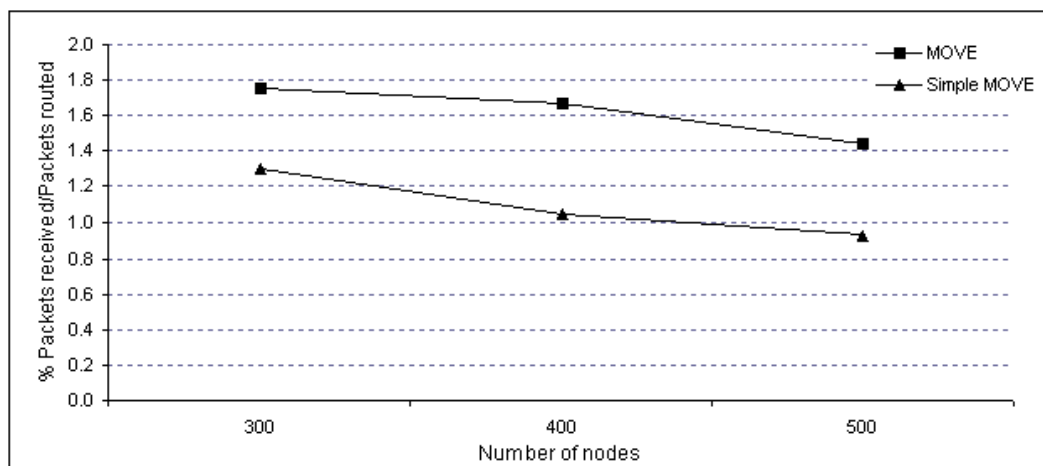


Figure 5.31. Received traffic over routed traffic

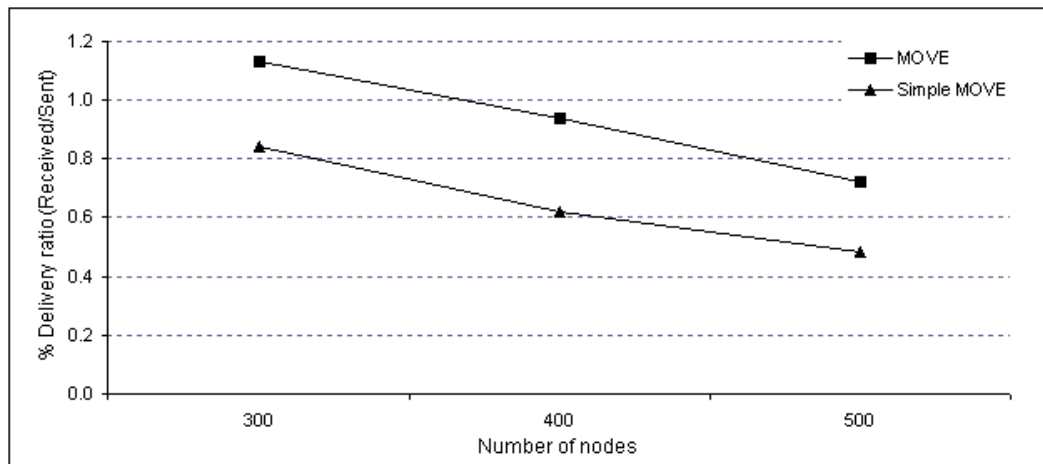


Figure 5.32. Delivery ratio

6. CONCLUSIONS AND FUTURE WORK

In this thesis, we propose a realistic vehicular mobility model for VANETs. The model utilizes a map to generate the mobility patterns of the vehicles while considering congestion on the roads, distance to vehicle in front and speed limits. We also show that the selection of the mobility model is crucial in the performance evaluation of a routing algorithm.

The proposed model is tested with AODV and OLSR routing protocols. The results show that the mobility model affects the number of nodes within the transmission range of a node. This, in turn, affects the broadcast traffic and collisions. Moreover, mobility model determines the topology changes in the network, which affects the lifetimes of routes and requires route reconstructions. AODV and OLSR performances differ when tested under the RWP and MOVE mobility. The number of intersections, grid size, and node density become important when dealing with VANET performance.

In the mobility model, the assignment of weights to road segments is simply done by taking only road lengths into account. The route of a vehicle does not change once it has been determined. As a future work, the route of a vehicle should be selected according to congestion and traffic load parameters for a more realistic approach. Moreover, user response times should be taken into account throughout the calculations. Traffic sign support may also be added. The effect of different boundary methods should be analyzed to reflect the effects of boundaries or symmetric insert approaches.

APPENDIX A: EQUATIONS OF A STRAIGHT LINE

The equation of a straight line can be written in two different forms. In the model, both forms are used to represent a road segment as a line and to check if a mobile's coordinate is on a particular road. Also, the movement along the road, projection of a coordinate is calculated with line equations.

$$y = m * x + n \tag{A.1}$$

$$a * x + b * y + c = 0 \tag{A.2}$$

To find the nearest road to a coordinate (X, Y) , the distance, d , from the road to that point is calculated as follows,

$$d = \frac{a * X + b * Y + c}{\sqrt{a * X^2 + b * Y^2}}. \tag{A.3}$$

The projected (X_p, Y_p) coordinates of point (X, Y) on a line are found as follows:

$$Y_p = \frac{Y + m * X + n}{2} \tag{A.4}$$

$$X_p = \frac{Y_p - n}{m} \quad (\text{A.5})$$

The gradient α used in finding the movement of a mobile on a road is found as

$$d_x = X_2 - X_1, \quad (\text{A.6})$$

$$d_y = Y_1 - Y_2, \quad (\text{A.7})$$

$$\alpha = \begin{cases} \text{atan}\left(\frac{d_y}{d_x}\right) + \pi & \text{if } d_x < 0, \\ \text{atan}\left(\frac{d_y}{d_x}\right) + 2 * \pi & \text{if } d_x < 0, \\ \text{atan}\left(\frac{d_y}{d_x}\right) & \text{otherwise} \end{cases}$$

where (X_1, Y_1) is the coordinate of the starting point of the road and (X_2, Y_2) is the coordinate of the ending point of the road.

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