MASTER'S THESIS

Position Information Dissemination in Vehicular Ad-hoc Networks

Parineeth M. Reddy

Supervisor: Dr. A.L. Ananda

SCHOOL of COMPUTING, NATIONAL UNIVERSITY OF SINGAPORE

2007

ACKNOWLEDGEMENTS

I express my gratitude to Dr. Ananda for supervising me. When I started the graduate program at NUS, pursuing research was completely new to me. Dr. Ananda helped me overcome the initial hurdles and guided me patiently. He has provided timely help and the right direction to my research. He also gave me the opportunity to teach an undergraduate course on computer networking which helped me strengthen my foundations in networking.

I thank Dr. Chan for teaching graduate courses on networking that were very useful for my research. Dr. Ananda and Dr. Chan have given valuable feedback about my research which has helped me refine my ideas.

I thank fellow researchers at the CIR lab for sharing their research ideas during the weekly CIR lab meetings. These discussions have provided me with useful insights for pursuing research.

I thank Sridhar for helping me with LaTeX.

Finally, I appreciate the facilities available at the CIR lab and at NUS.

ABSTRACT

Position information dissemination is pivotal in vehicular networks. Accurate position information of neighboring vehicles can help in providing better vehicle navigation and preventing accidents. In this paper, we study the periodic broadcast scheme, the distance based scheme and the velocity prediction scheme for disseminating position information with the desired position accuracy. We analyze the worst case performance of the periodic scheme, distance based scheme and velocity prediction scheme. We solve the problem of indefinitely long time intervals between consecutive position broadcasts in the distance based scheme and the velocity prediction scheme. The effect of packet loss on each of the schemes is also studied. Theoretical analysis and results from simulations show that the velocity prediction scheme significantly outperforms the distance based scheme and periodic broadcast schemes.

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Chapter 1

Introduction

1.1 Overview

Ad hoc networks are infrastructure-less networks that do not require centralized administration. Nodes co-operate with each other by acting as routers and forwarding data packets so that the packets reach their intended destination. Due to the lack of centralized infrastructure, wireless mobile ad hoc networks pose a challenging area for active research.

Ad hoc networks are best suited for situations where a centralized infrastructure doesn't exist or has been destroyed. Deployment of ad hoc networks has been proposed in the following areas,

- Enabling communication among people during an emergency (including communication among soldiers during war)

- Enabling users in a particular area to communicate with one another (for instance, delegates attending a conference can communicate with one another using an ad hoc network)
- Extending the coverage of base stations.

The most predominant ad hoc networks are wireless Mobile Ad hoc Networks (MANETs) consisting of wireless mobile nodes that can dynamically form the network. In spite of the advantages offered by ad hoc networks, the deployment of MANETs has been very limited. The main reason for the limited deployment of MANETs is the limited battery power of mobile devices. A mobile device can quickly drain its battery by routing messages of other users. So, users generally don't prefer using ad hoc communication to route messages of other users at the expense of their own battery power.

A new area where ad hoc networks are being deployed is Vehicular Ad hoc Networks (also known as VANETs). In Vehicular Ad hoc Networks, vehicles communicate with each other using the free ISM band without requiring a communication service provider. Although Vehicular Ad hoc Networks are similar to Mobile Ad hoc Networks, there are some important differences that distinguish VANETs from MANETs. Some of the differences include

1. Movement patterns

The movement pattern of vehicles is different from the movement of nodes in a general mobile ad hoc network. Vehicles move at much higher speeds compared to typical mobile nodes in MANETs. Vehicles seldom move at constant speeds throughout the journey. Vehicles frequently accelerate or slow down and change lanes. So, the protocols developed for a VANET should take into account the actual movement pattern of vehicles.

2. Power awareness

The protocols designed for a general mobile ad hoc network have to be more power aware since they are meant to be used by mobile devices that have limited battery power. On the other hand, protocols for vehicular ad hoc networks don't have to give undue importance for power consumption since vehicles have long-lasting power supplies.

3 Location Awareness

Mobile devices in a MANET should be inexpensive and must conserve power. So, the protocols used for MANETs cannot assume that mobile devices are fitted with Global Positioning Systems. On the other hand, it is cost-effective to fit vehicles with GPS and vehicles have much lesser power constraints compared to mobile devices. So the protocols for VANETs can make use of the location information obtained via GPS for efficient packet delivery.

Vehicular ad hoc networks are better suited for communication than ad hoc networks formed by handheld devices. Many of the critical problems faced by an ad hoc network formed by handheld devices are not relevant in vehicular ad hoc networks. For instance, unlike handheld devices which are limited by power, vehicles possess sufficient power for routing packets of other vehicles. Vehicles can easily be fitted with additional hardware such as Global Positioning Systems and special antennas.

The study of vehicular ad hoc networks is important since it can revolutionize transportation and make journey safer. The vehicular network can be used to support a wide range of applications. These can be broadly classified as traffic related applications and non- traffic applications.

The main traffic related applications in vehicular networks are avoiding road accidents and reducing traffic congestion. Vehicular ad hoc networks will improve road safety significantly by providing cooperative driver assistance that helps in avoiding accidents. Vehicles can regularly exchange their speed and location information. A warning can be given to the car driver if the car is approaching too close to another car. In case a collision is likely to occur, the vehicle can be slowed down by automatically applying the emergency brakes. If a vehicle is being driven dangerously then a notification can be given to the neighboring vehicles to keep way from the vehicle. Vehicular ad hoc networks can also provide information to assist overtaking and warn about obstacles and blindspots.

Vehicular ad hoc networks can be used to relay real-time traffic information to vehicles. The relayed traffic information can help the driver avoid traffic jams. The transmission of traffic information can be done in a completely infrastructure-less mode or using infrastructure gateways along the roads. The traffic information can then be overlaid on a map and displayed to the driver. This helps drivers to find alternative routes immediately and avoid the congested roads.

The main non-traffic application in vehicular ad hoc networks is car infotainment. Vehicular ad hoc networks can help in accessing nearby WiFi Access Points from the vehicle. [3] describes a cooperative strategy called CarTorrent for downloading large multimedia files in vehicular networks. In CarTorrent, a car requests the required multimedia file from a roadside gateway . The file download continues even after the car is out of range from the gateway by using the vehicular network.

Vehicular networks can also help in delivering advertisements based on the location of the vehicle. For instance, the driver of the vehicle can query for all the hotels that are within a vicinity of 10 kilometers. AdTorrent [2] is a system for delivering advertisements in vehicular networks. AdTorrent helps in providing targeted advertisements based on the needs of the user and eliminates the need for distracting advertisement along the road.

Due to the immense potential present in the field of vehicular networks many vehicle manufacturers are actively pursuing research in this field. A consortium of six companies (including DaimlerChrysler, Robert Bosch, Siemens AG) and three universities (Universities of Hannover and Mannheim, Technische Universitat Hamburg) set up FleetNet [1]. The main objective of FleetNet was to develop a platform for inter-vehicle communication. Several applications for vehicular networks such as cooperative driver assistance and traffic monitoring were studied. In November 2003, a prototype of FleetNet was successfully demonstrated at the DaimlerChrysler Research Center in Germany.

1.2 Objective

Exchanging position information is of prime importance in vehicular networks. Providing accurate vehicle position information can help in avoiding accidents. One of simplest scheme to exchange position information is to periodically broadcast the information. However when the desired position accuracy is high, a significant portion of the available bandwidth can be used up by the position messages. We address the issue of informing the position of a vehicle to its single hop neighbors so that the desired accuracy requirements are met and at the same time the traffic generated by the position messages is reduced.

1.3 Contribution

The main contributions of our work include:

- We study the distance based scheme and the velocity prediction scheme to decrease the traffic generated by transmitting position messages. Using the normal distance based scheme and the velocity prediction scheme can result in an indefinite time interval between two successive position broadcasts. This can result in vehicles that are outside the communication range of a vehicle not being informed about the vehicle's position. We solve this problem in this thesis.
- We theoretically analyze the worst case performance of each of the schemes.
- We perform simulations using different traffic models to study the behavior of the proposed schemes. Simulation results show that the velocity prediction scheme has a significantly better performance than the rest of the schemes.

1.4 Thesis Organization

The rest of the thesis is organized as follows. Section 2 surveys the research done in vehicular ad hoc networks. The research problem is defined and solved in section 3. The simulation details are provided in section 4. Section 5 gives the simulation results. We finally conclude in section 6.

Chapter 2

Literature Survey

2.1 Current Standards

The Dedicated Short Range Communication (DSRC) standards [4] have been proposed to specify the physical layer and MAC layer for vehicular networks. A DSRC standard that operates at 915 MHz was proposed for vehicular networks several years ago. However in this standard only a 12 MHz band is available for communication and the band is shared with other applications such as cordless phones. To provide a larger dedicated band for vehicular networks a new DSRC standard operating at 5.9 GHz has been proposed.

The Federal Communications Commission (FCC) allocated the 5.9 GHz band that operates between 5.850 GHz - 5.925 GHz in October 1999. Thus 75 MHz of the spectrum is now available for vehicular networks. The band can be used for vehicle-to-vehicle and vehicle-to-gateway communication. In August 2003, ASTM [5] (American Society for Testing and Materials) published the ASTM E2213-03 DSRC standard that describes the physical layer and the MAC layer for vehicular networks that operate in the 5.9 GHz band. The FCC is now referencing the ASTM E2213-03 standard for communication services in the 5.9 GHz band.

ASTM E2213-03 proposes to extend IEEE 802.11a standard and adapt it for vehicular networks. 802.11a makes use of Orthogonal Frequency Division Multiplexing (OFDM) to achieve high data rates. Using the standard proposed in ASTM E2213-03, the estimated transmission range in the 5.9 GHz band is about 1000 meters and the estimated data rate is in the range 6 Mbps - 27 Mbps. A comparison between the old DSRC standard operating at 915 MHz and the new DSRC standard operating at 5.9 GHz is given in table 2.1

	915 MHz	5.9 GHz
Range	30m	1000m
Data rate	0.5 Mbps	6 Mbps to 27 Mbps
Number of channels	1	7

Table 2.1: Comparison of DSRC standards

Until the hardware for the 5.9 GHz band becomes available, system testing can proceed with 802.11a hardware.

The IEEE 1609 family of standards for Wireless Access in Vehicular Networks (WAVE) have been proposed to define an architecture for communication in vehicular networks. These standards are also referred to as IEEE 802.11p. The standards are complementary to the DSRC standard for the 5.9 GHz band and are described below

- **IEEE P1609.1 Resource Manager** - This standard specifies the services and the interfaces for a WAVE Resource Manager application. The message formats and data storage formats that can be used by applications are defined.

- **IEEE P1609.2 Security Services for Applications and Management Messages** - This standard defines secure message formats and the circumstances for secure message exchange.
- **IEEE P1609.3 Networking Services** - This standard defines network services (including addressing and routing) and transport layer services.
- **IEEE P1609.4 Multi-Channel Operations** - This standard describes enhancements to the IEEE 802.11 MAC layer for multi-channel operations.

The formal 802.11p standard is scheduled to be published in July 2008.

2.2 Routing Protocols

Communication in vehicular networks can be classified into vehicle-vehicle communication and vehicle-gateway communication. Gateways are infrastructure nodes deployed along the road side that can be used to complement ad hoc vehicular networks. Routing in vehicular networks can be classified into three categories, broadcast routing, unicast routing and geocast routing

2.2.1 Broadcast routing

Broadcasting of packets is used in vehicular networks for carrying data packets to all nodes in the network. The simplest scheme that can be used for broadcasting is flooding. In flooding a node that receives a packet, forwards the packet only if the node has not already forwarded the packet earlier. Each packet contains a unique sequence number. The node stores the sequence numbers of packets it has forwarded. If a node receives a packet with a sequence number that the node has already forwarded, the node drops the packet.

Flooding however is highly inefficient and can result in the broadcast storm problem wherein the transmissions of the same message by several neighboring nodes severely contend with each other. In [6], several schemes were proposed to avoid the broadcast storm problem. These include

- **Probabilistic scheme** Each node delays the transmission of the packet for a random period of time and then forwards the packet with a probability p and drops the packet with a probability 1-p. An improvement to this scheme is investigated in the Appendix.
- **Counter based scheme** Each node has a counter that keeps track of the number of packets received with the same sequence number. If the count exceeds a threshold then the packet is dropped.
- **Distance based scheme** A node decides whether to forward the packet or not, based on the distance between it and the node from which it received the packet. If the distance between the current node and the previous hop node is less than d_{min}, the packet is not forwarded by the current node.
- **Coverage based scheme** A node decides whether to forward the packet or not, based on the new coverage area that the node can cover by forwarding the packet. Each node that forwards the packet also indicates its position in the packet. The receiving node can calculate the new area that can be covered

by it which was not covered by the nodes in the previous hops. If the new area that can be covered exceeds a predetermined threshold then the receiving node forwards the packet else the receiving node drops the packet.

To prevent neighboring vehicles from broadcasting a message at the same time and to ensure that vehicles quickly transmit the information across multi-hops, the following scheme was proposed in [7]. A node that receives a packet does not immediately forward the packet but instead waits for some time before forwarding the packet. The node computes the waiting time WT as follows

$$WT = MaxWT - \frac{MaxWT}{Range} * d$$

where MaxWT is the maximum waiting time and d is the distance between the previous hop node and the current node. Thus the waiting time is smaller if the previous hop node and current node are further apart. This ensures that mainly vehicles that are furthest away from the previous hop node take part in forwarding the message.

2.2.2 Unicast routing

Conventional unicast ad hoc routing protocols have difficulties in dealing with the high vehicle mobility in vehicular networks. Several studies have shown that position based unicast routing performs well in vehicular networks. [8] shows that position based routing works much better than conventional ad hoc protocols for highway traffic. [9] suggests that for communication over more than 2 hops in vehicular networks, position based routing has significantly better packet delivery and lower routing overhead than non-position based approaches.

In position based routing, every vehicle is aware of its position. The most widely suggested method for obtaining position information is using a GPS receiver at each vehicle. Similar to having a source IP address and destination IP address, each packet has information about the geographic position of the sender and the geographic position of the destination. Intermediate nodes between the source and destination route the packet based on the destination geographic position contained in the packet.

In order to send a packet to a destination node, the source node first needs to know the current geographic position of the destination node. This information is obtained using a location service. Location service is used to determine the position of a destination node. Examples of location services for vehicular networks include the Reactive Location Service [9]. In the Reactive Location Service the source node uses flooding to discover the current location of the destination node. Expanding ring search is used to limit flooding in the network.

Examples for position based routing include Greedy Perimeter State Routing [10] and Geographic Source Routing [11]. In Greedy Perimeter Stateless Routing (GPSR), nodes use beacons to exchange position information with neighboring nodes. The source node uses location service to determine the current position of the destination and indicates the destination position in the packets. Intermediate nodes greedily route the packet by forwarding packets to the neighbor node that is geographically closest to the destination. If there is no neighbor node that is closer to the destination than the current node, greedy forwarding fails. GPSR recovers by routing packets in perimeter mode. In perimeter mode, a planar graph of nodes in the network is constructed and the packets are routed along the faces of the planar graph until a node that is closer to the destination is reached, from where greedy forwarding resumes.

Geographic Source Routing (GSR) was developed mainly for routing in city environments. The main problems that are specific to city environments include obstacles such as buildings along the road. To overcome the problem of obstacles, packets are routed along the roads and road junctions. As the name suggests source routing is used wherein the source node indicates in the packet the entire path to be taken by the packet. First the source node uses flooding to find the location of the destination. Once the location of the destination has been found, the sending node uses the road maps of the on board navigation system to find the route the packet has to take. Dijkstras shortest path algorithm is used to find the route with shortest distance along the roads from source to destination. The sending node puts the information about the sequence of junctions the packet has to traverse in the packet header and forwards it.

2.2.3 Geocasting

Geocasting is a special multicast technique wherein the members belonging to the multicast group are nodes that are present in a particular geographical region (geocast region). When a packet is sent to a particular geocast region, all nodes in the region receive the packet. Membership of nodes to the multicast group changes as nodes move in and out of the geocast region. Examples for geocast protocols include Location Based Multicast [12] and Inter-Vehicle Geocast [13].

Two schemes of operation have been proposed for Location Based Multicast (LBM). In the first scheme, for a given source node and geocast region, a forwarding zone is computed. In the simplest case, the forwarding zone is the smallest rectangle that encloses the source and the geocast region. If a node is in the forwarding zone, then it forwards the packet to its neighbors else it drops the packet. In the second scheme, an intermediate node forwards the packet to the next hop only if the forwarding of the packet brings the packet d units closer to the destination.

2.2.4 Interesting routing strategies

1. Opportunistic forwarding

Vehicular traffic often comprises of large gaps which are devoid of vehicles. When the size of the gaps becomes larger than the communication range, the vehicular network becomes disconnected and vehicles in one partition will be unable to communicate with vehicles in the other partition. In such cases, routing of packets across the two partitions fails.

To overcome this problem, opportunistic forwarding of packets was proposed in [14]. The main idea in opportunistic forwarding is to make use of the motion of vehicles to deliver packets. If a vehicle is unable to forward the packet to the next hop, the vehicle does not immediately drop the packet, but instead stores the packet temporarily. When a favorable opportunity occurs, the stored packet is then transmitted to the next hop. For instance, if the vehicle that has stored the packet detects a new neighbor that is closer to the destination, then it forwards it to the new neighbor. Opportunistic forwarding is also known as carry and forward and mobility assisted routing.

Opportunistic forwarding was compared with pessimistic forwarding in [14]. Unlike opportunistic forwarding, in pessimistic forwarding a vehicle immediately drops the packet if the next hop vehicle is not found. At high vehicle densities, the packet delay using both forwarding schemes was close to zero. However with decrease in vehicle density, rate of increase in delay for pessimistic forwarding was significantly much higher than the rate of increase in delay for opportunistic forwarding. This clearly demonstrates that opportunistic forwarding can be very useful in sparse vehicular networks.

In [15], opportunistic forwarding at road intersections has been investigated. In [15] it is assumed that for each road segment, the vehicle densities and average velocities are known beforehand. Let R be the communication range. Let l_{ij} be the length of the road segment between intersection I_i and I_j. Let p_{ij} be vehicle density and v_{ij} be the average vehicle velocity for the road segment. The average inter-vehicle distance is $1/p_{ij}$. The delay d_{ij} for the road segment is calculated as
d_{ij} = propagation delay along the wireless channel, if $1/p_{ij} <= R$
$d_{ij} = (l_{ij}/v_{ij}) - \beta * p_{ij}$, if $1/p_{ij} > R$ where $\beta * p_{ij}$ is a correction factor.

The road segment having the lowest delay is chosen for forwarding the packet. Since vehicular ad hoc networks are unpredictable, the path taken by the packet is not pre-computed but instead dynamically computed throughout the packet forwarding process. By applying the above formulae, wireless transmission among paths with high vehicle density is preferred. In the absence of a wireless transmission path at an intersection, opportunistic forwarding is used and packets are forwarded along the path with the highest average vehicle velocity.

Opportunistic forwarding can also be used for opportunistic resource exchange. A resource is any information about an event indicating the position and the time of the event. For instance, the availability of a parking slot at a particular place and at a particular time can be viewed as a resource. The home of the resource is the place where the event occurred and the age of the resource is the time elapsed since the event occurred. The relevance of a resource decreases as the distance of the vehicle from the home increases and as the age of the resource increases. For instance, as a vehicle moves away from the parking lot or as time since the parking lot information was received increases, the resource becomes stale and less relevant to the vehicle.

In opportunist resource exchange, when two vehicles encounter each other and are within the communication range, they exchange their resources. After the resources exchange, each vehicle computes the relevance of the newly received resources and the old resources. If all resources do not fit into the available memory, the least relevant resources are removed. Using this technique, vehicles can maintain information about only the relevant resources as they move.

To calculate the relevance of a resource, the following equation was used in [16].

$$F(R) = -\alpha.t - \beta.d$$

where t is the age of the resource and d is the distance of the vehicle from the home. α is the time decay factor while β is the distance decay factor. Both α and β are non-negative. The greater the ratio α/β, the higher the sensitivity of relevance to time than to distance. It was also proved that by applying the above technique, a resource is always confined to a bounded area and that beyond an age threshold the resource disappears from the system.

2. Cluster based routing

In cluster based routing, nearby vehicles co-operate with one another and form clusters. All vehicles in the cluster can communicate with one another. Once a cluster is formed, one of the vehicles is chosen as the cluster head to maintain the cluster. New vehicles can join the cluster and current members of the cluster can leave the cluster. To keep the cluster stable, the connectivity of a new vehicle to the cluster may be checked for a threshold time period before admitting the vehicle into the cluster. Once a cluster becomes too large, it can be split to smaller clusters. To elect the cluster head several algorithms have been proposed. Among them, one of the simplest algorithms is the Lowest-ID clustering [17] . In Lowest-ID clustering, each node is assigned a distinct ID which is periodically broadcast to neighbors. A node whose ID is lower than the IDs of its neighbors becomes the cluster head.

The Lowest-ID clustering algorithm forms clusters that have a maximum diameter of 2 hops. The algorithm however is not well suited for vehicular networks since it does not take node mobility into account while choosing the cluster head. If the cluster head has high mobility relative to the vehicles in the cluster then there is a higher likelihood of the cluster breaking.

In [18], the MOBIC clustering algorithm was proposed to overcome the drawbacks of the Lowest-ID algorithm. MOBIC tries to choose the most stable node that has the least mobility relative to the nodes in the cluster as the cluster head. The metric used in MOBIC to determine the cluster head is the variation of received signal power from neighboring nodes. The node that has the least variation in received signal power from neighboring nodes is chosen as the cluster head.

The Lowest-ID algorithm and MOBIC were originally proposed for MANETs. In [19], MOBIC was used for clustering vehicles in VANETs. In [19], each cluster also comprises of a header and a trailer located at the front and rear of the cluster respectively. Intra-cluster communication involves nodes in the cluster sending packets to the header or trailer depending on the direction of the destination of the packet. The header and trailer are responsible for communication with neighboring clusters. Custody transfer mechanism was used in which a packet is buffered at a cluster until an acknowledgement is received from the next hop cluster.

2.3 Applications

1. TrafficView

Vehicles in a vehicular ad hoc network broadcast their positions so that they are aware of each others positions. The TrafficView application has been proposed in [21]. This application displays the traffic on the road to a driver based on the position information exchanged amongst the vehicles. The application can help in avoiding accidents. For instance, if a vehicle is being driven in an area covered with fog, the driver can now get more information about the traffic conditions in his vicinity and hence drive more safely.

2. Abnormal vehicle warning

Co-operative collision warning has been proposed in [22] to warn neighboring vehicles about abnormally moving vehicles. Vehicles on the road may suddenly begin to act abnormally due to an abrupt change in their movement. For instance, if a vehicle suddenly decelerates or stops or suddenly changes direction, the vehicle is treated as an abnormal vehicle. An abnormal vehicle generates Emergency Warning Messages (EWM) to warn surrounding vehicles. An emergency warning message contains details about the vehicles location, speed acceleration and direction of motion.

The presence of an abnormal vehicle influences the movement of neighboring vehicles. For instance, if a vehicle suddenly loses control it sends an Emergency Warning Message. The vehicles that are behind it have to now immediately apply emergency braking. These vehicles now have to give warning messages to their neighbors.

The emergency message delivery delay must be as small as possible (in the order of milliseconds) so that vehicles are informed well in advance. Since the wireless channel is lossy, to ensure that the emergency warning message is reliably delivered to neighboring vehicles, the messages are repeatedly transmitted. A multiplicative rate decreasing algorithm is used for transmitting emergency messages that ensures that vehicles are warned quickly and at the same time the traffic in the network does not get overloaded with emergency warning messages.

3. Regional alerts

[23] addresses the regional alert problem. Given an alert at a particular location, the regional alert problem involves informing all vehicles in the operational radius about the alert before they reach the region enclosed by the safety radius. The alerts are usually about events such as accidents or road conditions in a particular region of the vehicular network.

For instance, consider a vehicle X that drives through a bridge and discovers a patch of ice on the bridge. Vehicle X broadcasts an alert so that its neighbors are informed about the presence of the ice on the bridge. Vehicles which receive the broadcast further propagate the alert so that a vehicle is warned about the ice on the bridge before it enters the safety radius. So once vehicle X leaves the region, some other vehicle (eg. Vehicle Y) must continue to propagate the alert. The alert is not propagated beyond the operating radius.

[23] proposes the Bi-directional Perimeter based Propagation (BiPP) to ensure that vehicles are alerted before they enter the safety radius.To achieve this, a token is maintained for each direction of vehicle movement. A vehicle with the token has information about the alert and periodically broadcasts the alert to disseminate the alert to the vehicles behind it. The token and the alert are passed to the vehicles behind.

4. Information Collection in VANETS

The driver of a vehicle may need to collect information from the area he is in using the vehicular network. For instance, the driver may want to find the available parking slots in the region. [24] investigates information collection for parking slot search. Information collection comprises of the following steps

- Determining the search area and finding the optimal route for the data packet through the search area
- Forwarding the packet in the search area along the optimal route
- Collecting the required information as the packet traverses the search area
- Returning the packet to the vehicle that initiated the search when the search is complete

To compute the route of the packet through the network, the vehicular network can be first considered as a graph with the roads forming the edges and the intersections forming the vertices. The edges in the graph can be assigned weights based on the estimated number of vehicles on the road. For collecting information from all roads in the network, the packet has to be sent through all roads in the network. To accomplish this, the vehicular network graph is now inverted with the roads forming the vertices and the intersections forming the edges. The problem can now be viewed as the Traveling Salesman Problem which involves traversing all vertices at least once. By traversing all the vertices, all roads are covered while collecting information since each road is now represented as a vertex. The Traveling Salesman Problem is then solved to give the optimal route comprising of the sequence of roads that should be traversed by the packet.

5. Cab booking

The EZCab application has been proposed in [20], to allow people to book cabs using short-range wireless communication interfaces on their cell phones or PDAs. Unlike conventional cab booking which involves contacting a centralized cab booking centre, EZCab makes use of ad hoc networks formed of vehicles to book for cabs in the vicinity. The protocol comprises of the cab booking stage and the validation stage. For validation, a challenge response technique based on public key cryptography is used.

In the cab booking phase, the client first sends a request to book a cab along with details such as his current position and intended destination. This request is routed through the ad hoc network of cabs to the currently free cabs. If the driver agrees to pick up the client, then a message indicating details such as the expected arrival time of the cab and the license plate number of the cab are sent to the client. For validation purposes later, the public key of the driver is also sent to the client. On receiving the message from the cab, if the client agrees to hire the cab a message is sent to the cab along with the public key of the client. The cab driver can then drive to the client's location to pickup the client. The protocol ensures that a single cab is assigned to a client.

Timeouts are used at the client and the cab to prevent indefinite waiting. If a time out occurs at the client's device before getting a message from any cab, a new request for cabs is issued into the network. If a timeout occurs at the cab before getting a response from the client, then the cab can be made available to a new client.

When the cab approaches the client, the validation phase begins. The client needs to validate if the cab is indeed the one booked by him. The cab driver also needs to validate if he is picking up the client who had booked the cab earlier. To achieve this, a random number is encrypted using the client's public key to form the challenge. The challenge is sent in a message from the cab to the client. At the client's end, the client's private key is used to decrypt the message. The result for the challenge is computed at the client's side. The result is then encrypted using the cab driver's public key and sent to the cab. At the cab, the driver's private key is used to decrypt the message and verify the result. Thus both the client and cab driver can mutually authenticate each other. The client cannot claim a cab booked by a different person and the driver cannot pickup a client who has booked a different cab.

6. CarTorrent

Car Torrent has been proposed in [3] for co-operative content delivery in vehicular networks. To complement the vehicular ad hoc network, infrastructure networks comprising of gateways along the freeways are being proposed. The typical distance between two successive gateways may be in the range of 5 to 10 miles. Vehicles can download files from the gateways as they drive by the gateways. Some files may be large and cannot be downloaded during the time the vehicle is in range with the gateway. Rather than wait until the next gateway to download the remaining portions of the file, the CarTorrent scheme can be used.

In CarTorrent, as a vehicle comes in range with the gateway, the vehicle initiates a download and begins to download a random chunk of the file. The vehicle also gets a list of peers from the gateway to bootstrap peer discovery by the vehicle. After the vehicle moves out of range from the gateway, the vehicle gossips with its neighbors about availability of content. A gossip message indicates the chunks of files that are available at a vehicle. Gossiping is done using UDP and gossip messages are broadcast to the neighbors. If a vehicle that receives the gossip message is interested in any of the chunks indicated in the message, the vehicle forwards the message with a high probability. Vehicles that are uninterested in the chunks forward the message with a lower probability.

Once a vehicle discovers peers having a chunk of the file it is interested in, the vehicle decides the peer from whom to download. Peer selection can be done using different strategies such as choosing the closest peer, choosing the peer with the rarest chunk, etc. The chunk is obtained from the chosen peer using TCP. Since TCP over multiple hops performs very poorly in wireless networks with more than 4 hops [25], it is better to choose peers which are within 4 to 5 hops for downloading chunks of the file.

Chapter 3

Position Information Dissemination

3.1 Introduction

Position information can be exchanged amongst vehicles so that they are aware of each others location. One of the important problems that needs to be addressed while transmitting position information is determining when the vehicle should transmit its position. If a vehicle informs its position to its neighbors very frequently then too many messages may be generated. If the vehicle informs its position infrequently then the neighboring vehicles may not be aware about its position with the required accuracy.

Once a vehicle broadcasts its position information, the neighbors will not be aware about the change in its position till the next broadcast. Position accuracy of a vehicle is the difference between the actual position of the vehicle and the position of the vehicle as perceived by its neighbors. With increase in the required position accuracy, position messages have to be exchanged more frequently. For instance, more messages have to be transmitted if vehicles should know about each others positions with an accuracy of 1m than an accuracy of 10m.

If the required accuracy is $d_{ACCURACY}$ and the maximum vehicle speed is V_{max}, vehicles can use a simple scheme of exchanging messages periodically every $d_{ACCURACY}/V_{max}$ seconds to ensure that the accuracy requirements are satisfied. To prevent all vehicles from broadcasting their positions at the same time, simple randomization techniques can be applied. For instance, the time when the first position message is broadcast by each vehicle can be randomized. Another technique that can be applied involves picking a time interval of broadcast uniformly in the range $[\frac{d_{ACCURACY}}{V_{max}} - \delta, \frac{d_{ACCURACY}}{V_{max}}]$

The problem with the periodic broadcast scheme is that when $d_{ACCURACY}$ is in the range of a few meters the number of messages exchanged will be significantly high. Consider the case where the required position accuracy, $d_{ACCURACY}$, is 1 meter. Let V_{max} be 30 meters/second (108 km/h). Using the simple periodic broadcast scheme of sending position information messages every $d_{ACCURACY}/V_{max}$ seconds, the rate of messages sent by a single vehicle is 30 messages/second. Let the size of each message be 100 bytes. So each vehicle generates about 3000 bytes/s. Let the wireless communication range R be 250 meters. Let the number of lanes be 6 (3 in each direction). Assuming an average inter vehicle distance of 5 meters, the total number of vehicles in each lane over a length equal to the communication range R is 250/5 = 50 vehicles. The total number of vehicles in all lanes in a region of length R = 50 * 6 = 300 vehicles. The total amount of traffic generated in a region with length equal to R = number of vehicles * traffic generated by each vehicle = 300 * 3000 = 900,000 bytes/s = 6.86 Mbps.

The total bandwidth available in the proposed DSRC scheme is between 9 Mbps to 27 Mbps. This shows that using a simple periodic broadcast scheme, a significant amount of the available bandwidth can be used up. In our work, we tackle the problem of determining when a vehicle should transmit its position so that the required position accuracy is maintained and at the same time number of messages that need to be transmitted is reduced.

3.2 Related Work

TrafficView [21] application displays the position of vehicles to the driver. TrafficView makes use of multi-hop communication to disseminate the position information of the vehicles. Consider the case where each vehicle is interested in knowing the position of vehicles over a 20 km road stretch. If the inter vehicle distance is 5 meters, the number of vehicles over a 20 km stretch of road in a single lane is 4000. For 5 lanes of traffic the number of vehicles is 20,000. Assuming that each position message is 50 bytes, the total number amount space needed to store the position information in one vehicle about all vehicles within a 20 km stretch of road is 1 MB. The number of vehicles in the 5 lanes over a region of length 250 meters is 250. So, for a transmission range of 250 meters, 250 vehicles will be contending for the wireless medium. If each vehicle forwards the information of all vehicles in the 20 km stretch every time interval, the amount of data transmitted in a region of 250 meters is 250 MB for every broadcast period. Thus the amount of data transmitted every broadcast period is significantly high and can exceed the available bandwidth.

TrafficView solved this problem by reducing the amount of data transmitted over multiple hops using data aggregation schemes. The basic idea used is that if two vehicles are close together and have similar speeds, then the position information of the two vehicles can be aggregated with little error. A record for a vehicle consists of vehicle identification field (ID) , current vehicle position (POS) , vehicle speed (SPD) and a global broadcast time (BT) which indicates when the record was transmitted by a vehicle. The records (ID1, POS_1, SPD_1, BT_1) (ID_n, POS_n, SPD_n, BT_n) are aggregated into a single record (ID_1,, ID_n, POS_a, SPD_a, BT_a) according to the formulae below (d_i is the estimated distance between the vehicle ID_i and the current vehicle)

$$POS_a = \Sigma_{i=1}^{n} \alpha_i * POS_i$$

$$SPD_a = \Sigma_{i=1}^{n} \alpha_i * SPD_i$$

$$BT_a = min(BT_1, ..., BT_n)$$

$$\alpha_i = \frac{(\Sigma_{i=1}^{n} d_i) - d_i}{(n-1)\Sigma_{i=1}^{n} d_i}$$

Given a list of records, the records are aggregated and then stored in a fixed size message which is broadcast at regular intervals. To determine which records are aggregated, two aggregation algorithms (ratio based aggregation and cost based aggregation) have been proposed. In ratio based aggregation algorithm, the road is divided into regions (r_i) and an aggregation ratio (a_i) is assigned for each of the regions. Aggregation ratio indicates the number of records that would be aggregated into a single record. Given a fixed length message, each region is assigned a portion p_i ($0 < p_i < 1$) in the message. The role of the ratio based algorithm is to determine the road boundaries for the regions and the merging thresholds for the regions. A set of consecutive records in a region will be merged if the distance between the first and last record is less than the merging threshold.

The ratio based aggregation algorithm does not take into account the cost of aggregating two records. This is taken care of in the cost based aggregation algorithm. If d_1 and d_2 are the distances between the current vehicle (which is going to broadcast the message) and the vehicles represented in the two records, s_1 and s_2 are the number of vehicles in the two records and d_a is the distance between the current vehicle and the group of vehicles in the two records after aggregation, the cost of aggregating the two records is

$$cost = \frac{\mid d_1 - d_a \mid * s_1 + \mid d_2 - d_a \mid * s_2}{d_a}$$

The algorithm works by continuously merging the two records that have the least cost until the desired aggregation ratio for a region is achieved. If the cost of aggregating two records exceeds a threshold, the aggregation for the region stops. The aggregated records are then filled in the portion of the message reserved for the region. This procedure is repeated for all the regions.

The size of each message is limited to 2312 bytes in both aggregation algorithms. One obvious disadvantage using the aggregation algorithms is the loss of actual position information. So the aggregation ratios are chosen such that for nearby regions, fewer records are aggregated into a single record resulting in a smaller error in position accuracy of nearby vehicles.

Although TrafficView solved the problem of decreasing the traffic when transmitting position information over multiple hops, the time period of broadcast was fixed. The broadcast period is selected uniformly in the range [1.75 , 2.25] seconds. No rationale has been provided for choosing this value. In our work we try to address the problem of determining the time interval between two successive broadcasts The work in TrafficView [21] focused on reducing multi-hop traffic using aggregation, our primary focus is to ensure that a vehicle is aware of the position of its single hop neighbors with required position accuracy and at the same time reduce the number of position messages transmitted in the network.

In [27], the Speed Dependent Random Protocol was proposed for disseminating position information among vehicles. The time interval for transmitting position information is chosen from a random time interval based on the speed of the vehicle. For instance, for vehicles traveling with speed less than 30 km/h the time interval is chosen randomly in the range (2 seconds, 4 seconds) and if the speed is greater than 30 km/h the time interval is chosen randomly in the range (1 second, 2 seconds). The idea is that faster vehicles should inform their positions with a shorter time interval. Simulations were performed for different combinations of time intervals.

Motion prediction has been applied in MANETs and VANETs for routing. In [28], mobility prediction has been used for predicting the link expiration time and route expiration time in MANETs. In [29], the Prediction Based Routing protocol for VANETs has been proposed to predict how long a route will last between a vehicle and a gateway and to proactively create new routes before existing routes fail. Using mobility prediction to predict the position of the destination and next hop neighbors to improve performance of geographic routing protocols such as GPSR has been studied in [30].

The use of velocity prediction to determine the time interval of position message broadcasts has been suggested in [31]. However, no theoretical analysis of the worst case of velocity prediction has been performed. The effect of packet loss on position accuracy has not been investigated. To solve the problem of a vehicle not informing its position if it moves at uniform velocity, On-Demand Learning is used. In On-Demand Learning, when a node overhears a new neighbor, it transmits its position to inform the new neighbor. However, even with On-Demand Learning, the scenario where two nearby vehicles are not aware of each other's presence cannot be completely ruled out.

3.3 Schemes for position information dissemination

Apart from the periodic broadcast scheme, the following schemes can be used for position information dissemination:

1. Distance based position broadcast: In this scheme each vehicle broadcasts its position on covering a distance of $d_{ACCURACY}$. Since all vehicles may not travel with a speed of V_{max}, vehicles may take more time to transmit a position message while still ensuring that the position accuracy is $d_{ACCURACY}$. The algorithm for the distance based scheme is given below

Algorithm 1 Algorithm for the Distance Based Scheme

```
while (vehicle is on the road) do
    d_ACTUAL ← actual distance covered by vehicle since the previous position broadcast
    if (d_ACTUAL ≥ d_ACCURACY) then
        Send position message
    end if
    sleep(δt)
end while
```

2. Velocity prediction based position broadcast: In this scheme, each vehicle transmits its position, current speed and direction in a position message. The speed and direction in the message can be treated as the predicted speed and predicted direction till the next broadcast by the vehicle. Neighboring vehicles predict the position of the vehicle based on the speed and direction indicated in the message and the road layout that is provided by a digital map. The vehicle which sent the position message also computes the predicted position of itself. When the difference between the predicted position and its actual position is $d_{ACCURACY}$, the vehicle transmits a new position message. The algorithm for this scheme is given below

Algorithm 2 Algorithm for the Velocity Prediction Scheme

1: **while** (vehicle is on the road) **do**
2: $P_{ACTUAL} \leftarrow$ current position of the vehicle
3: $P_{PREDICTED} \leftarrow$ predicted position of the vehicle based on $V_{predicted}$, direction indicated in previous message.
4: $d_{ERROR} \leftarrow$ distance between $P_{PREDICTED}$ and P_{ACTUAL}.
5: **if** $(d_{ERROR} \geq d_{ACCURACY})$ **then**
6: Send position message with current position, current speed and current direction
7: $V_{predicted} \leftarrow$ current speed
8: **end if**
9: sleep(δt)
10: **end while**

3.4 Theoretical performance comparison of the position information dissemination schemes

Performance is analyzed based on the number of position messages transmitted in the vehicular network. The periodic broadcast scheme is the simplest to analyze and the performance in this scheme doesn't depend on the traffic conditions. The performance of distance based and velocity prediction schemes depends on the traffic conditions.

We compare the periodic broadcast scheme, the worst case of the distance based scheme and the worst case of the velocity prediction scheme. To simplify the theoretical performance analysis we don't take into account lane change and change in direction of vehicles. For the distance based scheme, the worst case occurs when the all vehicles move at the maximum speed V_{max}. This essentially reduces to the periodic broadcast scheme. The worst case for the velocity prediction scheme occurs when the distance between the predicted position and the actual position covered by the vehicle is maximum. This occurs when a vehicle having zero speed, broadcasts the position message and accelerates at the maximum rate of acceleration a_{max} until it reaches the speed V_{max}.

Let the time interval between two consecutive position message broadcasts for the worst case of the velocity prediction scheme be t_v and the rate of messages transmitted in the network per vehicle be N_v. Let the time interval between two consecutive position broadcasts for the worst case of the distance based scheme be t_d and rate of messages transmitted in the network per vehicle be N_d. Let the time interval between two consecutive position broadcasts for the worst case of the periodic broadcast scheme be t_p and rate of messages transmitted in the network per vehicle be N_p. Since the worst case of the distance based scheme is the same as the periodic scheme, $t_d = t_p$ and $N_d = N_p$.

Theorem 1: When $t_v \leq V_{max}/a_{max}$, $N_d/N_v = \sqrt{2} * V_{max}/\sqrt{a_{max} * d_{ACCURACY}}$

Proof: Consider case 1, where $t_v \leq V_{max}/a_{max}$. In the velocity prediction scheme, a vehicle transmits its position if the distance between the predicted position and the actual position is $d_{ACCURACY}$. In the worst case for the velocity prediction scheme, a vehicle that starts with zero initial speed, broadcasts the position message and accelerates at a_{max}. If $t_v \leq V_{max}/a_{max}$ the difference between predicted position and actual position is $\frac{1}{2}a_{max}t_v^2$.

$$\frac{1}{2}a_{max}t_v^2 = d_{ACCURACY} \tag{3.1}$$

$$t_v = \sqrt{\frac{2d_{ACCURACY}}{a_{max}}}$$

For the distance based scheme, a position message is sent by each vehicle at a time interval of $d_{ACCURACY}/V_{max}$. So

$$t_d = \frac{d_{ACCURACY}}{V_{max}}$$

$$\frac{t_v}{t_d} = \sqrt{\frac{2d_{ACCURACY}}{a_{max}}} * \frac{V_{max}}{d_{ACCURACY}}$$

$$\frac{t_v}{t_d} = \frac{\sqrt{2}V_{max}}{\sqrt{a_{max}d_{ACCURACY}}}$$

Since $N_v = 1/t_v$ and $N_d = 1/t_d$

$$\frac{N_d}{N_v} = \frac{\sqrt{2}V_{max}}{\sqrt{a_{max}d_{ACCURACY}}} \tag{3.2}$$

This proves Theorem 1.

Since $N_d = N_p$

$$\frac{N_p}{N_v} = \frac{\sqrt{2}V_{max}}{\sqrt{a_{max}d_{ACCURACY}}}$$

Theorem 2: When $t_v \leq V_{max}/a_{max}$, $N_d \geq 2N_v$

Proof: Equation 3.2 can also be expressed in an alternate form by considering the variable d_{max} which is the distance covered by a vehicle starting with zero velocity and accelerating at a_{max} until it reaches the velocity V_{max}. The time taken by a vehicle starting at zero velocity and accelerating at a_{max} to reach maximum velocity V_{max} is V_{max}/a_{max}. So

$$d_{max} = \frac{1}{2}a_{max}\left(\frac{V_{max}}{a_{max}}\right)^2$$

$$d_{max} = \frac{V_{max}^2}{2a_{max}}$$

Substituting for $V_{max} = \sqrt{2a_{max}d_{max}}$ in equation 3.2 we have

$$\frac{N_d}{N_v} = 2\sqrt{\frac{d_{max}}{d_{ACCURACY}}} \tag{3.3}$$

From 3.1 we have

$$d_{ACCURACY} = \frac{1}{2}a_{max}t_v^2$$

Since $t_v \leq V_{max}/a_{max}$

$$d_{ACCURACY} \leq \frac{V_{max}^2}{2a_{max}}$$

$$\Rightarrow d_{ACCURACY} \leq d_{max}$$

Since $d_{max} \geq d_{ACCURACY}$, we observe from equation 3.3 that $N_d \geq 2N_v$. This proves the theorem.

Since $t_v = 1/N_v$ and $t_d = 1/N_d$, $t_v \geq 2t_d$. Also since $N_p = N_d$, $N_p \geq 2N_v$ and $t_v \geq 2t_p$. So worst case analysis indicates that the rate of position messages transmitted per vehicle using the periodic broadcast scheme and distance based scheme is greater than the velocity based prediction scheme when $t_v \leq V_{max}/a_{max}$.

Theorem 3: When $t_v \geq V_{max}/a_{max}$, $N_d/N_v = (V_{max}^2 + 2a_{max}d_{ACCURACY})/2a_{max}d_{ACCURACY}$

In the velocity prediction scheme, a vehicle transmits its position if the distance between the predicted position and the actual position is $d_{ACCURACY}$. In the worst case for the velocity prediction scheme, when $t_v \geq V_{max}/a_{max}$, a vehicle starts with zero initial speed, broadcasts the position message and then accelerates at a_{max} , reaches a speed of V_{max} and continues at speed V_{max}. Let the time interval when the vehicle accelerates to reach V_{max} from zero speed be t_{v_a} ($t_{v_a} = V_{max}/a_{max}$). Let the time interval the vehicle moves at speed V_{max} be t_{v_b}. So $t_v = t_{v_a} + t_{v_b}$.

$d_{ACCURACY}$ = distance traveled during time interval t_v

$d_{ACCURACY}$ = distance traveled during time interval t_{v_a} + distance traveled during time interval t_{v_b}.

$$d_{ACCURACY} = \frac{1}{2}a_{max}t_{v_a}^2 + V_{max}t_{v_b}$$

Substituting $t_{v_a} = V_{max}/a_{max}$,

$$d_{ACCURACY} = \frac{1}{2}a_{max}\left(\frac{V_{max}}{a_{max}}\right)^2 + V_{max}t_{v_b}$$

$$t_{v_b} = \frac{d_{ACCURACY} - \frac{V_{max}^2}{2a_{max}}}{V_{max}}$$

$t_v = t_{v_a} + t_{v_b}$. Substituting for t_{v_a} and t_{v_b}

$$t_v = \frac{V_{max}}{a_{max}} + \frac{d_{ACCURACY} - \frac{V_{max}^2}{2a_{max}}}{V_{max}}$$

$$t_v = \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}V_{max}}$$

Since $t_d = d_{ACCURACY}/V_{max}$

$$\frac{t_v}{t_d} = \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}V_{max}} * \frac{V_{max}}{d_{ACCURACY}}$$

$$\frac{t_v}{t_d} = \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}d_{ACCURACY}}$$

Since $N_v = 1/t_v$ and $N_d = 1/t_d$

$$\frac{N_d}{N_v} = \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}d_{ACCURACY}}$$

This proves Theorem 3.

Since $N_p = N_d$, it follows that

$$\frac{N_p}{N_v} = \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}d_{ACCURACY}}$$

From the equations it is obvious that $N_d > N_v$ and $N_p > N_v$. Since $t_v = 1/N_v$, $t_d = 1/N_d$ and $t_p = 1/N_p$, $t_v > t_d$ and $t_v > t_p$.

To estimate a good practical value for a_{max}, the data available for the BMW Mini Cooper was used. The BMW Mini Cooper achieves an acceleration of 0 to 26.7 m/s (96 km/h) in 4.5 seconds. Assuming uniform acceleration, $a_{max} = (v - u)/t, a_{max} = 26.7/4.5 = 5.93m/s^2$.

Figure 3.1 shows the ratio N_d/N_v when V_{max} is 30 m/s (108 km/h) and a_{max} is 6 m/s^2. It is interesting to note from the figure that when $d_{ACCURACY} = 1$m, N_d/N_v

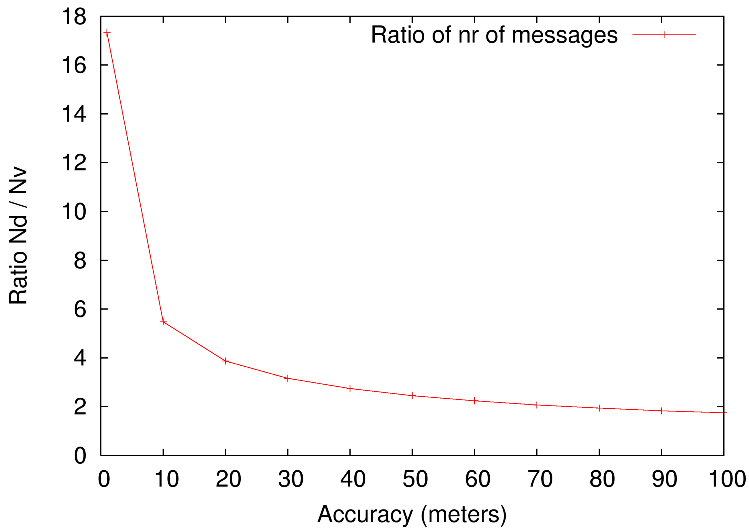


Figure 3.1: Ratio of message transmission rates for proposed schemes

= 17.32. So when $d_{ACCURACY}$ is 1 meter, the periodic broadcast scheme and the worst case of the distance based scheme send more than 17 times the number of packets sent by the worst case of the velocity prediction scheme. This clearly shows when $d_{ACCURACY}$ is small, in the range of a few meters, the velocity prediction scheme significantly outperforms the periodic broadcast scheme and the distance based scheme.

3.5 Informing position to new neighbors

One of the problems faced by using the distance based scheme and velocity prediction scheme is that in both schemes the vehicles may not broadcast their position information for an indefinite period of time. For instance in the distance based scheme, if a vehicle doesn't move then it will not broadcast its position information.

In the velocity prediction scheme if the vehicle moves at uniform velocity then the vehicle will not broadcast its position. Due to this problem, new vehicles that were originally out of range may not be informed about the vehicle's position. Clearly this is not desirable.

One possible solution to this problem is to forward the position of the vehicle over multi-hops so that the vehicles that are outside range of the vehicle are made aware of the vehicle. However if the vehicular network is sparse and there are no neighbors within range of the vehicle to forward the information over multi-hops then the problem still remains.

So we instead use the approach where each vehicle informs its position to its single hop neighbors while ensuring that new vehicles are informed before the inter-vehicle distance decreases below a pre-specified distance $d_{INTEREST}$.

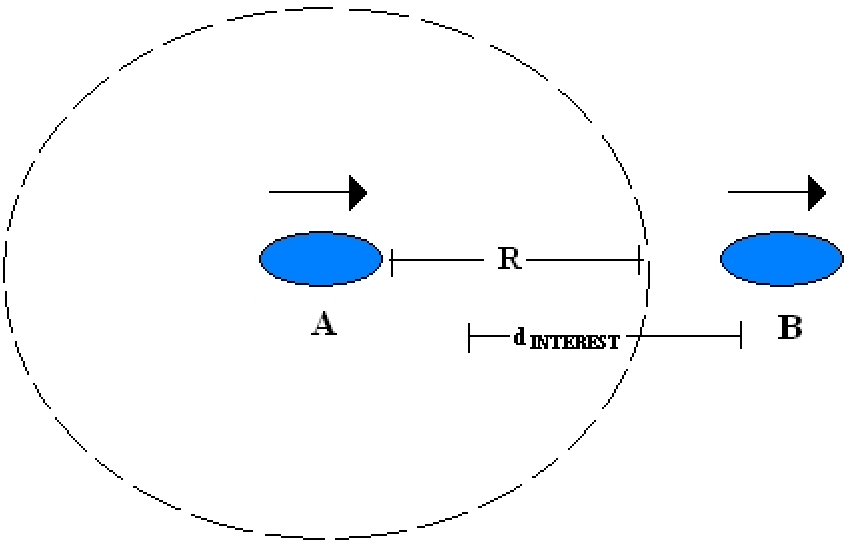


Figure 3.2: Vehicles should inform each other before inter vehicle distance is $d_{INTEREST}$

For instance, consider Figure 3.2. Initially Vehicle A and Vehicle B are outside the communication range of each other and are unaware of each others positions. By the time Vehicle A moves within a distance of $d_{INTEREST}$ of Vehicle B, Vehicle A and Vehicle B should be aware about each other.

Let the maximum possible velocity = V_{max}. Let the transmission range = R Let the time when the $Vehicle_i$ should next inform its position = T_i. The problem involves ensuring that for any pair of vehicles $Vehicle_i$ and $Vehicle_j$, $Vehicle_j$ knows about $Vehicle_i$ (and vice versa) before the distance between $Vehicle_i$ and $Vehicle_j$ is falls below $d_{INTEREST}$. Clearly $d_{INTEREST} < R$ if we use only single hop communication. T_i is the time interval when $Vehicle_i$ will next transmit its position information. The instantaneous speed of $Vehicle_i$ can vary with time. So we instead use the average speed of $Vehicle_i$ V_i at any instant of time defined as

V_i = total distance traveled by $Vehicle_i$ / total time taken by $Vehicle_i$.

Lemma 1: Given a group of vehicles just outside the range of $Vehicle_i$ moving towards $Vehicle_i$ at speed V_{max} in any possible direction, the inter-vehicle distance between $Vehicle_i$ and any vehicle in the group is minimum for the vehicle moving in the opposite direction.

Consider the figure 3.3. Let $Vehicle_i$ initially be at O. Circle C1 represents the communication range of $Vehicle_i$. Vehicles outside the communication range move

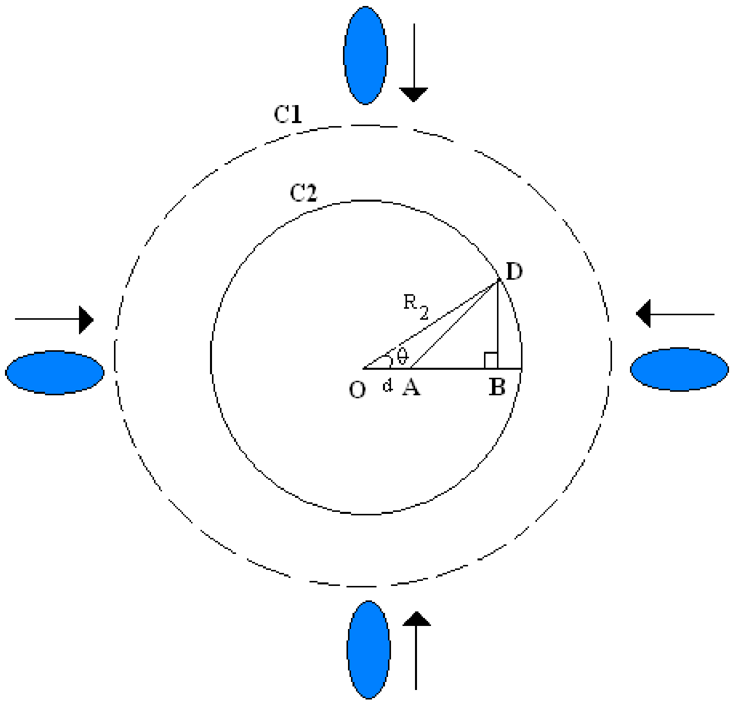


Figure 3.3: General case

towards $Vehicle_i$ at speed V_{max} in any possible direction. After a time instant δT, $Vehicle_i$ moves a distance of d and reaches the position A and the vehicles that were initially outside the communication range reach the edge of the circle C2.

Let $OA = d$. Let D be any point on C2. Let $OD = R_2$. Let angle AOD = θ. $OB = R_2 cos\theta$. $BD = R_2 sin\theta$

Since AB = OB - OA

$$AB = R_2 cos\theta - d$$

The inter vehicle distance between $Vehicle_i$ and a vehicle at D = AD. Applying Pythagoras theorem

$$AD^2 = AB^2 + BD^2$$

$$AD = \sqrt{(R_2 cos\theta - d)^2 + (R_2 sin\theta)^2}$$

$$AD = \sqrt{R_2^2 + d^2 - 2dR_2 cos\theta}$$

To find the maximum and minimum value for AD, we differentiate wrt θ.

$$\frac{d}{d\theta}\left(\sqrt{R_2^2 + d^2 - 2dR_2 cos\theta}\right) = 0$$

$$\Rightarrow sin\theta = 0$$

$$\Rightarrow \theta = 0 \; or \; \theta = \pi$$

Substituting the obtained values for θ we find that when $\theta = \pi$, inter vehicle distance $= \sqrt{R_2^2 + d^2 + 2dR_2}$. When $\theta = 0$, inter-vehicle distance $= \sqrt{R_2^2 + d^2 - 2dR_2}$

So the minimum value for inter vehicle distance occurs when $\theta = 0$. This corresponds to the vehicle moving in the opposite direction.

Lemma 2. If $Vehicle_i$ has to inform its position to new neighbors moving in any direction before the inter-vehicle distance falls below $d_{INTEREST}$ then it is sufficient that $T_i = (R - d_{INTEREST})/2V_{max}$

From Lemma 1 we know that amongst vehicles moving from outside the range of $Vehicle_i$ in any possible directions towards $Vehicle_i$, $Vehicle_i$ will first come within a distance of $d_{INTEREST}$ with the vehicle moving in the opposite direction. If $Vehicle_i$ informs the vehicle coming in the opposite direction before the inter-vehicle distance is $d_{INTEREST}$, then all other vehicles are also informed before their inter-vehicle distance with $Vehicle_i$ falls below $d_{INTEREST}$. So it is sufficient that we consider the vehicle moving in the opposite direction.

$$(V_i * T_i) + (V_{max} * T_i) = R - d_{INTEREST}$$

$$T_i = (R - d_{INTEREST})/(V_{max} + V_i)$$

The minimum value for T_i occurs when $V_i = V_{max}$. So it is sufficient that $T_i = (R - d_{INTEREST})/2V_{max}$.

The time interval between two consecutive position message broadcasts for the worst case of the velocity prediction scheme is t_v. By ensuring that vehicles also inform new neighbors by the time their inter-vehicle distance is $d_{INTEREST}$, t_v is now

$$t_v = min\left(\sqrt{\frac{2d_{ACCURACY}}{a_{max}}}, \frac{R - d_{INTEREST}}{2V_{max}}\right) when\ t_v \leq V_{max}/a_{max}$$

$$t_v = min\left(\frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}V_{max}}, \frac{R - d_{INTEREST}}{2V_{max}}\right) when\ t_v \geq V_{max}/a_{max}$$

Observing the values for t_v when $t_v \leq V_{max}/a_{max}$ and $t_v \geq V_{max}/a_{max}$ we have

$$\sqrt{\frac{2d_{ACCURACY}}{a_{max}}} \leq \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}V_{max}}$$

The time interval between two consecutive position message broadcasts for the worst case of the distance based scheme is t_d. By ensuring that vehicles also inform new neighbors by the time their inter-vehicle distance is $d_{INTEREST}$, t_d is now

$$t_d = min\left(\frac{d_{ACCURACY}}{V_{max}}, \frac{R - d_{INTEREST}}{2V_{max}}\right)$$

We already know from Theorem 2 and Theorem 3 that

$$\frac{d_{ACCURACY}}{V_{max}} < \sqrt{\frac{2d_{ACCURACY}}{a_{max}}}$$

and

$$\frac{d_{ACCURACY}}{V_{max}} < \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}V_{max}}$$

Putting all the equations together we have

$$\frac{d_{ACCURACY}}{V_{max}} < \sqrt{\frac{2d_{ACCURACY}}{a_{max}}} \leq \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}V_{max}}$$

So if we choose $d_{INTEREST}$ such that

$$\frac{d_{ACCURACY}}{V_{max}} < \sqrt{\frac{2d_{ACCURACY}}{a_{max}}} \leq \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}V_{max}} < \frac{R - d_{INTEREST}}{2V_{max}}$$

then the worst case results obtained in Theorem 1, 2 and 3 for the distance based scheme and velocity prediction scheme do not deteriorate further.

$$\Rightarrow \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{2a_{max}V_{max}} < \frac{R - d_{INTEREST}}{2V_{max}}$$

$$\frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{a_{max}} < R - d_{INTEREST}$$

$$d_{INTEREST} < R - \frac{V_{max}^2 + 2a_{max}d_{ACCURACY}}{a_{max}}$$

3.6 Overall algorithms

Taking into account informing vehicle position with the required accuracy and informing new neighbors before the inter-vehicle distance decreases below $d_{INTEREST}$, the overall distance based scheme and velocity prediction scheme are given below.

Algorithm 3 Algorithm for the Distance Based Scheme

while (vehicle is on the road) **do**
  $T \leftarrow$ time since previous position broadcast.
  $d_{ACTUAL} \leftarrow$ actual distance covered by vehicle since the previous position broadcast
  if $(d_{ACTUAL} \geq d_{ACCURACY})$ OR $(R - d_{ACTUAL} - V_{max} * T \leq d_{INTEREST})$ **then**
    Send position message
  end if
  sleep(δt)
end while

Algorithm 4 Algorithm for the Velocity Prediction Scheme

while (vehicle is on the road) **do**
  $T \leftarrow$ time since previous position broadcast.
  $d_{ACTUAL} \leftarrow$ actual distance covered by vehicle since the previous position broadcast
  $P_{ACTUAL} \leftarrow$ current position of the vehicle
  $P_{PREDICTED} \leftarrow$ predicted position of the vehicle based on $V_{predicted}$ and direction indicated in previous message.
  $d_{ERROR} \leftarrow$ distance between $P_{PREDICTED}$ and P_{ACTUAL}.
  if $(d_{ERROR} \geq d_{ACCURACY})$ OR $(R - d_{ACTUAL} - V_{max} * T \leq d_{INTEREST})$ **then**
    Send position message with current position, current speed and current direction
    $V_{predicted} \leftarrow$ current speed
  end if
  sleep(δt)
end while

Chapter 4

Simulation and Results

4.1 Modeling traffic movement

Two simulation models, the normal model and the accelerate-decelerate model were constructed to compare the periodic, distance based and velocity prediction schemes. The normal model tries to simulate realistic traffic conditions on highways. Vehicle overtaking and lane change are built into the model. The algorithm for the traffic model is given in Algorithm 5.

To study the robustness of the three schemes the accelerate-decelerate model was developed where vehicles continuously accelerate at the maximum rate of acceleration ($6m/s^2$) to reach the maximum velocity (30 m/s), then decelerate to at maximum rate of deceleration ($6m/s^2$) to reach the minimum velocity (2 m/s) and continue this cycle. The velocity prediction scheme has the worst performance when a vehicle continuously changes velocity. The accelerate-decelerate model helps in studying how the velocity prediction scheme performs in its worst case.

Algorithm 5 Algorithm for the modeling normal traffic movement

$V_{i_{max}} \leftarrow$ maximum speed of $Vehicle_i$
$V_i \leftarrow$ current speed of $Vehicle_i$
$a_{max} \leftarrow$ maximum acceleration
$T \leftarrow$ current time
$T_{stop} \leftarrow$ simulation stop time
$\Delta T \leftarrow$ time increment
while $(T < T_{stop})$ **do**
    Sort the vehicles based on their positions
    for all $Vehicle_i$ **do**
        $V_i \leftarrow V_i + a_{max} * \Delta T$
        if $(V_i > V_{i_{max}})$ **then**
            $V_i \leftarrow$ uniform random value in the range $(V_{i_{max}} - a_{max} * \Delta T, V_{i_{max}})$
        end if
        if (collision between $Vehicle_i$ and vehicle ahead in same lane is possible) **then**
            if ($Vehicle_i$ can move into a new lane) **then**
                change the lane of the $Vehicle_i$
            else
                slow down $Vehicle_i$ to the speed of the vehicle ahead
            end if
        end if
        update the position of $Vehicle_i$
    end for
    $T \leftarrow T + \Delta T$
end while

4.2 Simulation using NS2

The periodic broadcast scheme, distance based scheme and velocity prediction scheme were implemented and simulated using the network simulator NS2. The simulations comprised of 4 lanes of traffic, 2 lanes for each direction. Half a kilometer stretch of road was used for the simulations. The initial positions of vehicles are randomized. As the vehicles reach the end of the stretch of the road, the vehicles loop back to the beginning of the road. Each vehicle is assigned a separate maximum speed. The maximum speed of a vehicle is chosen using a normal distribution with mean speed of 25 m/s with a standard deviation of 5 m/s. The maximum speed of any vehicle cannot exceed 30 m/s (108 km/h). The maximum vehicle acceleration is 6 m/s^2.

To ensure that all vehicles don't transmit their position messages at the same time, the time when a vehicle transmits its first position message is explicitly randomized for the periodic scheme. No explicit randomization is applied for the distance based scheme and velocity prediction scheme.

The number of vehicles was varied from 10 to 100. $d_{ACCURACY}$ is varied from 1 to 10 meters. $d_{INTEREST}$ is taken to be 125 meters. The simulations were run on 802.11 MAC with a range of 250 meters and bandwidth of 2 Mbps. The size of the application layer packet is 60 bytes. The duration of each simulation is 100 seconds.

The total number of messages transmitted in the network, the average packet delay and the position error due to packet loss were measured.

4.3 Results

Figure 4.1 show the results for the periodic broadcast, distance based and velocity prediction scheme for the normal simulation model. From the figure we observe that the velocity prediction scheme transmits the least number of of position messages.

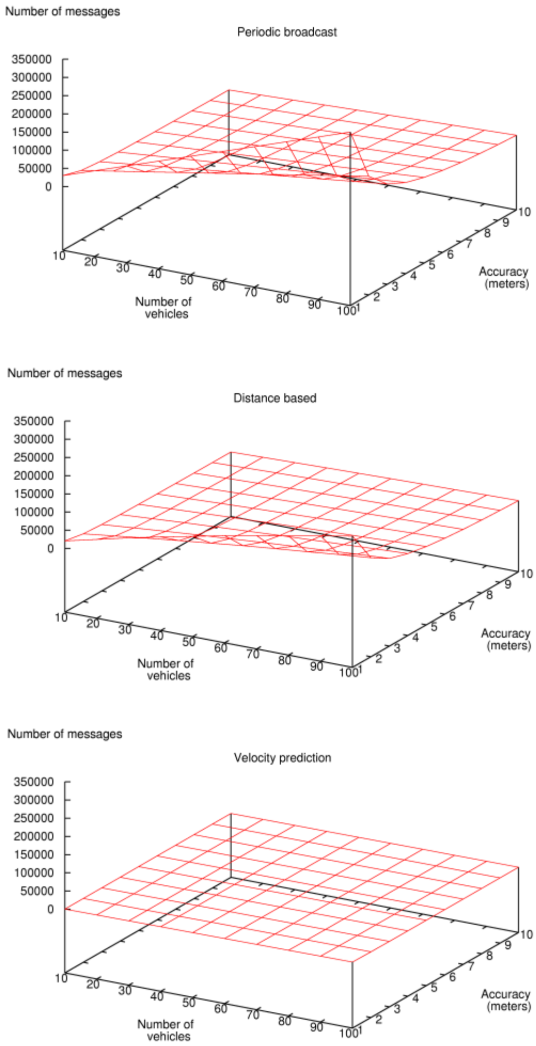
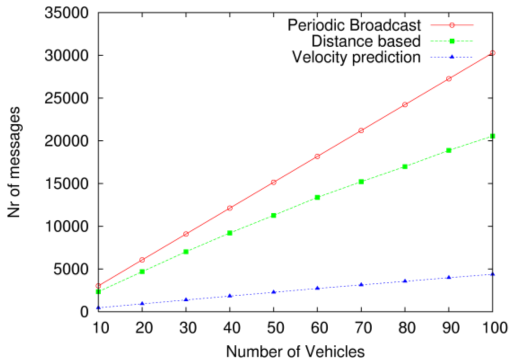
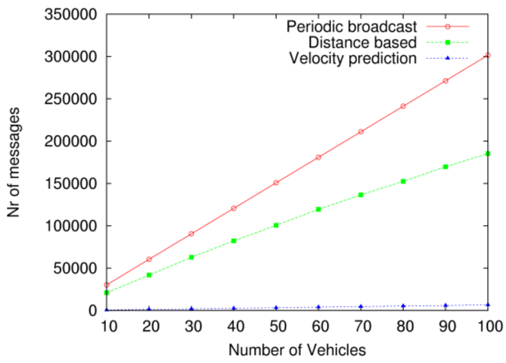


Figure 4.1: Number of messages transmitted in the normal model



(a) Accuracy = 10m

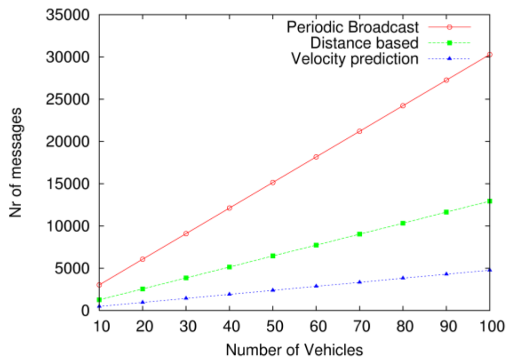


(b) Accuracy = 1m

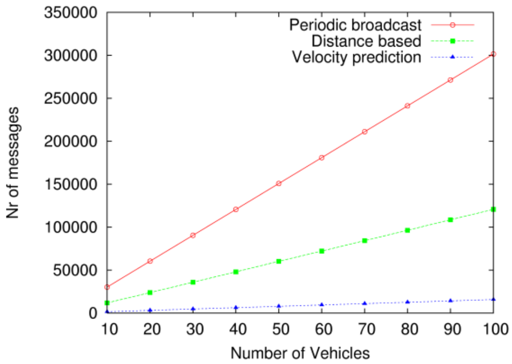
Figure 4.2: Number of messages transmitted in normal model

Figure 4.2(a) shows the total number of messages transmitted in the network during a period of 100 seconds in the normal model when $d_{ACCURACY}$ is 10 meters. When there are 100 vehicles in the network, the periodic broadcast scheme transmits more than 6 times the number of messages transmitted by the velocity prediction scheme and the distance based scheme transmits more than 4 times the number of messages transmitted by the velocity prediction scheme.

Figure 4.2(b) shows the total number of messages transmitted in the network during a period of 100 seconds in the normal model when $d_{ACCURACY}$ is 1 meter. When there are 100 vehicles in the network, the periodic broadcast scheme transmits about 45 times the number of messages transmitted by the velocity prediction scheme and the distance based scheme transmits about 28 times the number of messages transmitted by the velocity prediction scheme.



(a) Accuracy = 10m

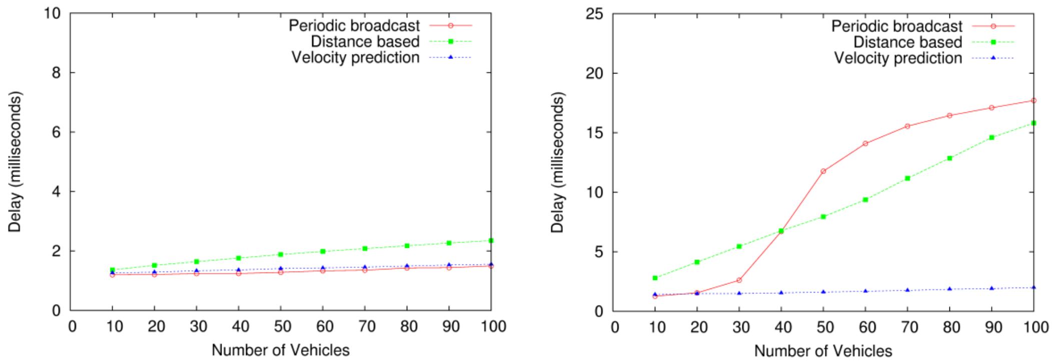


(b) Accuracy = 1m

Figure 4.3: Number of messages transmitted in Accelerate-Decelerate model

Figure 4.3(a) shows the total number of messages transmitted in the network during a period of 100 seconds in the accelerate-decelerate model when $d_{ACCURACY}$ is 10 meters. When there are 100 vehicles in the network, the periodic broadcast scheme transmits more than 6 times the number of messages transmitted by the velocity prediction scheme and the distance based scheme transmits more than 2 times the number of messages transmitted by the velocity prediction scheme.

Figure 4.3(b) shows the total number of messages transmitted in the network during a period of 100 seconds in the accelerate-decelerate model when $d_{ACCURACY}$ is 1 meter. When there are 100 vehicles in the network, the periodic broadcast scheme transmits about 18 times the number of messages transmitted by the velocity prediction scheme and the distance based scheme transmits about 7 times the number of messages transmitted by the velocity prediction scheme.

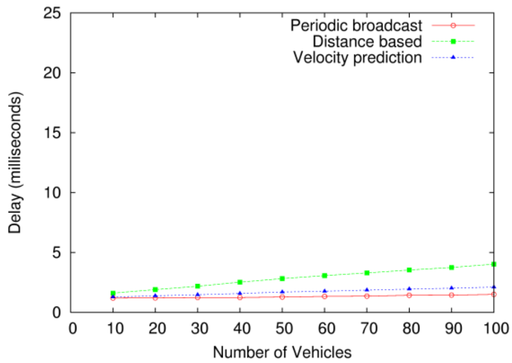


(a) Accuracy = 10m (b) Accuracy = 1m

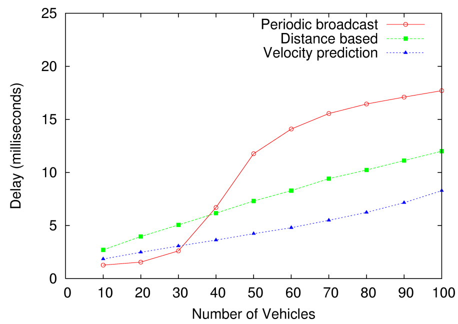
Figure 4.4: Average delay in normal model

Figure 4.4(a) shows the average delay in the normal model when $d_{ACCURACY}$ is 10 meters. The average delay of all the 3 schemes is comparable with the periodic broadcast scheme performing slightly better than the velocity prediction and periodic broadcast schemes. There is no significant rise in the delay as the number of vehicles in the network increases.

Figure 4.4(b) shows the average delay in the normal model when $d_{ACCURACY}$ is 1 meter. The velocity prediction scheme performs better than the distance based scheme and the periodic broadcast scheme. The average delay for the velocity prediction scheme is relatively the same even with increase in the number of vehicles, whereas the average delay for the periodic and distance based schemes increases with increase in number of vehicles in the network.



(a) Accuracy = 10m

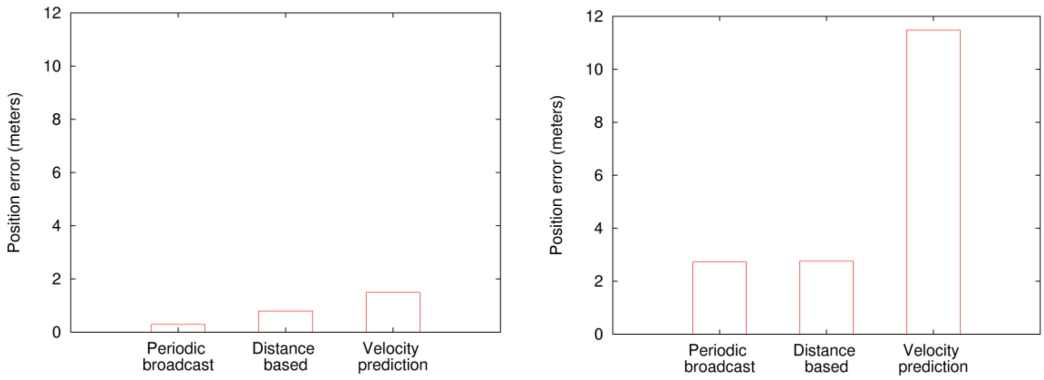


(b) Accuracy = 1m

Figure 4.5: Average delay in Accelerate-Decelerate model

Figure 4.5(a) shows the average delay in the accelerate-decelerate model when $d_{ACCURACY}$ is 10 meters. The average delay of all the 3 schemes is comparable with the periodic broadcast scheme performing slightly better than the velocity prediction and periodic broadcast schemes. There is no significant rise in the delay as the number of vehicles in the network increases.

Figure 4.5(b) shows the average delay in the accelerate-decelerate model when $d_{ACCURACY}$ is 1 meter. For all 3 schemes, as the number of vehicles increases, the average delay also increases.. The increase in average delay as the number of vehicles increases is smaller for the velocity prediction scheme than the periodic and distance based schemes.



(a) Average position error (b) Maximum position error

Figure 4.6: Position error with 2 percent loss

Uniform random loss was introduced to study the robustness of the three schemes to loss. Position error was calculated as Position of the vehicle indicated in current message - expected position of vehicle - $d_{ACCURACY}$ (error is taken to be zero in case Position of the vehicle indicated in current message - expected position of vehicle $< d_{ACCURACY}$).

Figure 4.6(a) shows the average position error when the loss rate is 2% in the normal simulation model comprising of 100 vehicles with $d_{ACCURACY} = 1$m. The periodic broadcast scheme has the least average position error while the velocity prediction scheme has the highest average position error. Figure 4.6(b) shows the maximum position error when the loss rate is 2% in the normal simulation model comprising of 100 vehicles with $d_{ACCURACY} = 1$m. The maximum position error in the velocity prediction scheme was found to be about 12 meters. Such a high position error cannot be tolerated in a vehicular network. So we first try to find the upper bound for the position error caused due to a single packet loss in the velocity prediction scheme. We then suggest a solution to overcome this problem.

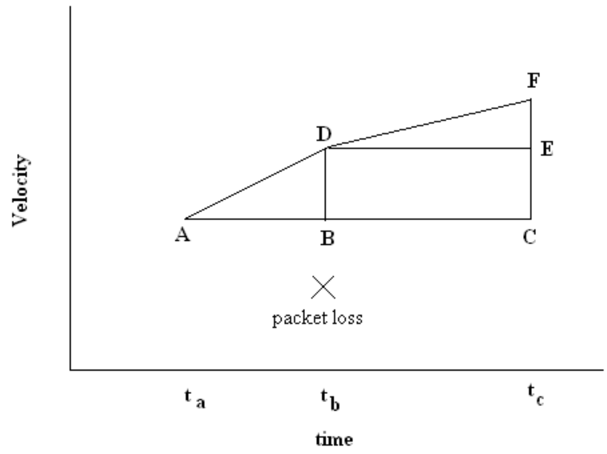


Figure 4.7: Position error due to single packet loss

To find the upper bound for position error due to a single packet loss, consider figure 4.7. To simplify the analysis, we do not take into account the change in direction of the vehicle while calculating the theoretical upper bound for position error. Let a vehicle initially have a velocity v and successfully broadcast its position at time t_a. The vehicle then accelerates and tries to broadcast the next position message at time t_b but this packet is lost. The vehicle then again accelerates and transmits the next position message successfully at t_c.

The total error in the position in the velocity prediction scheme would be the sum of the areas ABD, DEF and BCED. For maximum error, these areas should be maximum. ABD and DEF represent the distance traveled by the vehicle due to acceleration. Since in the velocity prediction scheme a position message is transmitted if the distance covered due to acceleration is $d_{ACCURACY}$, the maximum area of ABD is $d_{ACCURACY}$ and maximum area of DEF is $d_{ACCURACY}$. For area of BCED to be maximum, the length BC and BD must be maximum. BC represents the maximum time between two position broadcasts which in our velocity prediction scheme is $(R - d_{INTEREST})/V_{max}$. BD is the change in velocity of the vehicle between t_a and

t_b. BD is maximum if the vehicle accelerates at a_{max}. So

$$BD = a_{max}(t_b - t_a)$$

From equation 3.1 we know that

$$t_b - t_a = \sqrt{\frac{2d_{ACCURACY}}{a_{max}}}$$

So

$$BD = a_{max}\sqrt{\frac{2d_{ACCURACY}}{a_{max}}}$$

$$BD = \sqrt{2a_{max}d_{ACCURACY}}$$

So the maximum total error is

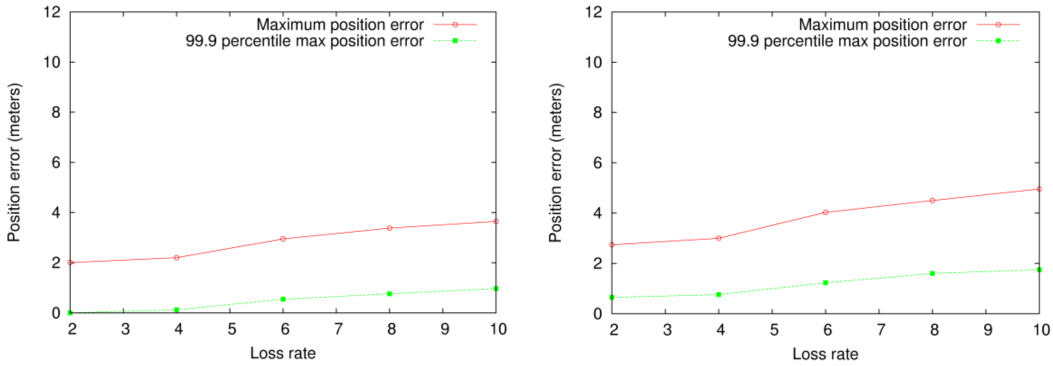
$$Total\ error = 2d_{ACCURACY} + \sqrt{2a_{max}d_{ACCURACY}}\left(\frac{R - d_{INTEREST}}{V_{max}}\right)$$

Since we allow an error of $d_{ACCURACY}$ the maximum net error is

$$Net\ error = d_{ACCURACY} + \sqrt{2a_{max}d_{ACCURACY}}\left(\frac{R - d_{INTEREST}}{V_{max}}\right)$$

If $d_{ACCURACY}$ is 1 m, a_{max} is 6 m/s^2, R is 250 m, $d_{INTEREST}$ is 125 m and V_{max} is 30 m/s then maximum net error is 15.43 m.

One solution to decrease position error is to retransmit the packet in case of a loss. The problem with retransmitting when packet loss occurs is that the sender has to depend on acknowledgements from the receiver to determine whether a packet has been lost. Since the position information is broadcast in the network, the number of acknowledgements received from the neighbors can be very high. Although the number of acknowledgements can be decreased using simple randomization techniques,



(a) Normal model (b) Accelerate-decelerate model

Figure 4.8: Maximum position error in velocity prediction scheme when $d_{ACCURACY}$ is 0.5m and $d_{INTEREST}$ is 240m

this would imply that the sender assumes that the packet has reliably reached all neighbors even though only a few of the neighbors responded with acknowledgements. Such an assumption may not be realistic in a wireless network.

To overcome this problem, we increased the rate of transmission of position messages in the velocity prediction scheme by operating at $d_{ACCURACY}$ and $d_{INTEREST}$ values that are better than the required values (for instance ensuring $d_{ACCURACY}$ is 0.5m even though the required $d_{ACCURACY}$ is 1m) .

Figure 4.8(a) shows the maximum position error and the maximum position error in 99.9% of the packets transmitted in the simulation with 100 vehicles, $d_{ACCURACY} =$ 0.5m and $d_{INTEREST} = 240$m for the velocity prediction scheme in the normal model. The maximum position error has decreased significantly. Even when the loss rate is 10%, the maximum position error is only 3.65 m.

Figure 4.8(b) shows the maximum position error and the maximum position error in 99.9% of the packets transmitted in the simulation with 100 vehicles, $d_{ACCURACY} =$ 0.5m and $d_{INTEREST} = 240$m for the velocity prediction scheme in the accelerate-decelerate model. The maximum position error has decreased significantly. Even when the loss rate is 10%, the maximum position error is only 4.96 m.

Although the rate of transmission of messages has increased, the number of messages transmitted by velocity prediction scheme is still only 28% of messages transmitted by the distance based scheme and 17% of messages transmitted by the periodic broadcast scheme.

The results show that the velocity prediction scheme performs significantly better than the distance based scheme and the periodic broadcast scheme in terms of number of messages transmitted and packet delay. Operating at better $d_{ACCURACY}$ and $d_{INTEREST}$ helps in significantly decreasing the position error due to packet loss in the velocity prediction scheme.

Chapter 5

Conclusion

In this thesis, vehicular ad hoc networks were introduced. The current standards emerging in vehicular networks were described. The research done in the routing in vehicular ad hoc networks was surveyed. The possible applications for vehicular networks and the techniques for implementing them have been explained.

We addressed position information dissemination in vehicular networks. The simplest scheme for position information dissemination is the periodic broadcast scheme. However the periodic broadcast scheme is inefficient. Two schemes, the distance based scheme and the velocity prediction scheme have been described in this thesis for disseminating position information to neighboring vehicles. The worst case analysis for all three schemes was studied. To analyze how the three schemes would perform practically, simulations were performed using the network simulator NS2 . Theoretical analysis and simulations indicate that the velocity prediction scheme performs better than the periodic broadcast scheme and the distance based scheme.

In the future, the research in position information dissemination can be extended. We have assumed that GPS provides accurate position information. However in practice, position measurements based are not accurate. In [26], the GPS error ranged from 4 meters to 106m and the average error was about 12.4 meters. Future work can try to address this problem. One possible solution to address this problem is to make use of other localization techniques such as ultrasound to complement the GPS measurements. In our work, we have used a simple velocity prediction scheme. Future work can investigate improving velocity prediction.

Appendix A

Adaptive Probabilistic Forwarding

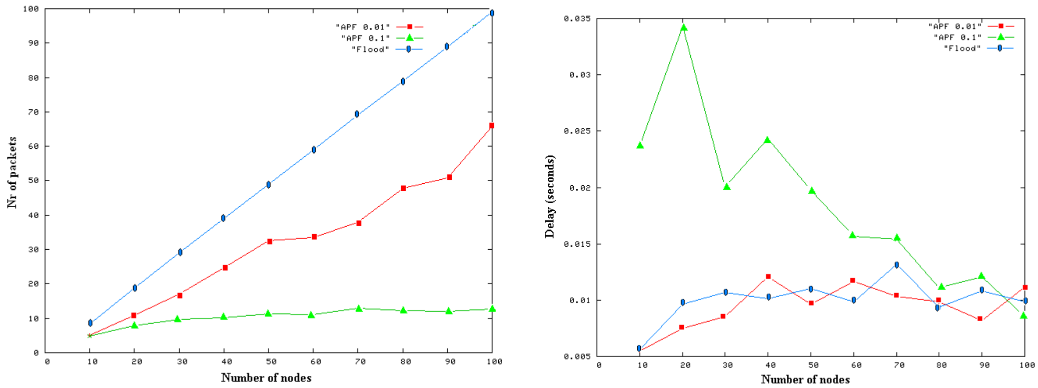
Flooding is the simplest scheme for informing a message to all nodes in the network. However flooding is inefficient and can result in the broadcast storm problem where several nodes may contend for the channel to transmit the same message. [6] proposed several solutions to the broadcast storm problem including the probabilistic scheme where a node forwards a packet with a probability p and drops the packet with a probability $1 - p$. One of the problems with this solution is that it is difficult to predetermine the value of p. So we investigated the Adaptive Probabilistic Forwarding (APF) algorithm that uses adaptive forwarding probability and delayed forwarding. The basic idea of the algorithm is that if a new packet is received, it should be buffered and should not be immediately transmitted. The packet forwarding is delayed by T_{Delay}. If no packets have been received by this time, then the packet will definitely be forwarded. The probability of forwarding the packet decreases as more packets of the same sequence number are received. The algorithm is described below

- When a packet is received, if the sequence number of the packet matches with any of the sequence numbers of already transmitted packets then drop the packet (this is also done in flooding).

- If the packet has not yet been transmitted by the node, it is not immediately forwarded, but instead stored in a buffer. The sequence number is also noted. The time when the packet will be forwarded, T_{Delay}, is picked using a uniform random distribution function which generates a random variable in the range 0 to $T_{MaxDelay}$. The probability of forwarding the packet, $P_{Forward}$, is initially set to 1. A timer which expires after T_{Delay} is started.
- Before the timer expires, if another packet with the same sequence number is received by the node, the probability of forwarding $P_{Forward}$ is halved. If the probability falls below a threshold probability $P_{Threshold}$, then the packet is dropped from the buffer and not retransmitted.
- Once the timer is triggered, the packet is removed from the buffer and forwarded with a probability $P_{Forward}$ and dropped with a probability $1-P_{Forward}$.

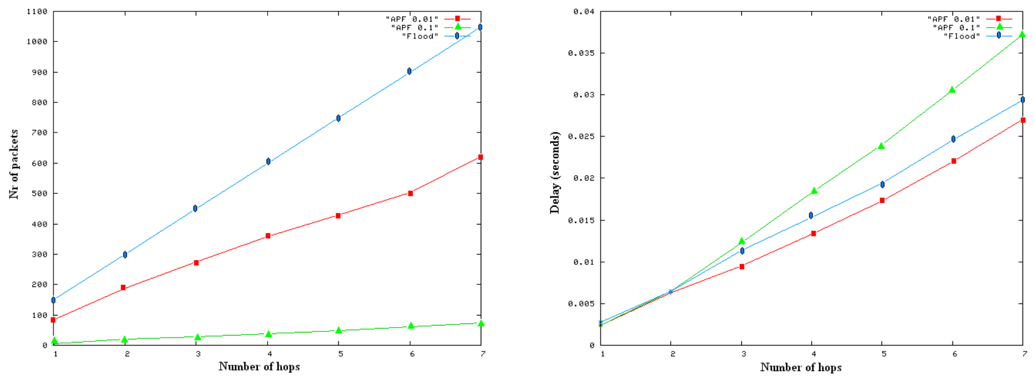
The Adaptive Probabilistic Forwarding routing algorithm was implemented as a routing module of the network simulator NS2. The Adaptive Probabilistic Forwarding algorithm was compared with flooding. During the simulation, a randomly chosen vehicle broadcasts a packet into the network at a random time. The remaining nodes try to forward the packet using flooding and Adaptive Probabilistic forwarding.

The transmission range of nodes is 250 m. The Medium Access Control layer used is 802.11. $P_{Threshold}$ is 0.05. $T_{MaxDelay}$ was varied in the range 0.01 seconds to 0.1 seconds. Two scenarios namely moving traffic and stationary traffic (where vehicles



(a) Nr of packets forwarded (b) Average delay

Figure A.1: Results for moving traffic



(a) Nr of packets transmitted (b) Average delay

Figure A.2: Results for stationary traffic

are stuck in a traffic jam) were studied. Figure A.1 shows the results for moving traffic and figure A.2 shows the results for stationary traffic.

For the moving traffic scenario, traffic over a 1 kilometer stretch of road is studied and the number of hops (4 hops in our case) was kept fixed. From figure A.1 we observe that for moving traffic when the number of nodes is high, the number of packets forwarded by Adaptive Probabilistic Forwarding (with $T_{MaxDelay} = 0.1$ seconds) is about 10 times less than the number of packets forwarded using the flooding scheme. The average delay for Adaptive Probabilistic Forwarding (with

$T_{MaxDelay} = 0.1$ seconds) is greater than the delay for flooding when there are fewer nodes in the network. However this delay is still in the order of milliseconds and is tolerable. As the number of nodes in network increases, the average delay for Adaptive Probabilistic Forwarding (with $T_{MaxDelay} = 0.1$ seconds) decreases.

For stationary traffic, the effect of flooding and Adaptive Probabilistic Forwarding was studied over multiple hops. From figure A.2 we observe that over 7 hops, more than 1000 packets are forwarded by flooding compared to about 100 packets forwarded by Adaptive Probabilistic Forwarding (with $T_{MaxDelay} = 0.1$ seconds). The average delay for forwarding the packet over multiple hops is less for flooding. However, the average delay for Adaptive Probabilistic Forwarding (with $T_{MaxDelay}$ $= 0.1$ seconds) is still small (about 35 milliseconds over 7 hops).

These results show that Adaptive Probabilistic Forwarding shows promise for being used to broadcast packets in vehicular networks.

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